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AI-Enhanced Physics Teacher Preparation: A Conceptual Design Framework for Developing Pre-Service Teachers' Topic-Specific Pedagogical Content Knowledge

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Abstract

The persistent difficulty students experience in learning Physics concepts has been widely linked to limitations in teachers' topic-specific pedagogical content knowledge (TSPCK). While teacher education programmes aim to strengthen pre-service teachers' instructional competence, many methodology courses remain insufficiently structured to support systematic TSPCK development and its enactment in classroom practice. Concurrently, the emergence of generative artificial intelligence (AI) tools has opened new possibilities for teacher education, yet limited research exists on how AI can be deliberately integrated into methodology courses to develop pre-service physics teachers' TSPCK. This conceptual paper presents a design framework for developing pre-service Physics teachers' TSPCK through the strategic integration of AI tools within a methodology course. Drawing on the TSPCK model (Mavhunga & Rollnick, 2013) and practice-based teacher education literature, the framework incorporates AI-enhanced Content Representations (CoRe), AI-assisted lesson observation and feedback, and AI-supported Video-Stimulated Recall (VSR) interviews to scaffold planning, enactment, and reflection. The paper synthesizes existing empirical evidence to justify the design features and demonstrates how AI tools can promote coherence between theory and practice in Physics teacher preparation. Ethical considerations, including bias, data privacy, and the role of AI as a pedagogical tool rather than a replacement for teacher reasoning, are discussed. The framework contributes to Physics education research by offering a context-responsive, technology-enhanced approach to TSPCK development that aligns with the transformative potential of AI in science teacher education.

Keywords: artificial intelligence, physics teacher education, methodology course, pre-service teachers, topic-specific pedagogical content knowledge

1 Introduction

Physics is one of the basic and foundational subjects in secondary school curricula worldwide. The concepts of physics are essential for understanding the complexities of modern technology and essential for technological advancement of a nation (Jegede & Adedayo, 2013). Although Physics is fundamental to the technological development of any nation, students often retain or develop misconceptions despite formal teaching and learning at the senior secondary school level (Achor et., al, 2023). Research document entrenched misconceptions related to force, motion, inertia, and action-reaction pairs that often persist even after instruction (Isra & Mufit, 2023; Kind, 2014; Sanborn et al., 2013). These learning difficulties have been widely attributed to the abstract nature of physics concepts and the inadequacy of instructional approaches that fail to address students' alternative conceptions (McDermott, 2001; Jegede & Adedayo, 2013). Teachers therefore require more than strong content knowledge; they need topic-specific pedagogical content knowledge (TSPCK) to transform physics content into forms that are accessible to students (Mavhunga & Rollnick, 2013; Shulman, 1986). TSPCK, which focuses on the interaction of five interrelated components, which include: knowledge of students' prior knowledge and misconceptions, curricular saliency, what makes the topic difficult to teach, representations, and conceptual teaching strategies. These five interrelated components have been identified as a critical determinant of effective science teaching (Mavhunga & Rollnick, 2013; Akinyemi, 2020; Maziebe, 2024; Miheso, 2018).

However, evidence suggests that many pre-service physics teachers graduate with limited capacity to integrate these knowledge components when teaching specific topics (Akinyemi, 2020; Miheso, 2018). This challenge is particularly evident in contexts where methodology courses emphasize general pedagogy rather than topic-specific instructional reasoning (Shezad et al., 2025). The persistent gap between theory and practice in teacher education has prompted calls for more deliberate, structured approaches to TSPCK development within methodology courses (Mavhunga & Rollnick, 2017; Nilsson & Karlsson, 2019). Concurrently, the emergence of generative artificial intelligence (AI) tools, including large language models (LLMs) such as ChatGPT, Claude, and Gemini, has opened transformative possibilities for education (Cooper, 2023; Achiam, et.al., 2023; Mollick & Mollick, 2024). In science teacher education, AI tools have the potential to generate multiple representations of scientific concepts, simulate student misconceptions, provide immediate feedback on lesson plans, and support reflective practice (Celik, 2023; Kubsch, et.al., 2025). However, limited research exists on how AI can be deliberately integrated into methodology courses to develop pre-service physics teachers' TSPCK, particularly for conceptually demanding topics. This paper addresses this gap by proposing a conceptual design framework for developing pre-service physics teachers' TSPCK through the strategic integration of AI tools within a methodology course. Drawing on the TSPCK model and practice-based teacher education literature, the framework incorporates AI-enhanced Content Representations (CoRe), AI-assisted lesson observation and feedback, and AI-supported Video-Stimulated Recall (VSR) interviews to scaffold planning, enactment, and reflection.

