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Beyond AI-TPACK: A Human-Centered Epistemic Pedagogy Framework for Mathematics Teacher Education in the Generative AI Era

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Abstract

The emergence of generative artificial intelligence (GenAI) has significantly transformed educational discourse, particularly within mathematics teacher education. While the Technological Pedagogical Content Knowledge (TPACK) framework remains influential in explaining technology integration, contemporary AI-mediated learning environments demand broader pedagogical and epistemic considerations. Existing AI-TPACK models largely emphasize technological efficiency, instructional automation, and digital competence, yet inadequately address critical concerns such as cognitive dependency, epistemic trust, reflective pedagogical judgment, ethical mediation, and preservation of authentic mathematical reasoning. Mathematics learning, rooted in abstraction, conceptual reasoning, metacognition, and logical coherence, becomes especially vulnerable in AI-mediated classrooms where algorithmic outputs may replace productive cognitive engagement.

This conceptual paper proposes a novel Humanistic-Epistemic Technological Pedagogical Content Knowledge (HE-TPACK) framework that extends traditional TPACK through four interconnected dimensions: Epistemic Awareness, Reflective Pedagogical Agency, Cognitive Integrity, and Ethical-Affective Mediation. Drawing upon TPACK theory, social constructivism, epistemic cognition theory, critical digital pedagogy, and human-AI collaboration discourse, the framework reconceptualizes mathematics teacher education for the generative AI era.

The paper critically examines the limitations of current AI-TPACK approaches, discusses the risks of cognitive outsourcing and algorithmic dependency in mathematics learning, and argues for a transition from techno-centric integration toward human-centered AI pedagogical orchestration. The HE-TPACK framework provides a theoretical foundation for redesigning mathematics teacher education programs capable of preserving conceptual understanding, ethical responsibility, pedagogical autonomy, and authentic mathematical cognition within increasingly intelligent educational ecosystems.

Keywords: Humanistic-Epistemic TPACK, AI-TPACK, Mathematics Teacher Education, Generative Artificial Intelligence, Epistemic Pedagogy, Cognitive Integrity, Ethical AI in Education.

1. Introduction

The rapid advancement of generative artificial intelligence has initiated a major transformation in educational systems worldwide. AI-powered technologies such as intelligent tutoring systems, adaptive learning platforms, conversational agents, and automated content generators are increasingly influencing teaching-learning processes. Unlike earlier educational technologies that primarily supported instructional delivery, generative AI systems can now generate mathematical explanations, construct lesson plans, solve symbolic problems, and simulate pedagogical interactions. Consequently, the role of teachers is evolving from technology users to reflective mediators of human-AI pedagogical relationships.

Within mathematics education, this transformation is particularly significant. Mathematics learning depends upon conceptual understanding, logical reasoning, abstraction, metacognition, and productive struggle. However, AI-mediated learning environments risk replacing meaningful mathematical cognition with rapid algorithmic responses. Students may increasingly depend upon AI-generated solutions without engaging in conceptual reasoning, thereby encouraging cognitive outsourcing, procedural dependency, and superficial learning.

Recent scholarship indicates that although AI technologies may improve instructional efficiency and personalized learning, they simultaneously raise concerns regarding epistemic authenticity, declining mathematical perseverance, and erosion of teacher agency (Chen, 2025; Cukurova et al., 2025). Discussions surrounding AI in mathematics education increasingly emphasize that the future challenge of teacher education is not merely technology integration but preserving authentic human cognition within AI-enhanced classrooms.

The Technological Pedagogical Content Knowledge (TPACK) framework developed by Mishra and Koehler (2006) remains one of the most influential frameworks for understanding technology integration in education. TPACK conceptualizes teacher expertise as the interaction among technological, pedagogical, and content knowledge domains. Although the framework significantly advanced educational technology research, its conceptualization emerged during a period when educational technologies functioned mainly as instructional support tools rather than autonomous knowledge-generating systems.

In the generative AI era, however, traditional TPACK and emerging AI-TPACK models appear insufficient in addressing deeper concerns related to epistemic judgment, ethical mediation, cognitive dependency, emotional dimensions of learning, and reflective pedagogical agency. Existing AI integration frameworks largely remain techno-centric, prioritizing technological adaptability and operational competence over reflective human-centered pedagogy.

This conceptual paper therefore proposes the Humanistic-Epistemic Technological Pedagogical Content Knowledge (HE-TPACK) framework. The framework extends traditional TPACK through four interconnected dimensions:

1. Epistemic Awareness (EA)
2. Reflective Pedagogical Agency (RPA)
3. Cognitive Integrity (CI)
4. Ethical-Affective Mediation (EAM)

The paper argues that mathematics teacher education must move beyond operational AI literacy toward reflective human-centered pedagogical orchestration capable of preserving authentic mathematical reasoning in AI-mediated educational ecosystems.

