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Reframing pedagogical content knowledge and topic-specific pedagogical content knowledge as dual frameworks for teaching and learning

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ABSTRACT

This commentary re-conceptualized pedagogical content knowledge (PCK) and topic-specific pedagogical content knowledge (TSPCK) as dual frameworks that go beyond improving instructional delivery to actively shaping student outcomes in the context of 21st century education. Drawing on selected literature published between 2008 and 2024, the analysis includes studies that directly examine the relationship between PCK/TSPCK and student learning outcomes such as conceptual understanding, problem-solving, and cognitive engagement as well as those exploring their integration in digitally enhanced learning environments. Studies included 25 published articles that provided empirical or theoretical insight into how PCK/TSPCK supports adaptive pedagogy in science, technology, engineering, and mathematics education and excluded if they only discussed general teacher competence without linking to learner outcomes or digital contexts. The commentary argues that in technology-supported classrooms, PCK and TSPCK must be reframed as dynamic, learner-centered constructs essential for aligning instructional strategies with digital fluency and educational equity.

Keywords: pedagogical content knowledge, topic-specific pedagogical content knowledge, digital pedagogy, student outcomes, science education, 21st cntury skills

INTRODUCTION

Since Shulman's (1986) original conceptualization of pedagogical content knowledge (PCK), the model has profoundly influenced teacher education and professional development. In recent years, topic-specific pedagogical content knowledge (TSPCK) has been recognized as a refined model that emphasizes the specific instructional challenges and content demands involved in teaching individual subject topics (Mavhunga & Rollnick, 2013). Despite its wide application, PCK is still predominantly perceived as a tool for evaluating teaching competencies, including content delivery, classroom management, and assessment design (Julie, 2015).

The evolving demands of 21st century education characterized by rapid technological innovation, learner diversity, and a shift toward constructivist pedagogy require a reconceptualization of the knowledge frameworks that inform teacher practice and student learning. Among these, PCK and TSPCK remain central to effective teaching, as they articulate how teachers transform subject matter into teachable forms that facilitate learner understanding (Kind, 2009; Shulman, 1986). While these frameworks have traditionally focused on teachers' instructional competencies, recent scholarships have positioned them as mediators not only of teaching quality but also of student learning outcomes (Mavhunga & Rollnick, 2016).

However, despite their theoretical robustness, PCK and TSPCK are often under-utilized or inconsistently operationalized in contemporary classrooms particularly in contexts shaped by digital technologies and data-driven instruction. The integration of cloud computing, computer simulations, and augmented reality in teaching calls for a dynamic rethinking of how pedagogical knowledge is structured and enacted. Studies by Papadakis et al. (2023a, 2023b) emphasize that such technologies demand instructional frameworks capable of facilitating personalized, interactive, and inquiry-based learning environments. Hence, this study proposes a reframing of PCK and TSPCK not only as constructs supporting teacher professional development but also as dual mediators of instructional effectiveness and learner success in digitally enriched contexts. To remain relevant, PCK and TSPCK must evolve in ways that account for the pedagogical opportunities and challenges posed by digital innovation. This study builds on the premise that these frameworks can no longer be viewed solely as reflective tools for teachers but must be repositioned as dual mediators facilitating both teacher decision-making and student cognitive engagement. Such a reframing aligns with contemporary emphases on student-centered, technology-enabled learning, where the role of the teacher is both knowledge transmitter and learning designer. This commentary challenges that narrow view and proposes that PCK and TSPCK should be conceptualized as dual frameworks serving both as tools for improving teacher practices and enhancing student learning outcomes.

LITERATURE REVIEW

Re-Conceptualizing PCK and TSPCK Beyond Teacher Evaluation

While teacher preparation programs have increasingly embedded PCK as a core component (Berry et al., 2015), the framework's value extends beyond teacher performance assessment. PCK supports educators in translating complex subject matter into accessible content, anticipating and addressing misconceptions, and designing meaningful learning experiences (Park & Oliver, 2008). TSPCK, in particular, provides topic-specific scaffolds that are crucial for conceptual development in subjects like chemistry and physics (Mavhunga & van der Merwe, 2020). When teaching strategies grounded in PCK are implemented, they are not merely instructional techniques they are mediators of student understanding.