2 Theoretical and Empirical Foundations

2.1 Topic-Specific Pedagogical Content Knowledge (TSPCK)

Shulman's (1986) introduction of pedagogical content knowledge (PCK) fundamentally reshaped understanding of teacher knowledge by emphasizing the integration of subject matter and pedagogy. Subsequent research has refined this construct, culminating in the Topic-Specific PCK (TSPCK) model (Mavhunga & Rollnick, 2013), which conceptualizes PCK as the interaction of five components specifically relevant to teaching a particular topic. These are: Knowledge of students' prior knowledge which involves understanding what students already know and the alternative conceptions they bring to the classroom; Curricular saliency which demands knowing which concepts are most important for students to understand and how they connect within the curriculum; What makes the topic difficult to teach which focus on anticipating specific challenges students face in learning particular concepts; Representations that involves using demonstrations, analogies, diagrams, and other tools to illustrate concepts and Conceptual teaching strategies which employ instructional approaches that promote conceptual understanding. The TSPCK model emphasizes the integrative nature of teacher knowledge and provides a basis for analyzing both planned and enacted instruction (Mavhunga, 2020; Park & Chen, 2012). Research has shown that deliberate engagement with these five components can strengthen pre-service teachers' pedagogical reasoning and improve the quality of their classroom teaching (Akinyemi, 2020; Mavhunga & Rollnick, 2013; Zondi, 2018).

2.2 Challenges in Developing TSPCK in Pre-Service Physics Teachers

Despite the recognized importance of TSPCK, research consistently documents challenges in its development among pre-service teachers. Studies indicate that pre-service teachers often demonstrate limited ability to anticipate student misconceptions, select appropriate representations, or enact coherent instructional strategies (Akinyemi, 2020; Nilsson, 2008; Nurulsari et al., 2020). These limitations have been attributed to several factors which include:

First, the method of teaching courses in many teacher education programmes emphasizes general pedagogical knowledge rather than topic-specific instructional reasoning. As a result, pre-service teachers may demonstrate limited understanding of how to transform specific subject matter into teachable content. Second, the theory-practice gap remains a persistent challenge, with pre-service teachers often struggling to translate pedagogical knowledge acquired in university settings into effective classroom practice (Mavhunga & van der Merwe, 2020; Phillips & Condy, 2023). This gap has been linked to limited opportunities for structured reflection on teaching practice during methodology courses (Nilsson & Karlsson, 2019). Third, research indicates that even when pre-service teachers demonstrate improved TSPCK in planning (personal PCK), this knowledge may not be fully enacted during classroom teaching (Can & Mehmet, 2021; Mazibe et al., 2024; Zondi, 2018). These challenges are particularly acute for conceptually demanding topics where students' misconceptions are deeply entrenched (Isra & Mufit, 2023; Kind, 2014). These findings therefore underscore the need for targeted instructional strategies that explicitly connect planning, enactment, and reflection.

2.3 Artificial Intelligence in Science Teacher Education

The emergence of generative AI tools has opened new possibilities for addressing the challenges of TSPCK development. Large language models such as ChatGPT, Claude, and Gemini can generate multiple representations of scientific concepts, simulate student misconceptions, provide immediate feedback on lesson plans, and support reflective practice (Celik, 2023; Achiam, et.al., 2023; Mollick & Mollick, 2024). In science teacher education specifically, AI tools have the potential to support TSPCK development in following ways:

Planning: AI can generate alternative representations of scientific concepts, identify potential student misconceptions, and suggest instructional strategies (Cooper, 2023; Kubsch et.al., 2025). For example, when teaching Newton's laws, AI can generate multiple analogies (e.g., table cloth trick, car stopping suddenly) and explain how each addresses specific misconceptions. This aligned with the five TSPCK components.

Enactment: AI can analyze classroom discourse, identify episodes where multiple TSPCK components interact, and provide automated feedback on instructional quality (Demszky et al., 2024). This capability is particularly valuable for pre-service teachers who may not receive sufficient observation and feedback during practicum placements.

