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EXPLORING PATHWAYS FOR INTEGRATING AUGMENTED REALITY IN CHEMISTRY TEACHING: MEDIATING TPACK FRAMEWORK FOR EFFECTIVE INSTRUCTION

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ABSTRACT

Aim/Purpose	To examine how chemistry teachers' content, pedagogical, and technological knowledge (CK, PK, TK) and their intersection domains, pedagogical content knowledge (PCK), technological content knowledge (TCK), technological pedagogical knowledge (TPK) interact within the Technological Pedagogical and Content Knowledge (TPACK) framework when integrating augmented reality (AR), with a particular focus on the mediating roles of PCK, TCK, and TPK in predicting overall TPACK.
Background	AR is increasingly used to visualise abstract and sub-microscopic chemistry concepts, yet little is known about how in-service teachers' TPACK is structured in this context. Prior TPACK studies have largely treated TPACK as a global construct or have replicated the original model with conventional technologies, offering limited insight into how intersectional domains function as pathways to TPACK in AR-enhanced chemistry teaching.
Methodology	A cross-sectional survey was administered to 337 in-service chemistry teachers who had prior experience using AR in their lessons. A validated TPACK questionnaire was contextualised to AR and reviewed by experts. Data were analysed using structural equation modelling to test a seven-factor measurement model

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	and to estimate direct and indirect effects among CK, PK, TK, PCK, TCK, TPK, and TPACK.
Contribution	The study refines the TPACK framework for AR-enhanced chemistry teaching by modelling mediating relationships among the intersection domains. It moves beyond confirmatory use of TPACK and shows which knowledge components actually function as leverage points for strengthening teachers' TPACK in an immersive-technology context.
Findings	The seven-factor TPACK structure demonstrated acceptable reliability and validity. CK and PK strongly predicted PCK; CK and TK predicted TCK; and PK predicted TPK. PCK, TCK, and TPK all had significant positive effects on TPACK, with TPK emerging as the strongest direct predictor. Mediation analyses showed that PCK and TPK are the main pathways through which CK and PK influence TPACK, whereas TCK selectively mediated the effect of CK. TK did not exhibit strong direct or indirect effects on TPACK.
Recommendations for Practitioners	Professional development should prioritise the design of AR-supported chemistry lessons that explicitly target PCK and TPK-topic-specific pedagogy and pedagogy-technology integration, rather than focusing primarily on tool operation. Teachers need support in orchestrating AR activities, aligning them with curricular goals, and managing cognitive load and classroom interaction.
Recommendations for Researchers	Researchers should continue to model TPACK as a network of interacting components, paying particular attention to intersection domains and mediation effects. Instruments should be further refined for AR-specific contexts and complemented with classroom observations and artefact analyses.
Impact on Society	By clarifying how teachers' knowledge supports meaningful AR integration in chemistry, the study can inform professional development programmes and policy initiatives that seek to improve students' understanding of complex scientific concepts, especially in systems where resources for laboratory work are limited.
Future Research	Future studies should employ longitudinal or intervention designs to track changes in PCK, TCK, TPK, and TPACK during AR-focused professional development; extend the model to additional variables such as teacher beliefs and institutional support; and compare patterns across subjects, educational systems, and different types of AR applications.
Keywords	Augmented Reality (AR), Technological Pedagogical Content Knowledge (TPACK), chemistry education, interactive learning environments

INTRODUCTION

The integration of technology into education has become increasingly significant in the 21st century, fundamentally reshaping how educators design, deliver, and assess instruction. As digital innovations continue to advance, educators are challenged to identify effective strategies for integrating emerging technologies to enhance student engagement and learning outcomes. Among these innovations, Augmented Reality (AR) has attracted considerable attention for its potential to merge real and virtual environments, creating immersive and interactive learning experiences that extend beyond the limitations of traditional classrooms (Azuma, 1997; Billinghurst & Duenser, 2012; Duc et al., 2025).

Despite the growing interest in AR-based learning, its effective integration into classroom teaching remains inconsistent. Many teachers still face challenges in aligning AR applications with pedagogical objectives and content knowledge. Successful implementation requires a balanced interplay of technological, pedagogical, and content knowledge – a relationship conceptualized within the TPACK framework (Mishra & Koehler, 2006).

However, most existing studies focus either on students' learning outcomes or general technology adoption, overlooking how AR influences the internal components of teachers' TPACK development - particularly in Chemistry, where conceptual abstraction, laboratory safety, and equipment limitations make digital visualization tools especially valuable (Imaduddin & Astuti, 2022; Ripsam & Nerdel, 2024). Understanding how Chemistry teachers integrate AR through the TPACK framework is, therefore, crucial for identifying both competency needs and instructional transformation pathways that can enhance teaching effectiveness.