Technology-Enhanced Learning and the Transformation of PCK/TSPCK

The rapid expansion of educational technologies, including cloud-based platforms, augmented reality, and artificial intelligence (AI) tools, has reshaped instructional dynamics. Papadakis et al. (2023a) demonstrate that integrating computer simulations and smart cloud technologies supports open and adaptive learning pathways. This technological mediation alters the nature of content delivery and requires that teachers rethink how they construct learning experiences aligning closely with the principles of PCK and TSPCK.

Further, Papadakis et al. (2023b) argue that the interaction between augmented reality and cloud-based systems enhances learner interactivity and motivation. These tools necessitate new forms of pedagogical reasoning, where technology becomes integral to knowledge transformation. For teachers, this implies developing not only content expertise but also technological pedagogical fluency.

Al-Huwail et al. (2025) add another dimension by exploring how students increasingly use AI applications for academic purposes. Their findings suggest a growing expectation for digital competence not just from students, but from educators as well. In such environments, pedagogical knowledge must extend to include strategies for guiding learners in the ethical and effective use of AI technology.

Student Learning as a Central Component

The direct correlation between teachers' PCK/TSPCK and students' learning outcomes has been substantiated by recent studies (Hill et al., 2025; Jacob et al., 2020). These findings reveal those teachers who possess high-quality PCK/TSPCK substitute greater student engagement, deeper conceptual understanding, and improved academic achievement. This impact is particularly prominent in complex scientific concepts where students' misconceptions often hinder learning progress (Gess-Newsome et al., 2019). In this light, PCK serves as both a reflective tool for educators and a framework for diagnosing and enhancing student learning.

Moreover, in an era where education is increasingly aligned with 21st century competencies such as critical thinking, creativity, and collaboration, PCK/TSPCK supports the design of inquiry-based and student-centered learning environments (Taguma & Barbara, 2019; Voogt & Roblin, 2012). Lessons constructed with TSPCK allow teachers to differentiate instruction and meet the cognitive demands of diverse learners because in its nature TSPCK based instruction focused on prior knowledge of learners, curricular saliency, what is difficult/easy to learn, representations and conceptual teaching strategies (Dejene & Belachew, 2023).

Implications for Teacher Education and Curriculum Design

Recognizing PCK and TSPCK as dual frameworks necessitates a fundamental paradigm shift in the design and implementation of teacher education programs. Future educators must not only master subject content and pedagogy but also learn to analyze how their instruction affects student learning complexities (Kind & Chan, 2019). This reorientation requires embedding student learning analysis into teacher training modules and integrating feedback loops that connect instructional methods with student performance metrics (Li & Copur-Gencturk. 2024).

Curriculum developers must also ensure that learning activities reflect both teacher instructional goals and student learning processes. The goal is to create coherent learning experiences in which pedagogical choices are explicitly tied to desired student outcomes (van Driel et al., 2023).

Critical Engagement with Implementation Complexities

While PCK and TSPCK provide robust frameworks for understanding and improving instructional quality, implementing these frameworks across diverse educational systems is not without challenges. One major complexity lies in aligning these conceptual tools with teacher education policies that often prioritize content coverage and standardized assessment over pedagogical innovation. In many low-resource or highly centralized education systems, teacher preparation programs lack the structural flexibility and professional autonomy to meaningfully integrate PCK/TSPCK development into curricula (Menter et al., 2019). Even in more decentralized systems, the focus on measurable learning outcomes frequently sidelines pedagogical knowledge in favor of surface-level accountability metrics (Darling-Hammond, 2017).

Another challenge is the uneven preparation of teacher educators themselves. Many are content experts with limited exposure to the theories underpinning PCK/TSPCK, leading to inconsistent modeling in university-based instruction (Nilsson, 2008). Without institutional frameworks that support collaborative planning, mentoring, and reflective practice, the transfer of TSPCK from theory to classroom application remains fragmented. Therefore, integrating PCK and TSPCK into national teacher education policies demands not only curriculum reform but also long-term investment in educator capacity-building and system-level coherence.

