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Bridging the Gap: The AI-TPACK Model for Teacher Professional Development in Early Childhood AI Literacy

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Abstract

The pervasive integration of Artificial Intelligence (AI) into the social and educational fabric of society has precipitated an urgent and non-negotiable need for AI literacy, a competency that must now be cultivated from the earliest years of schooling. While a burgeoning body of research has begun to demonstrate the feasibility, benefits, and methodologies for introducing AI concepts to young children, a profound and persistent barrier threatens to undermine this progress: a widespread lack of teacher readiness. This comprehensive conceptual paper addresses this critical impediment by proposing the AI-TPACK Model, a novel professional development framework that explicitly adapts and extends the Technological Pedagogical Content Knowledge (TPACK) model for the specific context of early childhood AI literacy. The AI-TPACK Model is then introduced as a multi-stage framework comprising four synergistic modules: (1) Foundational AI Concepts, (2) ECE-Appropriate AI Tools, (3) AI-Specific Pedagogy, and (4) Ethical Integration. The paper contributes to the field by providing a structured pathway for transforming ECE educators from apprehensive observers to confident facilitators of AI literacy, thereby ensuring that the integration of AI in early learning environments is both pedagogically sound and ethically grounded. This framework serves as a critical foundation for future research, policy development, and institutional implementation, positioning effective teacher preparation as the crucial linchpin for the responsible and equitable future of AI in early learning environments.

Keywords

AI Literacy, Early Childhood Education, AI-TPACK Model, TPACK

Framework, Pedagogical Integration

1. Introduction

The 21st century has been characterized by a digital revolution that is fundamentally reshaping human civilization. At the heart of this transformation lies Artificial Intelligence (AI), a field that has evolved from theoretical computer science and science fiction into an ubiquitous force permeating nearly every aspect of daily life [1]. From recommendation algorithms that curate our digital experiences to autonomous systems that manage critical infrastructure, AI technologies are becoming increasingly embedded in our social, economic, and educational ecosystems [2]. This technological paradigm shift has irrevocably entered the educational sphere, prompting a fundamental re-evaluation of the skills, knowledge, and literacies required for children to thrive as informed citizens, critical thinkers, and ethical participants in an increasingly digitally mediated world [3].

In response to this transformation, the concept of "AI literacy" has emerged as a critical component of modern education [4]. The definition of AI literacy has evolved significantly from early conceptualizations that focused primarily on understanding basic technical concepts [5]. Contemporary frameworks now define AI literacy more holistically as a set of competencies that enable individuals to critically evaluate AI technologies, communicate and collaborate effectively with AI systems, use AI as a tool responsibly and creatively, and understand the social and ethical implications of AI applications [6]. This expanded definition reflects the growing recognition that technological proficiency alone is insufficient; students must develop the critical capacities to navigate, question, and shape the AI-powered world they are inheriting.

This imperative for AI literacy extends beyond older students and adults to the earliest years of education. The Early Childhood Education (ECE) period, encompassing ages 3 to 8, represents a uniquely formative stage for cognitive, social, emotional, and moral development [7]. It is during these years that children begin to construct their fundamental understanding of the world, develop foundational cognitive schemas, and form initial attitudes toward technology and learning [8]. This developmental period therefore represents a crucial window for introducing foundational technological concepts in a safe, guided, and developmentally appropriate manner that aligns with the play-based, experiential approaches that characterize high-quality early childhood practice [9].

Pioneering empirical work has convincingly demonstrated that young children are not only capable of engaging with AI concepts but can do so with enthusiasm, comprehension, and surprisingly sophisticated understanding [9]. Studies utilizing social robots like PopBots have successfully taught preschoolers about rule-based systems and supervised machine learning through carefully designed interactive games and activities [10]. Similarly, research with conversational agents such as Zhorai has shown that children as young as four can grasp core ideas of machine learning through natural dialogue and interaction [11]. These findings challenge traditional assumptions about young children's cognitive capacities regarding abstract technological concepts and suggest that early exposure to AI literacy, when properly scaffolded, can build foundational understanding that supports later learning [12].

In their seminal scoping review, scholars meticulously mapped this nascent but rapidly evolving landscape of AI literacy in ECE [13]. Their synthesis of 16 empirical studies published between 2016 and 2022 provided an invaluable overview of the tools, pedagogical approaches, assessment methods, and learning outcomes documented in this emerging field. However, their analysis also surfaced a consistent and deeply concerning theme that threatens to undermine the potential of AI literacy initiatives: the most significant barrier to the effective integration of AI literacy is not a lack of technological tools or child capability, but a profound deficit in teacher readiness. The authors identified "lack of teachers' AI knowledge, skills, confidence, and attitudes" as the most frequently cited challenge, further exacerbated by a "lack of teaching guidelines" and "lack of curriculum design" [14]. This finding reveals a critical and dangerous disconnect in the current trajectory of AI in education: the field is energetically developing increasingly sophisticated tools for children while largely failing to equip the very educators who are essential to mediating, contextualizing, and facilitating children's learning with these technologies.

This conceptual paper directly confronts this disconnect by arguing that the current fragmented and often techno-centric approach to AI in ECE is both unsustainable and potentially inequitable. Without a systematic, evidence-based, and scalable model for teacher professional development, the promise of AI literacy will remain unfulfilled for the vast majority of young children, potentially exacerbating existing digital divides and creating new forms of educational inequality [15]. The rapid pace of AI development means that waiting for teachers to gradually develop competence through informal means will inevitably leave education systems struggling to catch up with technological change, ultimately failing to prepare children for the world they will inhabit [16].

Incorporating Su *et al.*, this paper addresses the pressing issue of teacher preparedness for implementing AI. We start by moving beyond a vague notion of a "readiness gap" to systematically deconstruct the idea into three core, intertwined challenges. To address this gap, we have built our AI-TPACK model—a holistic framework grounded in the well-established TPACK model [17], providing structured pathways to professional development from theoretical insight to confident classroom practice. Ultimately, our aim is to catalyze a broader movement; we conclude not just with ideas but with a concrete call to action for researchers, policymakers, and institutions to collaborate in building systemic capacity for AI literacy in early childhood education.