2. Evolution of TPACK in the Context of AI-Mediated Education

The TPACK framework emerged from Shulman's (1986, 1987) concept of Pedagogical Content Knowledge and was formally developed by Mishra and Koehler (2006) to explain the integrated relationship between technology, pedagogy, and content. The framework consists of seven interconnected domains:

- Content Knowledge (CK)
- Pedagogical Knowledge (PK)
- Technological Knowledge (TK)
- Pedagogical Content Knowledge (PCK)
- Technological Content Knowledge (TCK)
- Technological Pedagogical Knowledge (TPK)
- Technological Pedagogical Content Knowledge (TPACK)

TPACK shifted educational technology discourse away from purely techno-centric approaches by emphasizing meaningful pedagogical integration. In mathematics education, the framework became especially valuable due to increasing use of dynamic geometry software, virtual manipulatives, graphing tools, and interactive visualization technologies.

Recent studies have attempted to adapt TPACK within AI contexts through AI-TPACK models emphasizing AI literacy, automated lesson planning, and AI-assisted instructional design (Mailizar et al., 2026; Xie & Luo, 2025). While these models acknowledge the significance of AI in education, they often remain operationally focused and insufficiently address epistemic reasoning, ethical mediation, and preservation of authentic mathematical cognition.

Generative AI differs fundamentally from previous educational technologies because it increasingly participates in knowledge production itself. AI systems can now simulate explanations, recommend instructional decisions, and generate symbolic reasoning pathways. Consequently, teachers require competencies extending beyond technological fluency toward critical epistemic evaluation and reflective pedagogical judgment.

Recent discourse on teacher-AI collaboration suggests that future classrooms will involve complex interactions between human pedagogical reasoning and algorithmic systems (Cukurova et al., 2025). Therefore, mathematics teacher education requires frameworks capable of balancing technological innovation with human cognitive integrity.

3. Limitations of Existing AI-TPACK Models

Although AI-TPACK models contribute to understanding AI integration in teacher education, several conceptual limitations remain.

3.1. Techno-Centric Orientation

Most AI-TPACK frameworks continue to prioritize technological adaptability, productivity, and automation rather than reflective pedagogy and human cognition. Existing models often emphasize prompt engineering, AI-assisted planning, and instructional optimization while insufficiently examining how AI may influence conceptual understanding and learner reasoning.

Papert's (1987) critique of techno-centrism remains highly relevant within AI-mediated classrooms because generative AI possesses the capacity to overshadow authentic human thinking.

3.2. Lack of Epistemic Evaluation

Generative AI systems may produce mathematically convincing but conceptually inaccurate explanations. Teachers therefore require epistemic competencies enabling them to verify:

- logical coherence,
- mathematical authenticity,
- conceptual validity,
- and representational accuracy.

However, most AI-TPACK models inadequately conceptualize teachers' role as epistemic evaluators.

3.3. Cognitive Outsourcing

Recent educational discourse increasingly warns against cognitive outsourcing, wherein learners externalize reasoning processes to AI systems (Chen, 2025). Excessive dependence upon AI-generated solutions may weaken:

- conceptual reasoning,
- mathematical perseverance,

- metacognitive regulation,
- and productive struggle.

Mathematics learning fundamentally depends upon effortful engagement and conceptual negotiation. Uncritical AI dependency risks transforming mathematics into procedural completion rather than reflective inquiry.

3.4. Ethical and Humanistic Concerns

AI integration also raises ethical concerns involving:

- algorithmic bias,
- inequitable access,
- emotional disengagement,
- data privacy,
- and culturally insensitive instructional representations.

Current AI-TPACK models rarely position ethical mediation as a central pedagogical responsibility.

3.5. Marginalization of Teacher Agency

The increasing automation of lesson planning and instructional recommendations may reduce teachers to passive implementers of AI-generated pedagogical decisions. However, teaching remains fundamentally relational, contextual, and ethically mediated. Human pedagogical judgment therefore cannot be replaced by algorithmic systems.

These limitations indicate the need for a broader human-centered pedagogical framework.

4. Mathematics Learning in the Generative AI Era

Generative AI introduces both opportunities and pedagogical tensions within mathematics education.

AI systems can support:

- differentiated instruction,
- adaptive feedback,
- multilingual explanations,
- conceptual visualization,
- and personalized scaffolding.