Reflection: AI can support reflective practice by generating targeted reflection prompts, summarizing patterns in teaching practice, and identifying areas for growth (Achiam, et al., 2023; Mollick & Mollick, 2024). When integrated with video-stimulated recall, AI can help pre-service teachers articulate their pedagogical reasoning and connect theory to practice.

Despite these potential benefits, research on AI integration in science teacher education remains limited, with few studies explicitly examining how AI tools can be deliberately integrated into methodology courses to develop TSPCK. This gap provides the rationale for the conceptual framework proposed in this paper.

2.4 Ethical Considerations in AI-Enhanced Teacher Education

The integration of AI tools in teacher education raises important ethical considerations that must be addressed in any design framework (Shezad et.al., 2025; Oye, Frank & Owen, 2024). These include:

Bias and fairness: AI tools may reflect biases present in their training data, potentially generating content that privileges certain perspectives or reinforces stereotypes (Oye, Frank & Owen, 2024). In science teacher education, this could manifest as biased representations of scientific concepts or assumptions about student backgrounds. Teacher educators must critically evaluate AI-generated content and ensure it reflects diverse perspectives and equitable practices.

Data privacy: Data privacy is a critical concern because the collection and analysis of student data may result in unauthorized access, breaches, or misuse (Oye, Frank & Owen, 2024). Therefore use of AI tools for lesson observation and feedback requires careful attention to data privacy and security. For instance all Video recordings of classroom teaching contain sensitive information, and pre-service teachers must be fully informed about how their data will be used, stored, and protected.

Role of AI as tool versus replacement: The impact of AI on educators is also examined, with particular attention to concerns about job displacement and the changing roles of teachers in AI-supported classrooms (Oye, Frank & Owen, 2024). AI should therefore be positioned as a tool to support, not replace, pedagogical reasoning. For instance pre-service teachers and teacher educators must develop the capacity to critically evaluate AI-generated content and make independent instructional decisions. The framework proposed in this paper emphasizes AI as a scaffold for TSPCK development, not a substitute for teacher expertise.

Equitable access: The integration of AI tools in teacher education programmes may exacerbate existing inequalities if some pre-service teachers lack access to these technologies as observed by (Duan & Zhao, 2024). Programmes must ensure equitable access and provide adequate training in AI literacy.

3 The AI-Enhanced TSPCK Framework: Design Components

This section presents the conceptual design framework for developing pre-service physics teachers' TSPCK. In this study the framework integrates AI tools with three established pedagogical tools: Content Representations (CoRe), lesson observation, and Video-Stimulated Recall (VSR) interviews.

3.1 Phase 1: AI-Enhanced CoRe for Planning

The CoRe tool, developed by Loughran, Mulhall, and Berry (2004), is a planning tool that elicits teachers' reasoning about key ideas in a topic. It supports articulation of misconceptions, representations, and instructional strategies, thereby capturing personal TSPCK (Mavhunga & Rollnick, 2013). In the proposed framework, the CoRe tool is enhanced through integration with AI tools in the following ways:

AI-assisted identification of misconceptions: Pre-service teachers prompt AI to identify common misconceptions about a particular topic (e.g Newton’s laws of motion) based on educational research literature. The AI generates a list of potential misconceptions (e.g., "heavier objects fall faster," "continuous force needed for motion"), which pre-service teachers evaluate and refine based on their understanding of their students.

AI-generated representations: Pre-service teachers prompt AI to generate multiple representations (e.g., demonstrations, analogies, diagrams, real-life examples). The AI produces a range of options which the pre-service teachers select and adapt those most appropriate for their context, explaining their reasoning.

AI-suggested teaching strategies: Pre-service teachers prompt AI to suggest instructional strategies for specific concepts and misconceptions. The AI generates options aligned with research-based practices, and pre-service teachers critically evaluate and adapt these suggestions.

Peer and AI review: After completing their CoRe, pre-service teachers submit it to both peer review and AI analysis. The AI provides feedback on completeness, coherence, and alignment with TSPCK components, identifying gaps or areas for strengthening. Pre-service teachers revise their CoRe based on this feedback.