2. Literature Review

2.1. The Evolution of AI Literacy

The concept of AI literacy has evolved significantly since the term was first coined by Burgsteiner *et al.* and Kandlhofer *et al.* in 2016 [5] [18]. Initially conceived as understanding basic AI concepts and principles, the definition has expanded to encompass a broader range of competencies. Long and Magerko (2020) defined AI literacy as "a set of competencies that enable individuals to critically evaluate AI technologies, communicate and collaborate effectively with AI, and use AI as a tool online, at home, and in the workplace" [19]. This definition reflects a shift from purely conceptual understanding to include practical, critical, and ethical dimensions.

More recently, Ng proposed a framework that conceptualizes AI literacy through the lenses of AI concepts, practices, and perspectives [20]. This framework emphasizes not only what individuals should know about AI but also what they should be able to do with AI and how they should approach AI ethically and responsibly. This evolution mirrors broader trends in educational technology that recognize the importance of moving beyond technical proficiency to develop critical digital citizenship [14].

2.2. AI in Early Childhood Education

In early childhood education, there is recent and emerging research on AI with promising findings in many areas. Williams *et al.* (2019) created PopBots, a toolkit using social robots to teach preschool children about AI concepts such as rule-based systems, supervised machine learning, and generative AI [21]. Their investigation showed that young children could recognize the ideas when presented using developmentally appropriate activities. Similarly, Lin *et al.* (2020) created Zhorai, a conversational agent that helped children explore machine learning concepts through dialogue and interaction [22]. Over and above particular interventions focusing on AI literacy, AI systems have been used in ECE settings to help meet different learning goals. Personalized forms of education can benefit from intelligent tutoring systems [23] and AI-driven educational robots to enhance language learning and social skills [24]. Yet these apps tend to situate children as consumers of AI rather than creators, and thus there's a call for an approach to engage with children in order to foster their understanding of how AI works [25].

2.3. Teacher Professional Development for Technology Integration

Based on literature on teacher professional development for technology integration, we have identified multiple key factors that are critical to the positive integration of technology for teachers. The Technological Pedagogical Content Knowledge (TPACK) framework is one of the most influential models that seeks the understanding of knowledge on how teachers can integrate technology into their teaching effectively [26]. TPACK highlights the intricate interactions between technological knowledge, pedagogical knowledge, and content knowledge, and holds that synthesis of the knowledge in the respective domains is necessary for good integration. The success of TPACK-informed professional development has been documented empirically and across various educational contexts and technologies [27]. However, the application of TPACK to AI literacy in early childhood settings remains largely unexplored. This gap is particularly significant given the unique characteristics of both AI as a technology and early childhood as an educational context.

3. The Imperative for AI Literacy in Early Childhood

Before attempting to solve the teacher readiness gap, however, it is necessary to fully clarify the reasons why AI literacy is both a necessary and important aspect of today's early childhood education. That has to do far more than being tech savvy or ready for the workforce; it has to do with the developmental suitability of AI, initial citizenship skills, and the exceptional learning opportunities presented by the concepts AI offers for children.

3.1. Demystification and Foundational Understanding

Young children are naturally curious about the world and more and more they come to experience AI in their daily lives more commonly and with little or no acknowledgment [28]. Children are coming of age in a world embedded with AI, including everything from inquiry on smart speakers, access to tailored content on tablets, and play with interactive toys that integrate AI features [29]. Left to do so unguided and without accompanying explanations, children can fall prey to the "animistic" stereotypes commonly theorized by psychologists, believing that human-like thoughts, feelings and intentions underpin all intelligent-looking machines [30]. Prompt events about AI literacy make such technologies less mysterious by showing the work done by the systems [31]. By doing the kinds of activities that make visible the "rules" that regulate a robot, or by showing how dependent a machine learning model is on data, children develop accurate mental models of how AI operates and why AI is different from human intelligence [10]. This grounding in early concepts may also be developmentally appropriate compared to trying to correct deeply held misconceptions later in life since a foundation of early schemas is more resistant to challenge [10].

3.2. Fostering Critical and Ethical Thinking

The early childhood classroom forms a good stage for planting the seeds of digital ethics and critical thinking about technology [20]. As AI systems are not neutral, they are made by our choices, our values, and our biases, and they can perpetuate or even amplify current social inequalities [18], a phenomenon critically examined in foundational works on algorithmic bias [32]. Through these intentional activities and discussions, teachers can provoke developmentally appropriate discussions about fairness, privacy, accountability, and transparency of AI systems [1]. When an image recognition task does not correctly identify a toy belonging to a given culture, or when a voice assistant behaves differently in response to diverse accents, those things become immediately teachable moments about algorithmic bias and about the significance of heterogeneous and representative data [5]. In that early encounter with the social aspects of technology, educators create what they describe as a "critical disposition" toward technology, in which children begin to challenge technological systems instead of simply accepting them as objective or an inescapable outcome [18].

3.3. Some Common Mistakes

The pedagogical models of AI literacy in ECE, specifically play-based learning, project-based exploration, hands-on experimental methods, and collaborative problem-solving are pre-eminent foundations of high-quality early childhood practice [3], and are supported by research on digital play that advocates for the meaningful integration of technology within play-based pedagogies [30]. A well-designed AI literacy activity does not mean that we stray from traditional early childhood pedagogy, but rather its context, offering new and relevant use cases [9]. Building a block structure that a robot can navigate fosters spatial reasoning, sequencing skills, and computational thinking [21]. Teaching a classifier to recognize sounds from different animals integrates literacy, science, and pattern recognition. Programming a simple robot to navigate a maze develops planning, problem-solving, and debugging skills [10]. In the process, AI literacy is a way to build on and add to existing developmental achievements instead of another siloed topic vying for a small proportion of instructional time [9].