Such affordances may strengthen inclusive mathematics learning environments when critically mediated by teachers.

However, recent research also highlights significant risks. Students may increasingly prioritize rapid answer generation over conceptual understanding. Cognitive outsourcing may weaken mathematical resilience, inferential reasoning, and metacognitive reflection (Cukurova et al., 2025). Several educators further report growing concern regarding students' declining willingness to engage in productive struggle and independent reasoning.

Mathematics is not merely answer acquisition; it involves justification, proof, symbolic interpretation, and conceptual coherence. Therefore, mathematics teachers in AI-mediated classrooms must function as:

- epistemic guides,
- reflective mediators,
- ethical facilitators,
- and orchestrators of meaningful mathematical cognition.

This transformation necessitates reconceptualizing teacher preparation beyond operational technology integration.

5. The Humanistic-Epistemic TPACK (HE-TPACK) Framework

The Humanistic-Epistemic Technological Pedagogical Content Knowledge (HE-TPACK) framework extends traditional TPACK by integrating four additional dimensions designed to preserve human cognition, pedagogical authenticity, and ethical responsibility.

5.1. Epistemic Awareness (EA)

Epistemic Awareness refers to teachers' ability to critically evaluate AI-generated mathematical knowledge. This includes verifying:

- conceptual correctness,
- logical consistency,
- representational appropriateness,
- contextual relevance,
- and mathematical authenticity.

Recent studies indicate that teacher candidates increasingly negotiate trust and verification while interacting with AI-generated pedagogical suggestions (Flavin, Hwang, & Morales, 2025). Therefore, future mathematics teachers require epistemic competencies extending beyond technological proficiency.

5.2. Reflective Pedagogical Agency (RPA)

Reflective Pedagogical Agency refers to teachers' ability to remain active instructional decision-makers within AI-mediated environments.

This dimension emphasizes:

- contextual pedagogical judgment,
- learner-centered adaptation,
- reflective instructional planning,
- and critical mediation of AI-generated recommendations.

Rather than surrendering pedagogical authority to AI systems, teachers critically adapt technological outputs according to learners' cognitive and socio-cultural needs.

5.3. Cognitive Integrity (CI)

Cognitive Integrity refers to preserving authentic mathematical cognition in AI-supported learning environments.

This dimension focuses on:

- productive struggle,
- metacognitive reasoning,
- conceptual understanding,
- inferential thinking,
- and mathematical perseverance.

Teachers practicing Cognitive Integrity use AI as a scaffold rather than a substitute for human reasoning.

5.4. Ethical-Affective Mediation (EAM)

Ethical-Affective Mediation addresses the ethical and emotional dimensions of AI-enhanced mathematics education.

This dimension includes:

- algorithmic fairness,
- equity,
- emotional support,
- culturally responsive pedagogy,
- humane digital interaction,
- and ethical instructional decision-making.

The framework recognizes that effective mathematics teaching remains deeply relational and emotionally mediated despite technological advancement.

HE-TPACK conceptualizes teacher knowledge as a dynamic interaction between traditional TPACK domains and humanistic-epistemic dimensions.

Within the framework:

- Technological Knowledge is critically mediated through Epistemic Awareness.
- Pedagogical Knowledge is strengthened through Reflective Pedagogical Agency.
- Content Knowledge is preserved through Cognitive Integrity.
- Human interaction and learner wellbeing are guided through Ethical-Affective Mediation.

Consequently, HE-TPACK transforms technology integration into reflective human-centered pedagogical orchestration rather than technological management.