3.2 Phase 2: AI-Assisted Lesson Observation and Feedback

Lesson observations focus on how planned knowledge is enacted during teaching. In the proposed framework, AI tools support observation and feedback in the following ways:

Automated episode identification: AI tools analyze video recordings of lessons to identify episodes where multiple TSPCK components interact (Mavhunga, 2020; Park & Chen, 2012). This supports the identification of Simple, Proficient, or Sophisticated TSPCK episodes (Miheso, 2018).

Automated feedback: AI tools generate preliminary feedback on instructional quality, focusing on evidence of TSPCK components in teaching practice. The feedback highlights strengths and identifies areas for growth, which pre-service teachers discuss with supervisors.

Teacher-AI co-observation: Pre-service teachers and supervisors collaboratively review AI-generated observation reports, discussing alignment with the pre-service teacher's intentions and planning. This supports development of observational expertise and reflective practice.

3.3 Phase 3: AI-Supported VSR Reflection

VSR interviews prompt reflective explanations of instructional decisions using classroom video excerpts (Loughran, 2006). In the proposed framework, AI tools support VSR in the following ways:

AI-generated reflection prompts: Based on analysis of lesson video and CoRe planning, AI generates targeted reflection prompts aligned with the five TSPCK components. For example, "In the clip where you used the book demonstration, what specific misconception were you trying to address?"

AI-assisted comparison of planned and enacted TSPCK: AI analyzes the pre-service teacher's CoRe and lesson video to identify alignment or mismatch between planned and enacted TSPCK. This comparison is used as a starting point for reflective discussion.

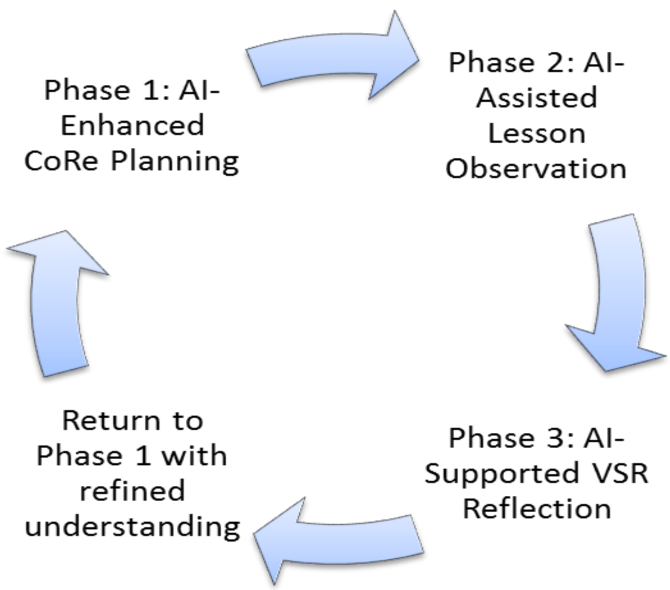
Personalized feedback and goal setting: Based on the VSR discussion and AI analysis, pre-service teachers set specific goals for future teaching practice. AI tracks progress across multiple teaching episodes and provides longitudinal feedback.

3.4 Cyclical Integration

The three phase cyclical process emerged as an analytical framework as part of an ongoing doctoral study on TSPCK in method of teaching courses (Sabo, in progress). Figure 1 describes these processes integrating AI with insights from each phase informing the next. Pre-service teachers complete multiple cycles across a methodology course, progressively developing their TSPCK and reflective capacity.

Figure **1**

3-Phase Cyclic Process



4 Implications for Physics Teacher Education

The proposed framework has several implications for physics teacher education programmes seeking to integrate AI into methodology courses.

4.1 Curriculum Innovation: Integrating AI Literacy

The framework requires that methodology courses explicitly teach AI literacy, enabling pre-service teachers to critically evaluate AI-generated content and use AI tools effectively. This aligns with the journal's theme of "Curriculum innovation: integrating AI literacy and tools into science teacher education."

4.2 Reorienting Practice-Based Teacher Education

The framework reinforces the importance of practice-based teacher education (Grossman et al., 2009) by connecting planning, enactment, and reflection through AI-enhanced cycles. This addresses the theory-practice gap identified in the literature (Mavhunga & van der Merwe, 2020; Phillips & Condy, 2023).

4.3 Supporting Supervisors and Mentors

The framework provides structured support for supervisors and mentors, who may lack expertise in both TSPCK and AI tools. AI-generated feedback and observation reports serve as a starting point for supervisory conversations, reducing the burden on supervisors while maintaining the importance of human judgment.