3.4. Future Readiness and Equity Considerations

Finally, the implementation of AI literacy in early childhood contributes profoundly to preparedness and pedagogical equity. With AI technologies increasingly interwoven within all domains of life, knowledge of the fundamental principles and limitations of these technologies will be essential for full engagement with civic, economic, and social life [13], laying the groundwork for responsible digital citizenship [33]. The ease of learning about (and interaction with) these technologies can be achieved through early exposure, which may be a way to combat gender and racial biases in technology domains that are likely to emerge at a young age [2]. More explicitly, without deliberate initiatives to implement AI literacy in early childhood contexts, this important concept risks becoming yet another realm in which well-represented children benefit early from informal learning opportunities at home, possibly compounding existing achievement gaps. Schools, hence, have a critical responsibility in providing equitable access to early AI literacy.

3.5. Acknowledging Potential Challenges and Counterarguments

While the case for early AI literacy is compelling, it is crucial to acknowledge legitimate concerns. Critics may point to issues such as the potential for increased screen time, the complexity of data privacy and security when dealing with young children's information, and the developmental appropriateness of introducing abstract AI concepts. The responsible implementation of the AI-TPACK framework directly addresses these concerns. It emphasizes "unplugged" activities (Module 1) to minimize screen time, integrates ethical discussions about data and privacy from the outset (Modules 1 & 3), and is fundamentally grounded in developmentally appropriate practice [22], translating complex ideas through play, storytelling, and concrete experiences. Thus, the framework presented here is designed not to ignore these challenges, but to provide a structured path for navigating them responsibly.

4. Deconstructing the Teacher Readiness Gap: Three-Dimensional Challenge

Teacher Readiness for AI Literacy Integration Su *et al.* [12], is not a single problem, but rather an organic result of many intertwined but independent constructs. This three-dimensional conceptualization emerged from a systematic analysis of the 16 empirical studies reviewed by Su *et al.* [12]. Our analysis involved a qualitative thematic synthesis of the reported challenges and barriers faced by educators in these studies. We iteratively coded the text, identifying recurring themes related to teacher preparedness. This process revealed three predominant and interconnected themes, which we have formalized as the core dimensions of the teacher readiness gap: conceptual knowledge, self-efficacy, and pedagogical capacity. The findings from this systematic analysis thus directly inform and underpin the framework presented in this section. Drawing upon a systematic review of literature concerning educational technology, teacher professional development, and early childhood education, we conceptualize this shortfall along three broad dimensions that need to be focused on simultaneously and synergistically if we are to have professional development work that delivers real improvements.

4.1. The Conceptual Knowledge Dimension

Early childhood education professionals are also most likely inexperienced with computer science, engineering, or other related technical fields. As a result, there is an immeasurable knowledge gap about what we refer to as AI Content Knowledge (AI-CK)—knowledge of certain AI concepts, principles, limitations, and the practical implications of those concepts. Tools and platforms, including PopBots [10], Google's Teachable Machine [14], Cognimates [24], or educational robots, are engineered with accessibility of service users in mind but still require the facilitating adult to grasp underlying principles and be able to communicate in visible terms. A teacher needs to understand, at a minimum, how sensors are a set of "senses" of technology, how machine learning models find patterns in the data, how rule-based systems make decisions, and how generative AI creates new content. There it will be that absent this basic AI-CK, a teacher simply will play the technician in terms of setting the activity up and doing procedural activities while they struggle to scaffold for children their own understanding of a concept, answer a question that they are bound to wonder, or make a meaningful connection with what the children already know and what they have already experienced, or even pinpoint them for any future misunderstanding that arises. They simply cannot grasp that conceptual knowledge is not just academic but rather is more of a critical component of the teacher's ability to provide meaningful experience and is regularly identified as the main cause of distress and avoidance from educators by many teachers who are exposed to AI applications.

4.2. The Self-Efficacy and Confidence Dimension

Partly related to the knowledge gap is a powerful psychological hurdle called low self-efficacy. According to Bandura's social cognitive theory, teacher self-efficacy is the belief in one's ability to organize and carry out the planned activity to achieve the goal of a given teaching task [29]. In the domain of AI literacy, this relates to perceived capabilities to comprehend AI concepts, be proficient with AI tools and troubleshoot technical problems, and to enable meaningful learning experiences of AI tools [6]. The high perceived complexity, abstract quality, and opaque "black box" design of many AI systems may pose serious concerns, including anxiety, technostress, and imposter syndrome among practitioners [34]. This is especially true in early childhood education, where teachers perceive themselves more as the caregivers and developmental guides than the "tech experts" [35]. Such low self-efficacy represents a powerful psychological deterrent; studies repeatedly find that teachers with low self-efficacy who do not think they can comprehend or teach a topic appropriately, are extremely unlikely to choose to self-administer a subject despite the existence of resources, administrative pressure, and perceived significance [23]. This is supported by research specifically on building self-efficacy for technology integration [36]. It is therefore just as vital to overcome this affective barrier as to bridge the cognitive level, since confidence in making this adjustment is not only the building block of openness to attempt new activities but also encourages working at a level that is open to being "tough" under pressure and to develop a conducive classroom climate for technology exploration.

4.3. The Pedagogical Capacity Dimension

However, although early childhood teachers need good material knowledge of AI-PK, they need to have the knowledge of translation of AI concepts and tools into an effective, interesting, developmentally sensitive learning environment for early childhood teachers. Play is an important component of the early childhood classroom; it is a uniquely situated pedagogy that values interactive learning, real-world, hands-on teaching, hands-on activities, and a blend of learning domains. Direct instruction options to teach AI concepts to older students or adults are mostly ineffective and inappropriate in this age group. Such teachers also need a wealth of knowledge to teach practical strategies to translate abstract thinking such as "training a machine learning model" into a game of physical object sorting, using a digital tool like Teachable Machine to extend children's innate interests in classification or conducting collaboration projects whereby children make it their group effort to code a robot [37]. They need guidance in how to ask open questions that stimulate computational thinking, how to navigate the challenges of logistics and technology use in a play-based classroom, how to record and monitor AI-enabled learning and children's processes of engagement in this area, and how to connect AI experiences with curricula. This pedagogical capacity dimension is related to the knowledge and ability to instruct, not just to know what to teach, but to know how to do it well with very young learners with distinct developmental profiles, interests, and ways of knowing [38].