To illustrate the practical value of PCK and TSPCK, consider the case of a science methods course in South Africa, where pre-service teachers are taught chemical equilibrium using a TSPCK-informed framework. Mavhunga and Rollnick (2013) found that when instruction explicitly addressed common misconceptions, representations, and task sequencing specific to equilibrium, pre-service teachers significantly improved both in content mastery and in their ability to design student-centered lessons. This shows that TSPCK is not simply a theoretical abstraction; it serves as a scaffold for anticipating learner difficulties and adjusting pedagogy accordingly.

Similarly, in a mathematics education project in Finland, digital tools such as dynamic geometry software were used to teach Euclidean concepts. The teacher's TSPCK enabled her to blend visual-spatial reasoning with inquiry-based tasks, resulting in higher engagement and better conceptual retention among students (Fjærestad & Xenofontos, 2025). These examples demonstrate that integrating TSPCK leads to more context-sensitive teaching, adaptive instructional design, and ultimately, improved learner outcomes.

METHODOLOGY

This commentary adopts a literature-based argumentative design to reframe PCK and TSPCK as interdependent frameworks that shape both instructional practice and student learning outcomes in digitally mediated, 21st century science education. The analysis is informed by a targeted review of scholarly literature using a purposive sampling technique.

The target population consisted of approximately 90 peer-reviewed journal articles and book chapters published between 2008 and 2024, identified through comprehensive searches in Scopus, ERIC, and Google Scholar. Keywords used included "PCK," "TSPCK," "student outcomes," "digital pedagogy," "science education," and "technology-enhanced learning." From this population, a sample of 25 articles was selected based on relevance and alignment with the commentary's focus.

Inclusion criteria were:

(a) publications explicitly linking PCK or TSPCK to student-centered outcomes such as conceptual understanding or problem-solving,

(b) studies set within science or STEM education, and

(c) literature that explore the integration of digital technologies or innovative pedagogical approaches into teaching and learning practices.

Exclusion criteria ruled out works that:

(a) focused solely on general teaching knowledge without addressing student impact,

(b) lacked theoretical or empirical grounding, or

(c) did not address the use of technology in instructional design.

The final sample was thematically analyzed to explore how PCK and TSPCK mediate between instructional effectiveness and learner engagement, particularly within digitally supported learning environments. This analysis forms the foundation for the proposed reconceptualization of these frameworks as essential tools for navigating the complexities of 21st century education.

CONCLUSION

PCK and TSPCK should be understood as dynamic, interdependent frameworks that shape both instructional quality and student learning outcomes. Rather than serving merely as evaluative tools, they offer a conceptual foundation for designing responsive, student-centered pedagogies especially critical in the context of 21st century science education. Their utility lies in enabling educators to navigate complex content, address misconceptions, and adapt teaching strategies to diverse and evolving learning environments, including those enriched by digital technologies. To advance meaningful and future-ready education, it is imperative that educators, curriculum designers, and policymakers embrace PCK and TSPCK as flexible, evolving constructs essential for cultivating deep understanding and transformative learning experiences.

Further Implications for Science Learning in the 21st Century

The implications of repositioning PCK and TSPCK are far-reaching for science education in the 21st century. For teacher education, programs must embed topic-specific pedagogical reasoning alongside digital literacy, ensuring that science teachers are equipped to design, reflect on, and adapt instruction using tools such as virtual labs, simulations, and cloud platforms. Professional development initiatives should support the development of TSPCK within realistic teaching scenarios and include exposure to data-informed teaching practices.

In terms of curriculum design, the integration of PCK-informed digital resources such as augmented reality models for molecular structures or cloud-based simulations for chemical reactions can make abstract concepts more accessible and engaging. Curriculum planners should ensure that learning outcomes are aligned not only with scientific content but also with students' cognitive development and technological engagement.

At the classroom level, science educators should use TSPCK to anticipate common student misconceptions and apply differentiated instructional strategies. Digital tools, including AI-powered feedback systems, offer real-time insights into student understanding and can be used to fine-tune instructional delivery. This reinforces the importance of blending pedagogical expertise with technological capability.

Finally, at the policy and research levels, there is a need for sustained inquiry into how PCK and TSPCK can be expanded to accommodate digital teaching innovations. Policymakers should support frameworks that prioritize pedagogical reasoning in science standards and provide resources for building teacher capacity in these areas. Research should continue to explore how these knowledge domains influence science learning outcomes across diverse educational settings.

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