Technologically, AR superimposes digital content onto the physical world, providing an interactive and engaging way to deliver information (Azuma, 1997; Chen & Tsai, 2012). In the context of science education, this capability enables the conversion of abstract ideas into tangible scenarios, which is especially beneficial in courses such as chemistry. For instance, AR enables students to visualize intricate molecular structures and processes, thereby greatly enhancing their comprehension (Billinghurst & Duenser, 2012; Bujak et al., 2013). Although there are potential advantages, there is a lack of study explicitly investigating the impact of AR on the TPACK components in the field of chemistry education (FitzGerald et al., 2013; Wu et al., 2013).

The integration of AR into educational practices poses both opportunities and challenges. While AR can enhance the learning experience, its impact on teachers' integration of technological, pedagogical, and content knowledge remains underexplored. AR integrates virtual elements into real-world settings, allowing students to see and interact with complex chemical structures, reaction mechanisms, and laboratory operations in 3D. Consequently, this immersive experience improves comprehension and recall of tough ideas that might otherwise be difficult to grasp using standard teaching approaches (Akçayır & Akçayır, 2017). For instance, AR applications like MolView and AR ChemLab allow students to manipulate molecular geometries, visualize electron density maps, and simulate laboratory experiments without the associated safety risks or material costs.

Beyond visualization, AR can adapt learning to learners' varying levels of competency. AR promotes active learning and critical thinking by enabling self-paced exploration (Wu et al., 2013). Furthermore, using AR in the chemistry curriculum enhances collaborative learning. Students may collaborate in groups to solve chemical issues or conduct experiments, and they may utilize AR to efficiently communicate and develop their ideas. Studies have proved that AR improves students' spatial thinking and conceptual comprehension, which are key qualities in studying chemistry (Cheng & Tsai, 2012).

Successful integration of AR requires more than technological proficiency alone. Teachers must possess a balanced combination of technological, pedagogical, and content knowledge (Harris et al., 2009). The TPACK framework emphasizes that effective teaching with technology emerges from the dynamic interplay between teachers' understanding of subject matter (CK), teaching strategies (PK), and technological tools (TK) (Schmidt et al., 2009). While numerous studies have examined the TPACK model in general contexts, few have empirically investigated how specific emerging technologies, such as AR, influence teachers' development and interaction within this framework, and even fewer have done so in the domain of Chemistry education.

Although prior research has confirmed that AR can enhance students' motivation, engagement, and conceptual understanding (Bower et al., 2014; Cheng & Tsai, 2012), the core problem driving this research is the lack of systematic evidence regarding how AR shapes teachers' integration of knowledge in real classroom contexts (Paristiowati et al., 2020). Therefore, the core problem driving this research is the limited understanding of how AR affects the components and interrelationships of the TPACK framework among Chemistry teachers. Although AR has shown promise in enhancing students' learning experiences, there is a lack of systematic evidence regarding how it shapes teachers' technological, pedagogical, and content integration in real classroom contexts (Paristiowati et al., 2020).

Without such understanding, efforts to implement AR remain fragmented or unsustainable. Understanding this relationship is crucial for two reasons. First, it provides insights into the professional competencies teachers need to develop to incorporate AR effectively into Chemistry instruction. Second, it informs policymakers and curriculum designers about the kinds of professional development and institutional support needed to facilitate sustainable technology integration in science education.

Crucially, the findings of this study offer dual benefits for educators, policymakers, and the broader educational community. First, for educators, understanding the impact of AR on TPACK can inform the development of targeted professional development programs that enhance teachers' skills in integrating technology into their teaching (Angeli & Valanides, 2009; Niess, 2005). Second, for policymakers, the insights gained can inform the formulation of educational policies that support the adoption of innovative technologies such as AR in schools (Ertmer & Ottenbreit-Leftwich, 2010; Mishra & Koehler, 2006). Ultimately, the study contributes to the academic discourse on technology integration in education, providing a foundation for future research in this area (Graham, 2011; Voogt et al., 2013).

To address the persisting gap identified since 2013, this study investigates the effects of Augmented Reality on the TPACK framework among Chemistry teachers. The study aims to identify how AR integration influences the interrelationships among technological, pedagogical, and content knowledge domains, and to determine the key factors that support effective technology-enhanced Chemistry instruction. An extensive and systematic review of the existing literature undertaken in this study suggests that the gap identified in 2013 persists, highlighting the continued absence of sufficient empirical evidence in this area. Accordingly, the research is guided by the following refined questions:

RQ1: What specific factors influence the integration of Augmented Reality into Chemistry teaching within the TPACK framework?

RQ2: How are the components of the TPACK framework represented when Chemistry teachers implement Augmented Reality in their instruction?

RQ3: In what ways does the use of Augmented Reality affect Chemistry teachers' overall TPACK and their teaching practices?