5. Theoretical Foundation: The AI-TPACK Model

To coherently and effectively respond to these three dimensions of the teacher readiness gap, we introduce the AI-TPACK Model, an inclusive approach based on the renowned Technological Pedagogical Content Knowledge (TPACK) model by Mishra and Koehler [14]. The AI-TPACK Model is a specialized evolution and extension of TPACK, explicitly designed to address the unique challenges and opportunities of preparing early childhood educators for AI literacy integration.

5.1. TPACK Foundations

The original TPACK framework offers a strong theoretical perspective for comprehending the complex knowledge bases that teachers require to successfully incorporate technology in their teaching. According to TPACK, technology integration is not just the addition of technological knowledge to existing content and pedagogical knowledge. Rather, it demands a synergistic, contextualized and dynamic interpretation of the interdependence of three central components: Content Knowledge (CK), Pedagogical Knowledge (PK) and Technological Knowledge (TK). It also distinguishes three secondary knowledge sources at the confluence of the core domains: Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK). The central aim is to develop TPACK, or the integrated understanding, which consists of the integration of these knowledge domains, to allow teachers to plan and design learning experiences that have technology, content, and pedagogy in harmony [25].

5.2. Specification of AI-TPACK Model

To respond to the current demand for teacher preparedness in Early Childhood Artificial Intelligence (AI) education this study uses the Technological Pedagogical Content Knowledge (TPACK) framework to develop an AI-specific model—AI-TPACK Framework. (**Figure 1**)

A critical, cross-cutting theme that permeates all aspects of the AI-TPACK model is ethical consideration. Unlike being a separate knowledge domain, ethical reasoning about AI—encompassing fairness, accountability, transparency, and privacy—is integrated throughout the framework. It informs AI-CK (understanding algorithmic bias), AI-PK (strategies for discussing ethics with children), and AI-TK (evaluating the ethical implications of tools). Consequently, ethical considerations are inherently woven into the intersections (AI-PCK, AI-TCK, AI-TPK) and are a fundamental component of the integrated AI-TPACK, ensuring that teachers are prepared to address the societal dimensions of AI in a developmentally appropriate manner, including critical discussions of fairness and oppression as analyzed in broader technological contexts [32].

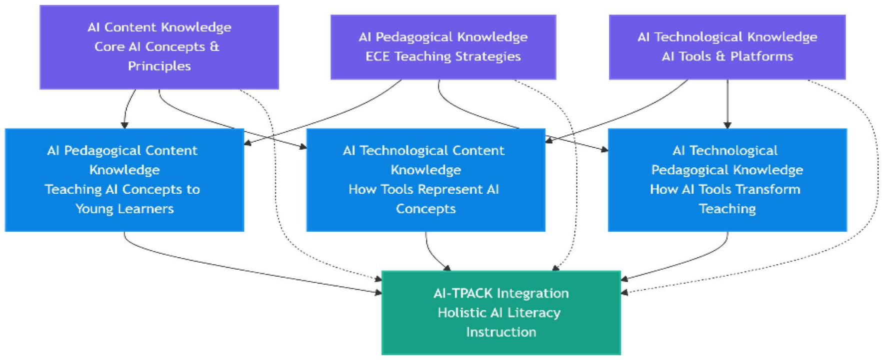

Figure 1. AI-TPACK conceptual framework.

5.3. Core Knowledge Domains

Artificial Intelligence learning Content Knowledge (AI-CK)—A teacher's basic understanding of various basic AI principles, which include perception, representation and reasoning, machine learning, natural interaction, and social impact. He has an understanding of the actual applications, restrictions and ethical questionings of AI as part of "Five Big Ideas of AI". This paper builds on frameworks like the "Five Big Ideas of AI" [20] and considers awareness concerning the AI's role in practice.

AI Pedagogical Knowledge (AI-PK)—This part of learning involves knowledge about how to teach and learn AI concepts and their application to early childhood education. This ranges from play-based, project-based, and guided-discovery techniques; from an understanding of how young children learn and develop, to advocacy for nurturing equitable contexts for AI exploration.

AI Technological Knowledge (AI-TK)—Includes knowledge of AI tools and platforms like Teachable Machine [31], PictoBlox, educational robots, and other conversational agents. But it goes beyond the operational part so far—it also encompasses conceptual literacy of how the technologies act, what they can offer, and what they can do for classroom practice [25].

The intersection of topics, fields, and ideas is a natural learning outcome for the introduction of AI and AI literacy at school. Knowledge and skills related to an integrated approach are the subject of future efforts.

AI Pedagogical Content Knowledge (AI-PCK): How to bring AI-based materials within reach of young learners so that misconception recognition, use of age-appropriate analogies with children's minds (like "computer brains", which can illustrate machine learning) and logical organization of learning are accomplished effectively is now their basic line of investigation.

AI Technological Content Knowledge (AI-TCK) Knowing how AI tools can illustrate and represent AI concepts. For example, Teachable Machine renders classification accessible, and block-based coding environments also help children to understand sequencing and logic.

AI Technological Pedagogical Knowledge (AI-TPK)—Understand how AI tools reform curriculum and teaching practice. Teachers recognize, for example, that a social robot can boost engagement among shy children, that accessible interfaces can support diverse learners, and that collaborative use of AI tools can enhance communication and teamwork.

The Integrative Core. The framework centers around AI-TPACK Integration, which corresponds to AI literacy integration into every aspect of instruction. This understanding allows educators to work collaboratively across pedagogies, content offerings, and technology—developing learning experiences that integrate AI tools with pedagogical practices and conceptual objectives.

The promise of the AI-TPACK framework is that it eschews siloed, one-size-fits-all professional development. Only training on AI-CK, then, misses the mark on pedagogy: workshops focusing only on AI-TK don't create conceptual depth. AI-TPACK highlights the inter-relating strength and skill-building process with respect to this task, resulting in confident, context-attuned pedagogy that promotes primary AI literacy in young learners [25].