6. Conceptual Relationship within HE-TPACK

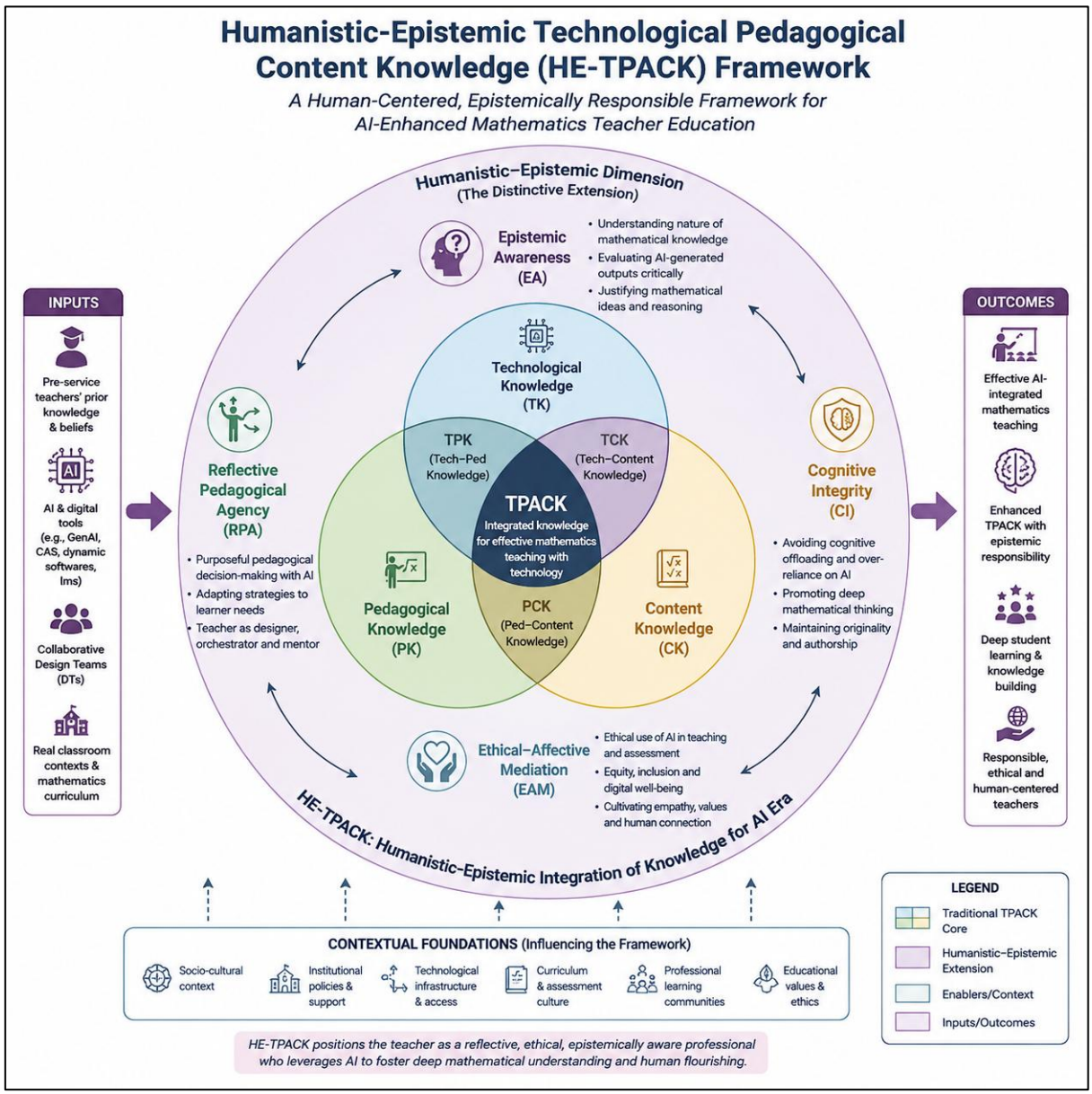

Figure 1: The Humanistic-Epistemic TPACK (HE-TPACK) Framework

7. Implications for Mathematics Teacher Education

The emergence of generative AI necessitates substantial restructuring of mathematics teacher education programs.

Traditional ICT training models emphasizing operational digital skills are no longer sufficient. Future mathematics teachers must develop competencies enabling them to:

- critically evaluate AI-generated content,
- preserve conceptual understanding,
- ethically integrate AI systems,
- and sustain pedagogical autonomy.

Teacher education curricula should therefore incorporate:

- AI epistemic literacy,
- reflective AI pedagogy,
- ethical AI integration,
- human-AI collaborative instructional design,
- and metacognitive mathematics pedagogy.

Pre-service teachers should engage in reflective activities such as:

- AI critique assignments,
- collaborative lesson design,
- epistemic reflection journals,
- and contextual evaluation of AI-generated mathematical explanations.

Teacher preparation must ultimately move beyond technological competence toward reflective pedagogical wisdom.