LITERATURE REVIEW

Augmented Reality (AR) superimposes digital information, such as three-dimensional models, animations, or simulations, onto the physical environment, thereby enabling learners to interact simultaneously with real and virtual objects (Azuma, 1997; Billinghurst & Duenser, 2012). In education, AR has been used to support situated and inquiry-based learning, as it allows students to manipulate virtual representations directly within authentic contexts rather than in decontextualized, screen-based environments. In STEM subjects, AR has shown potential to improve spatial reasoning, support conceptual change, and increase learner engagement (Bower et al., 2014; Bujak et al., 2013; Wu et al., 2013).

Building on the integration of technology in educational contexts, the TPACK framework provides a robust model for understanding how educators can blend their knowledge of technology, pedagogy, and content. Figure 1 presents the TPACK framework, adapted from Mishra and Koehler (2006), which illustrates the intersections of these three domains to enhance teaching and learning.

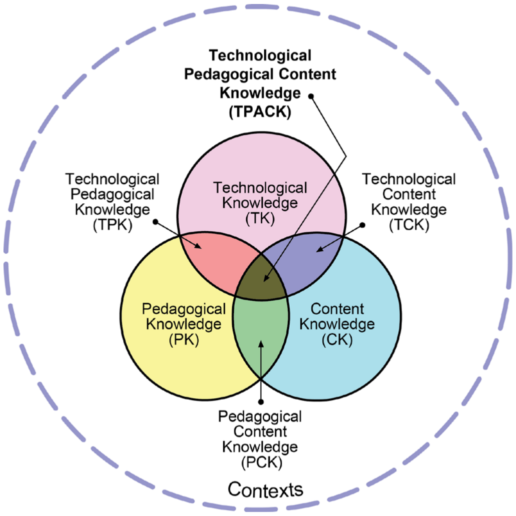

Figure 1. The TPACK framework (adapted from Mishra & Koehler, 2006)

TPACK THEORETICAL FRAMEWORK

Chemistry is a particularly suitable domain for AR integration because much of its core content-molecular structures, bonding, reaction mechanisms, and particulate-level processes-is inherently abstract and invisible to the naked eye (Di Serio et al., 2013). AR applications can render these phenomena as manipulable 3D models that can be rotated, enlarged, and inspected from multiple perspectives, bridging the gap between macroscopic observations, symbolic representations, and microscopic structures (Cheng & Tsai, 2012; de Jong et al., 2013). For example, MolView-like tools and AR chem-lab environments enable learners to visualize stereochemistry, explore electron density distributions, and simulate laboratory procedures without safety risks or material constraints. Such affordances are particularly valuable for chemistry topics that students frequently find difficult, such as equilibrium, acid–base reactions, or organic mechanisms.

However, the successful use of AR in classrooms does not depend solely on the technology itself but also on teachers' capacity to orchestrate AR activities in pedagogically meaningful ways (Makransky et al., 2016). Findings across AR studies repeatedly indicate that when AR is employed as a mere "add-on" for visual appeal, learning gains are modest, whereas carefully designed AR tasks aligned with clear conceptual goals can substantially enhance understanding (Akçayır & Akçayır, 2017). This suggests that teachers' professional knowledge for integrating AR is a critical determinant of educational impact. Yet much of the AR literature continues to focus on student perceptions or usability rather than on teachers' knowledge structures and decision-making, particularly in chemistry education.

The TPACK framework for technology integration

The TPACK framework (Mishra & Koehler, 2006) is grounded in Shulman's (1986, 1987) work. The notion of PCK provides a comprehensive lens for examining the knowledge teachers need when integrating technology. TPACK distinguishes three primary domains – CK, PK, and TK – and four intersection domains: PCK, TCK, TPK, and the integrative TPACK domain (Graham et al., 2012).

CK denotes mastery of disciplinary concepts, principles, and practices. In chemistry, CK includes understanding of chemical bonding, molecular structure, stoichiometry, reaction kinetics, and the nature of scientific modelling. PK refers to knowledge of instructional strategies, classroom management, assessment, and theories of learning that allow teachers to design effective learning environments across topics and grade levels. TK encompasses familiarity with and the ability to operate and adapt to digital tools that support teaching and learning (Graham, 2011; Mishra & Koehler, 2006).

The intersections of these domains capture how teachers combine knowledge areas in practice. PCK describes teachers' capacity to transform subject matter into forms accessible to learners, for instance, by using analogies, multiple representations, or diagnostic questions that target common misconceptions (Depaepe et al., 2013; Shulman, 1986). TCK concerns how technology is used to represent, visualize, or simulate disciplinary content, while maintaining scientific accuracy (Koehler, Mishra, & Cain, 2013). TPK denotes understanding of how technology reshapes pedagogy, such as when collaborative platforms, simulations, or AR environments require adapted facilitation strategies, new forms of feedback, or novel assessment approaches (Chai et al., 2013; Harris et al., 2009). At the centre, TPACK reflects teachers' ability to design coherent, technology-rich learning experiences that align content, pedagogy, and technology with contextual constraints and student needs.