6. The AI-TPACK Professional Development Framework

The AI-TPACK Model is mapped into a multi-module, sequential professional development framework for teachers to be offered over 4 - 6 weeks for reflection, peer collaboration, and iterative practice between sessions. The framework is tailored to be built upon sequentially, moving teachers from foundational knowledge to integrative application while simultaneously addressing all three dimensions of the readiness gap.

Each of the four PD modules is explicitly designed to develop specific components of the AI-TPACK model, as detailed in **Table 1**. This structured progression ensures a coherent journey from building discrete knowledge bases toward their sophisticated integration [26].

Table 1. Mapping of AI-TPACK professional development modules to AI-TPACK components.

Professional Development Module	Primary AI-TPACK Focus	Secondary/Integrated AI-TPACK Components
Module 1: Foundational AI Concepts	AI Content Knowledge (AI-CK)	(Lays foundation for all)
Module 2: AI Tool Exploration	AI Technological Knowledge (AI-TK)	AI Technological Content Knowledge (AI-TCK)

Continued

Module 3: AI Pedagogical Translation	AI Pedagogical Knowledge (AI-PK)	AI Pedagogical Content Knowledge (AI-PCK), AI Technological Pedagogical Knowledge (AI-TPK)
Module 4: AI-TPACK Synthesis	AI-TPACK Integration	AI-CK, AI-TK, AI-PK, AI-PCK, AI-TCK, AI-TPK

6.1. Module 1: Foundational Knowledge—Deconstructing AI (AI-CK Focus)

- Primary Goal: To demystify AI and build foundational conceptual understanding, thereby directly targeting the Knowledge Dimension and beginning to address the Self-Efficacy Dimension by demonstrating the accessibility of core concepts.
- Core Content: This module introduces AI not as magic or incomprehensible complexity, but as a human-designed tool based on identifiable principles. It leverages the "Five Big Ideas" of AI developed by Touretzky *et al.* [20]—Perception, Representation & Reasoning, Learning, Natural Interaction, and Social Impact—and adapts them for an ECE context using familiar analogies and concrete examples. The module is predominantly "unplugged", using physical, non-digital activities to make abstract concepts tangible and accessible.
- Activity Example (Perception): A "Sensor Scavenger Hunt" where teachers first use their own senses (sight, hearing, touch) to explore the environment and then map these sensory experiences to a robot's analogous sensors (camera, microphone, touch sensor), discussing similarities and differences.
    - Activity Example (Learning): A "Pattern Party" game where teachers sort physical objects (e.g., buttons, leaves, fabric swatches) by different attributes, then reflect on how their sorting rules resemble how a machine learning algorithm finds patterns in data.
    - Activity Example (Ethics): A "Fairness Discussion" using picture books or scenarios that raise questions about fairness, bias, and inclusion, with explicit connections to how these issues manifest in AI systems.
- Outcome: Teachers can articulate basic AI concepts in their own words, identify real-world AI applications in their classroom and home environments, demonstrate initial understanding of AI ethics, and experience a confidence boost through realizing that the core ideas are accessible regardless of technical background.

6.2. Module 2: AI Technological Familiarity—Hands-On Tool Exploration (AI-TK Focus)

- Primary Goal: To reduce technophobia and build practical, hands-on experience with a curated set of ECE-appropriate AI tools, further bolstering Self-Efficacy and beginning to form AI Technological Content Knowledge (AI-TCK) by connecting tools to concepts.

- Core Content: This module functions as a structured "playground" or "sandbox" session. (**Figure 2**) Teachers engage in low-stakes, exploratory interaction with key platforms identified in the literature as particularly suitable for early childhood. The emphasis is deliberately placed on the user experience and the conceptual affordances of the tool rather than on achieving expert-level proficiency or completing predetermined products [25].

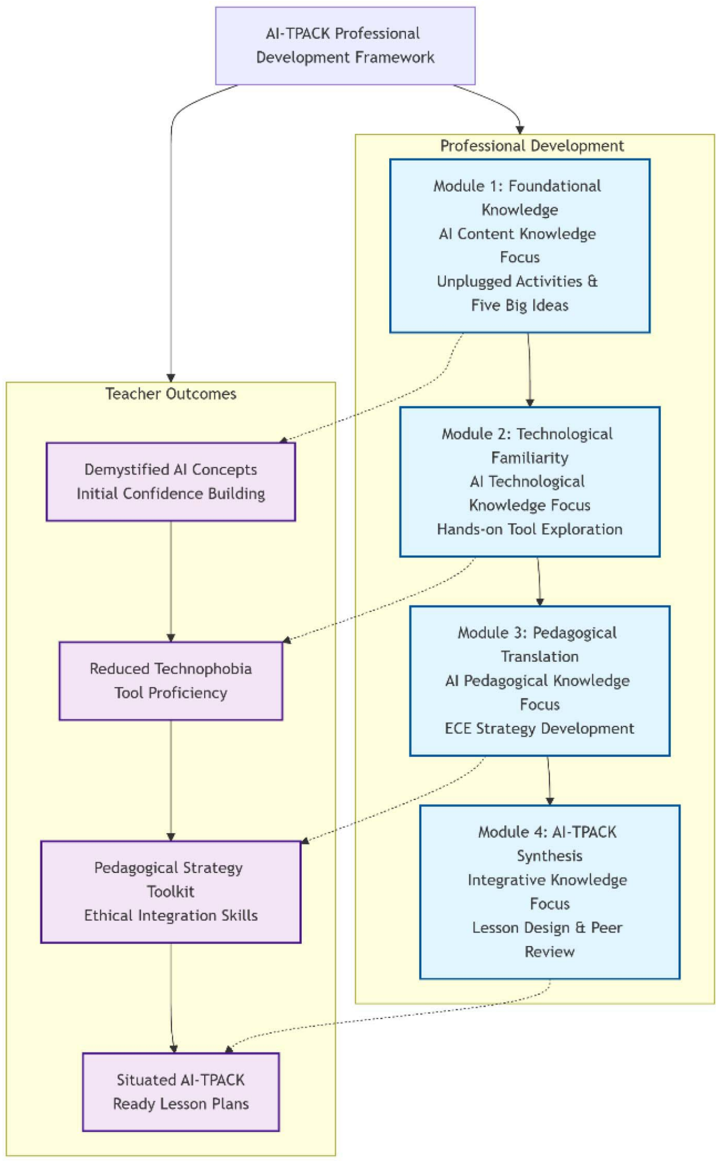

Figure 2. Presents the structure in its evolution.