4.4 Ethical Implementation

The integration of AI tools in teacher education programmes requires careful attention to ethical considerations, including bias, data privacy, equitable access, and the role of AI as a tool rather than a replacement for pedagogical reasoning. Programmes must develop clear policies and provide training for both faculty and pre-service teachers.

5 Discussion

5.1 Addressing the Theory-Practice Gap

The proposed framework addresses a persistent challenge in teacher education: the gap between knowledge acquired in university settings and its application in classroom practice (Mavhunga & van der Merwe, 2020; Phillips & Condy, 2023). By integrating planning, enactment, and reflection within a single framework, the approach supports coherence between these domains. AI tools enhance this coherence by providing immediate feedback, generating targeted prompts, and supporting comparison of planned and enacted practice. This aligns with research emphasizing the importance of practice-based approaches in teacher education (Grossman et al., 2009; Stender et al., 2017) and the role of reflection in deepening pedagogical reasoning (Nilsson & Karlsson, 2019). The framework extends this work by demonstrating how AI tools can be strategically integrated to support TSPCK development.

5.2 Personalizing TSPCK Development

AI tools enable personalization of TSPCK development by providing feedback and prompts tailored to individual pre-service teachers' planning, teaching, and reflection. This addresses the diversity of prior knowledge and learning needs among pre-service teachers, which is often overlooked in traditional methodology courses. By generating targeted suggestions and highlighting specific areas for growth, AI can support differentiated professional learning.

5.3 AI as Scaffold, Not Replacement

The proposed framework positions AI as a scaffold to support, not replace, pedagogical reasoning. Pre-service teachers critically evaluate AI-generated content, make independent instructional decisions, and develop their professional judgment. This is a crucial distinction that preserves the central role of the teacher in educational decision-making.

5.4 Limitations and Future Directions

The framework presented in this paper is conceptual and requires empirical validation. Future research should investigate the implementation and impact of the framework, examining:

1. How pre-service teachers experience and perceive AI-enhanced TSPCK development
2. The quality of AI-generated feedback and its usefulness for learning
3. The impact of the framework on pre-service teachers' planning, enactment, and reflection
4. Ethical considerations in practice and strategies for addressing them

6 Conclusion

This paper has presented a conceptual design framework for developing pre-service physics teachers' TSPCK through the strategic integration of AI tools within a methodology course. By integrating AI-enhanced CoRe, AI-assisted lesson observation and feedback, and AI-supported VSR interviews, the framework offers a structured, practice-oriented approach to bridging theory and practice in physics teacher education. The framework contributes to physics education research by responding to the transformative potential of AI in science teacher education while maintaining a focus on developing pre-service teachers' pedagogical reasoning and professional judgment. The framework aligns with the broader theme of science education research in the age of artificial intelligence by demonstrating how AI can enhance, rather than replace, the work of science teacher educators and pre-service teachers. As AI tools continue to evolve, teacher education programmes must adapt to ensure that pre-service teachers are prepared to teach in a world shaped by AI while developing the pedagogical expertise that remains central to effective science teaching.

7 Recommendations

Based on the proposed framework, the following recommendations are offered:

1. Teacher education programmes should adopt topic-specific designs within methodology courses that integrate AI tools to support TSPCK development.
2. Teacher educators should prioritize reflective tools that make instructional reasoning explicit, using AI to generate targeted prompts and feedback.
3. Pre-service teachers should be provided with AI literacy training to critically evaluate AI-generated content and use AI tools effectively.
4. Future empirical studies should implement and evaluate the framework to examine its impact on pre-service teachers' planning, enactment, and reflection.
5. Ethical guidelines for AI integration in teacher education should be developed, addressing bias, data privacy, equitable access, and the role of AI as a pedagogical tool rather than a replacement for professional judgment.

8 Declarations

Conflict of Interest: The authors declared that they have no conflict of interest.

Author Contributions: Bala Sabo: Conceptualization, Methodology, Literature Review, Writing of original draft, Writing, review and editing. Abubakar Sa'adatu Mohammed: Conceptualization, supervision, review and editing. Dauda Abubakar: Conceptualization, supervision, review and editing. Al-Munnir Abubakar: Conceptualization, supervision, review and editing. All authors read and approved the final manuscript.

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