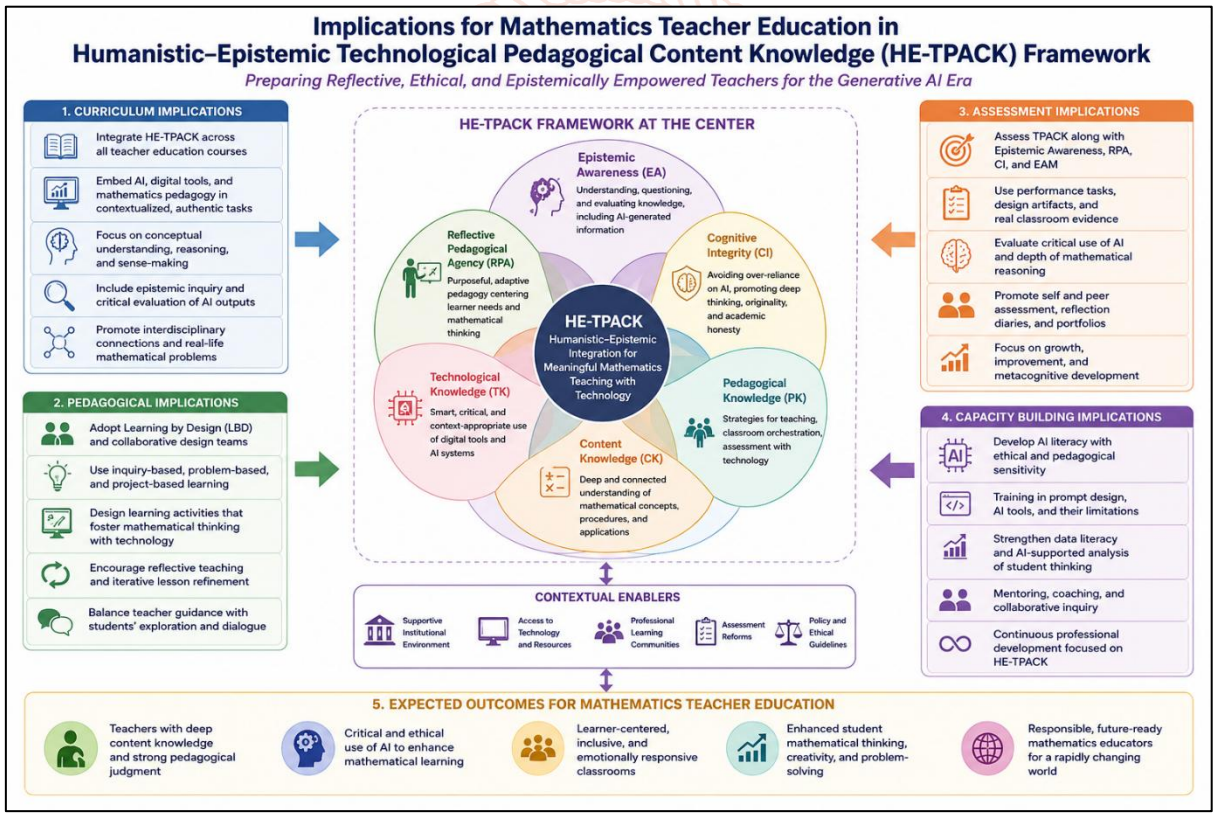

Figure 2: Implications for Mathematics Teacher Education in Humanistic-Epistemic Technological Pedagogical Content Knowledge (HE-TPACK) framework

8. Future Research Directions

The HE-TPACK framework offers several possibilities for future research:

1. Development and validation of HE-TPACK measurement scales.
2. Longitudinal studies examining pre-service teachers' epistemic development.
3. Comparative studies between TPACK and HE-TPACK.
4. Investigation of cognitive outsourcing in AI-mediated mathematics learning.
5. Studies exploring ethical AI pedagogy within teacher education.
6. Qualitative research examining reflective pedagogical agency.
7. Cross-cultural studies on human-centered AI integration.

Such investigations may further strengthen theoretical understanding of human-AI pedagogical relationships.

9. Conclusion

The emergence of generative artificial intelligence has fundamentally transformed mathematics teacher education. Although AI technologies offer substantial instructional possibilities, they simultaneously raise concerns regarding cognitive dependency, epistemic authenticity, ethical mediation, and pedagogical agency.

Traditional TPACK and emerging AI-TPACK frameworks, while valuable, remain insufficient in addressing the deeper humanistic and epistemological implications of AI-mediated learning environments.

This conceptual paper proposed the Humanistic-Epistemic Technological Pedagogical Content Knowledge (HE-TPACK) framework as a novel extension designed to preserve authentic mathematical reasoning, reflective pedagogy, ethical responsibility, and human cognition.

By integrating Epistemic Awareness, Reflective Pedagogical Agency, Cognitive Integrity, and Ethical-Affective Mediation into traditional TPACK structures, the framework reconceptualizes mathematics teacher education for the generative AI era.

The paper argues that the future challenge of education is no longer merely technology integration but preserving human meaning-making, conceptual depth, pedagogical autonomy, and ethical responsibility within increasingly intelligent educational ecosystems.

Thus, mathematics teacher education must transition from technology integration toward human-centered AI pedagogical orchestration.

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