- Tool 1: Google's Teachable Machine [31]. Teachers practice creating simple image and sound classification models using personal objects or their own voices, directly experiencing the process of "training" an AI and observing how changes in training data affect performance. This activity directly illustrates the "Learning" big idea and introduces concepts of data quality and bias.

- Tool 2: PictoBlox or Cognimates. Teachers use these block-based programming environments with AI extensions to create simple interactive projects, such as programming a character to respond to different gestures or sounds. This connects the familiar concept of sequencing and commands (foundational coding) with AI functionalities, building bridges between existing and new knowledge.
- Tool 3 (Optional): Simple Robotics. If resources permit, teachers explore basic programmable robots (e.g., Bee-Bots, Cubetto) or more advanced AI-interfaced robots (e.g., PopBots), focusing on how sensors and programmed rules create observable behaviors.
- Outcome: Teachers overcome initial apprehension about using AI tools, gain practical AI-TK through successful experimentation, begin to understand how these specific technologies (AI-TK) represent and illustrate the AI concepts (AI-CK) learned in Module 1, and develop troubleshooting strategies for common technical challenges.

6.3. Module 3: AI Pedagogical Translation—Designing for Young Learners (AI-PK Focus)

- Primary Goal: To build the specific pedagogical skills and knowledge required to translate AI concepts and tools into effective, engaging, and developmentally appropriate early learning experiences, directly addressing the Pedagogical Capacity Dimension.
- Core Content: This is the crucial "how to teach it" module. It explicitly connects the AI-CK from Module 1 and the AI-TK from Module 2 to the specialized pedagogies of early childhood education, facilitating the development of AI Pedagogical Content Knowledge (AI-PCK) and AI Technological Pedagogical Knowledge (AI-TPK).
- Pedagogical Strategies: Workshop leaders model and co-construct strategies for scaffolding complex ideas, facilitating open-ended inquiry, integrating AI activities into learning centers, managing technology in a play-based environment (e.g., rotation systems, collaboration protocols), fostering productive collaborative group work around a single device, and documenting children's learning processes and understanding.
- Ethical Integration: Guided discussions and case studies are used to explore practical approaches for introducing age-appropriate conversations about AI ethics. Teachers develop strategies for using children's literature, dramatic play scenarios, and real-world examples to discuss fairness (bias), privacy (data collection), responsibility (how we use AI), and transparency (how AI decisions are made) in ways that are meaningful for young children.
- Case Study: Teachers analyze and critique published lesson plans, video examples, and research vignettes from studies such as the PopBots curriculum [27] or the Zhorai activities [11], identifying the underlying pedagogical principles (AI-PK) and analyzing how these principles are effectively applied (AI-PCK,

AI-TPK).

- Outcome: Teachers develop a personalized toolkit of pedagogical strategies for AI literacy instruction, begin to form a critical understanding of what constitutes effective and appropriate AI literacy experiences in ECE settings, and create preliminary activity ideas tailored to their specific classroom context and student population.

6.4. Module 4: AI-TPACK Synthesis—Integrative Lesson Design and Peer Review

- Primary Goal: To synthesize all knowledge domains into original, actionable lesson plans, achieving the ultimate goal of developing situated AI-TPACK through collaborative design and critique.
- Core Content: This module is structured as a collaborative, project-based workshop. In small, supportive groups, teachers work through a structured design thinking process to create their own comprehensive AI literacy lesson plan. They are provided with an AI-TPACK-informed template that prompts them to explicitly articulate the connections between all knowledge domains:

1) The specific AI Concept (AI-CK) they are targeting and why it is developmentally appropriate.

2) The Pedagogical Approach (AI-PK) they will use (e.g., guided play, project-based learning, learning centers) and how it aligns with ECE best practices.

3) The Specific AI Tool (AI-TK) and a clear rationale for how it supports the targeted concept and chosen pedagogy.

4) Clear Learning Objectives for the children, aligned with early learning standards where possible.

5) A concrete plan for introducing and discussing relevant Ethical Considerations.

6) Strategies for Assessment and Documentation of children's learning.

- Peer Review and Micro-Teaching: Groups present their draft lesson plans and receive structured, constructive feedback from peers and facilitators using a protocol focused on AI-TPACK integration. Teachers then engage in "micro-teaching", a key segment of their activity to the cohort, providing an opportunity to practice facilitation skills and receive additional feedback in a low-risk environment.
- Outcome: Teachers produce at least one vetted, detailed, and ready-to-implement lesson plan. More importantly, they leave with the experience, confidence, and conceptual understanding of having successfully navigated the complex process of AI-TPACK-aligned instructional design, creating a sustainable foundation for continued innovation and adaptation in their own practice beyond the professional development program.

7. Implementation and Assessment Framework

This model for building AI-TPACK Proficient Educators is put into action via an implementation framework, where the model is sequentially built, providing support for this system as it turns into measurable outcomes. This framework has been architected to encompass three interleaved phases which are Support Structures, Assessment Framework and Desired Outcomes. (**Figure 3**)

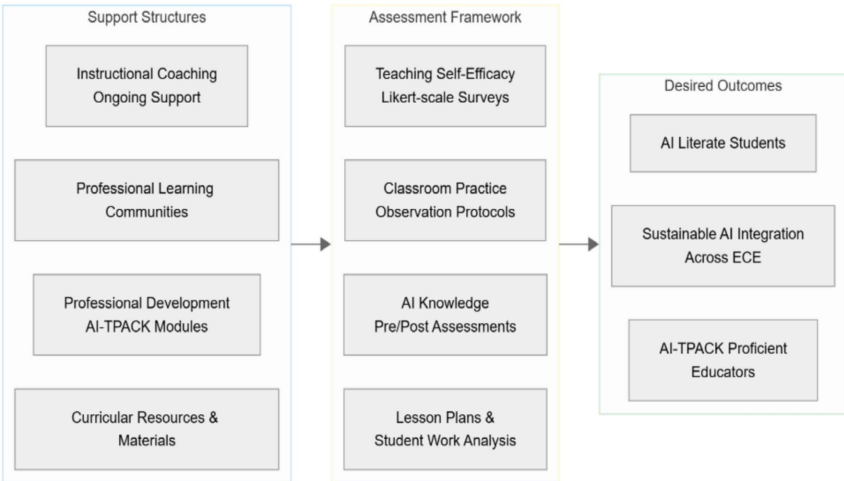

Figure 3. Presenting the structure in its evolution.

7.1. Support Structures: Mechanisms of Support

Phase One forms the critical scaffolding for educator development via four fundamental support structures:

1) PLC (Professional Learning Community): These are structured collaborative groups of educators who work cyclically to improve their AI implementation practices. The PLCs aren't just discussion forums but are data-driven teams. Such collaborative structures are a cornerstone of effective professional development, fostering sustained engagement and collective efficacy [18].

- Analyze Student Work: Review collaborative outputs from AI-integrated lessons aimed at uncovering misconceptions and gaps in student learning.
- Interrogate Teaching Practices: Discuss lesson plans and approaches to implementation with peers using an AI-TPACK-aligned perspective.
- Collaborate and Problem Solve: Tackle common integration issues involving ECE AI, such as choosing AI tools that are appropriate for a given age group or describing concepts to the child in developmentally appropriate ways.
- Build a Shared Resource Library: Collect and modify a shared set of effective strategies, tools or lesson ideas, building an increasing reservoir of knowledge.

2) Professional Development (AI-TPACK Modules): It is comprised of a collection of tiered learning modules that build the constructivist idea of integrated learning modules. Research underscores that effective PD is ongoing, content-focused, and aligned with teachers' classroom contexts [26]. The modules expand on tool-centric instruction to cover:

- AI Principles for ECE (The "TK"): Basic information on algorithms, data, pattern recognition, and machine learning based on unplugged activities and simple, useful applications, which young children can appreciate.

- Pedagogical Strategies (The "PK"): Instructional approaches including guided play, storytelling, and inquiry-based learning that are designed to be beneficial in order to develop AI concepts for ECE.
- Content Integration (The "CK"): How AI literacy interacts and supports teaching at a traditional ECE content level such as literacy, numeracy, and creative arts.

3) Instructional Coaching & Ongoing Support: This mechanism provides personalized, job-embedded assistance to fill the gap between PD and classroom practice. Instructional coaching is a powerful model for translating PD into practice, providing tailored feedback and support that leads to lasting change in instructional methods. [34] Coaches collaboratively plan lessons with educators to:

- Co-plan Lessons: Help them customize AI-TPACK module ideas into lesson plans tailored to their classroom-specific circumstances.
- Model Demonstrations: Watch live demonstration or video demonstration model lessons to help students see how AI integrates well in the classroom.
- Provide Side-by-Side Coaching: Provide face time for live feedback and support for implementing new activities with AI.
- Facilitate Reflection: Educators should be invited to a post-lesson debrief in class to make connections between teaching actions and student success and how these can be enhanced and fine-tuned in a step-by-step process.

4) Curricular Resources & Materials: To reduce implementation barriers, the platform provides a reviewed list of practical resources for educators to lean on. Access to high-quality, ready-to-use resources is critical for reducing the initial burden of implementation and encouraging teacher adoption of new practices [35].

- Exemplar Lesson Plans: Simple, ready-to-use plans that demonstrate high-quality, AI-TPACK integration.
- Activity Kits and Manipulatives: "Unplugged" activity kits that teach core AI concepts without screens.
- Digital Toolkits: A curated list of age-appropriate AI applications and platforms plus accompanying guides for their pedagogical use.
- Multimedia Resources: Short videos, interactive simulations and picture books that help introduce AI concepts to younger learners.

7.2. Assessment Phase: A Multi-Modal Feedback Loop

We assess the competencies built during implementation using an extensive multi-method assessment framework to obtain an overall picture of impact.

1) Classroom Practice Observation Protocols: These are standardized rubrics used by instructional coaches or peers to objectively document and evaluate AI-TPACK in action. The protocols assess indicators such as:

- The clarity of AI concepts presented.
- The effectiveness of pedagogical choices in making concepts accessible.

- The depth of student engagement and discourse around AI.
- The seamless integration of AI learning with core ECE content.

2) AI Knowledge Pre/Post Assessments: An empirically validated instrument that quantitatively measures the growth in educators' conceptual understanding of AI. They are generally scenario-based questions and concept inventories that test knowledge about machine learning, data bias, and the thinking process behind an algorithm and give a strong indication of what new knowledge teachers acquire in their professional development.

3) Teaching Self-Efficacy Likert-scale Surveys: These are time series surveys that examine changes in educators' self-efficacy in their integration of AI. They rate confidence using a standardized scale involving areas such as "I can describe what an algorithm is for a preschooler" or "I can troubleshoot issues using an AI tool in my classroom".

4) Lesson Plan & Student Work Analysis: This qualitative approach consists of a systematic review of two important artifacts:

Lesson Plans: We analyze the sophistication of AI-TPACK integration of lesson plans, aligned with learning objectives, and developmental appropriateness.

Student Work: Is analyzed for evidence of understanding, computational thinking, and being able to articulate ideas about AI, thereby providing empirical evidence of learning outcomes.

7.3. Desire Outcomes: Specific Multi-Level Impact Goals

This model finally reaches the end result of a cascade of desired results, ultimately the success of implementation and performance assessment yields:

1) Sustainable AI Integration Across ECE: The institutional outcome, where AI becomes a normalized, effectively used, and continuously improved component of the ECE curriculum, rather than a temporary initiative.

2) AI-TPACK Proficient Educators: The key outcome is where educators exhibit fluid, responsive, reflective expertise to assimilate AI knowledge within their classroom practice.

Sustainable AI Integration Across ECE: The institutional outcome, with AI as a normalized, effective, and always improving element within the entirety of the ECE curriculum, not just a piece of a "temporary" initiative [36] [37].

3) AI Literate Students: The ultimate goal, where little learners start to have a basic, critical, strong insight into AI and will be best placed to participate in the digital age in society, thereby helping to bridge, rather than widen, the digital divide [38] [39].

8. Discussion and Implications for Future Research

The new AI-TPACK Model represents a crucial paradigm shift that shifts the understanding of the AI integration process, from one of technical upskilling to one of holistic pedagogical and professional transformation. This work has many implications that include theoretical understanding, practical implementation, and laying the groundwork for a future research agenda.

8.1. Theoretical and Practical Implications

Theoretically, the AI-TPACK Model provides a contextualized explanation of TPACK and how it applies to the emerging field of early childhood AI literacy. It fills an important gap in the literature by outlining the knowledge intersections needed for successful teaching in this area. It builds upon established reviews of the TPACK literature [34]. Additionally, the explicit incorporation of self-efficacy as a pivotal dimension of the model recognizes that, unfortunately, affective variables have rarely been treated adequately as a key variable in technology integration. Focusing on teacher confidence also complements the knowledge domains and provides a richer view of teacher readiness, drawing on the foundational theory of the concept [29] and related empirical studies [35]. Lastly, the emphasis of the model on ethical issues as a cross-cutting theme seems a vital contribution beyond content knowledge, as well as a step forward in the recognition of the need to equip educators with the skills to respond to the social and ethical nuances of new technologies, including critical awareness of algorithmic bias [32].

Practically speaking, the model provides clear guidance to educational practitioners, administrators and policymakers. It offers a framework for designing and implementing effective professional development to fill a critical development gap in the current practice. The model provides clarity for education leaders in how they should allocate their resources, highlighting the need for investments in technology to be strategically paired with continued investments in building complementary pedagogical and content knowledge. Additionally, the framework provides a direction for meaningful integration of AI literacy into established early childhood curriculum, leading to a sustainable, embedded approach, rather than approaching it as an isolated or supplemental subject.

8.2. Limitations and Boundary Conditions

Limitations and boundary conditions of the present work have to be acknowledged. The proposed model for AI-TPACK emerged largely out of studies conducted in well-resourced educational systems and so could depend on a considerable adaptation to low-resource settings or cultural diversity to be applicable. The dynamic nature of the field itself poses a challenge since AI technologies are evolving rapidly, and the technological knowledge components of the framework need to change continuously to remain relevant. More importantly, as a conceptual model AI-TPACK calls for extensive empirical validation by the implementation of research with a wide variety of contexts to modify its elements and quantitatively evaluate its utility for practice.

8.3. Rationale for Future Research

Considering these aspects, an overall agenda needs to be formulated to promote the model as well as the area of early childhood AI education from multiple angles.

One, further robust efficacy studies, preferably both quasi-experimental designs and randomized controlled trials are required to quantitatively measure AI-TPACK professional development's influence on teacher knowledge, self-efficacy and eventually student learning outcomes. At the same time, the research of qualitative implementations on phenomenological, ethnographic, case study approaches, is necessary to investigate the lived experiences of educators and to identify drivers or barriers to implementation and to document how the concept is contextualized in real-life situations. Longitudinal studies following the development of AI-TPACK over time would be valuable to inform the sustainability of integrative knowledge and long-lasting support for practitioners' development. To ensure global applicability and equity for the model, future work should consider cross-cultural adaptations of the model, exploring the use of AI-TPACK in different linguistic, cultural, and resource settings. At the systemic level, research into policy analysis is required to determine the district, state, and national policy levers that will best facilitate widespread implementation of comprehensive professional development in AI literacy. Most important of all, the next step in this work is examining child outcomes. For example, studies must explore how teachers' development of AI-TPACK competencies directly impacts children's learning, not only by helping them make sense of AI concepts but also by fostering their critical thinking, ethical reasoning, and general disposition towards technology. This comprehensive research agenda will be essential for verifying, refining, and scaling the AI-TPACK Model for the challenges and opportunities of an AI-infused future.

9. Conclusion

The path to meaningful, equitable, and developmentally sound AI literacy in early childhood settings is one of the most critical issues in education for our time. Given that AI technology is changing just about every aspect of society, the need to support kids in using, engaging with, and influencing these technologies is greater than it has ever been. The strong record that young children are able to grapple with AI ideas (cataloged by Su *et al.* [12]) offers hope, although it exposes an important gap in present paradigms whereby not even the best-designed tools and curricula can be fully applied without properly skilled teachers. This paper has synthesized published literature to create a more targeted explanation of the teacher readiness gap along three interrelated dimensions—conceptual knowledge, self-efficacy, and pedagogical capacity, which together present a significant obstacle to achievement. To that end, we have introduced the AI-TPACK Model—a robust, theoretically grounded, and practical learning framework created as a specialized expansion of the TPACK model. The AI-TPACK Model offers a transparent, iterative approach to the process of moving early childhood educators from timid spectators to proactive, critical, and competent stewards of AI literacy. By equipping educators with the integrated knowledge that defines AI-TPACK, our intent is not only to teach how to operate and use new tools; our goal is to empower educators to design meaningful and engaging learning experiences that ready children more than just to connect with AI—and to use the tools to question them, and influence their development in better, more humane directions. The AI-TPACK Model marks an important shift away from the technology-centric method of early childhood education and toward pedagogy-centered strategies that recognize the real aim lies not in merely using technology but in enabling children to become critically aware actors within a mediated world of technology. For teachers, the future of AI in education won't just be determined by the level of intelligence of our machines but by wisdom, readiness, and pedagogical skill. Investing in professional development through tools like AI-TPACK is one of the most important investments we can make to help position our students for a world where technology will truly serve humanity, and our youngest are prepared to negotiate with that world bravely, critically, and responsibly.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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