A substantial body of empirical research has validated TPACK across disciplines, including mathematics, science, and language education. Studies consistently report that CK, PK, and TK alone are insufficient for high-quality technology integration; rather, teachers' effectiveness is strongly associated with the development of PCK, TCK, and TPK, which mediate the transformation of foundational knowledge into classroom practice (Adipat, 2021; Benton-Borghi, 2014). Nevertheless, most of this work has examined "technology" in a broad sense, encompassing desktop software, learning management systems, generic simulations, or digital content, without isolating the affordances of specific technologies such as AR or VR.

TPACK and emerging technologies: The case for augmented reality

Recent studies have begun to explore TPACK in relation to emerging immersive technologies. Research in language learning, biology, and teacher education shows that AR can positively influence teachers' TK and TCK by prompting them to experiment with new tools and to reconceptualize how disciplinary content is represented (Belda-Medina & Calvo-Ferrer, 2022; Buchner & Zumbach, 2020). In chemical education, AR environments have been reported to support teachers in illustrating 3D molecular geometry, dynamic reaction mechanisms, and invisible laboratory processes, thereby enriching their TCK and PCK (Bullock & Huwer, 2024; Yamtinah et al., 2023)

Yet, these studies are often small-scale or descriptive, focusing on case studies of individual teachers or short professional development interventions. Few have employed structural models to examine how AR-specific experiences reshape the relationships among TPACK components. In addition, much prior work treats TPACK as a single composite score, obscuring how foundational domains (CK, PK, TK) interact with intersection domains (PCK, TCK, TPK) to produce overall TPACK for AR integration. As Hair et al. (2019) recommend, examining latent constructs and their structural paths is crucial for understanding how teacher knowledge develops and where targeted support is needed.

Augmented reality also introduces unique pedagogical and cognitive demands that may alter the importance of particular TPACK components. For instance, because AR activities often require students to move, manipulate objects, and coordinate physical and virtual information, teachers must design tasks that manage cognitive load and guide attention effectively, functions strongly associated with PK and TPK. At the same time, the scientific accuracy of AR visualizations depends on teachers' CK and TCK, as inappropriate or oversimplified models can reinforce misconceptions rather than resolve them. These characteristics suggest that AR is not a neutral replacement for other technologies but a distinct context in which the interplay among TPACK components warrants closer investigation.

TPACK Components in AR-enhanced chemistry teaching

In AR-enhanced chemistry instruction, each TPACK component takes on specific roles that extend beyond its generic definition. CK enables teachers to identify which chemistry concepts genuinely benefit from AR visualization (e.g., molecular orbitals, intermolecular forces, redox processes) and to evaluate whether AR representations are scientifically sound. Teachers with robust CK can anticipate students' likely misconceptions and select AR tasks that directly confront these difficulties, rather than simply decorating lessons with 3D models (Angeli & Valanides, 2009; Mohamad, 2021)

PK underpins teachers' ability to embed AR within coherent instructional sequences, such as inquiry cycles, problem-based learning, or formative assessment routines. For example, teachers may design AR-supported prediction-observation-explanation activities in which students manipulate molecular models, record observations, and refine their reasoning through guided discussion (Buchner & Zumbach, 2020; Jang & Tsai, 2012).

TK refers not only to operating AR applications but also to understanding their constraints, troubleshooting issues, and selecting tools that align with curricular goals and classroom resources (Ertmer & Ottenbreit-Leftwich, 2010). However, some studies suggest that simply increasing TK does not automatically lead to sophisticated AR integration if teachers lack the pedagogical and content-based frameworks to harness AR effectively (Belda-Medina & Calvo-Ferrer, 2022; Hew & Brush, 2006).

The intersection domains-PCK, TCK, and TPK-are particularly critical in AR contexts. PCK enables teachers to design AR tasks that reveal underlying chemical principles rather than merely visual phenomena; for example, using AR to compare multiple representations of equilibrium rather than showing only static molecular snapshots (Cheng & Tsai, 2012). TCK guides decisions about which AR visualizations best represent specific concepts and how to align them with symbolic equations or experimental data (Koehler, Mishra, Kereluik, et al., 2013; Schmid et al., 2021). TPK describes how teachers adapt classroom management, scaffolding, and assessment strategies when students use AR, such as orchestrating group interactions around shared devices or integrating AR-based observations into formative feedback (Chai et al., 2013).

Empirical findings increasingly indicate that these intersection domains act as bridges between foundational knowledge and overall TPACK. For instance, recent studies report that PCK mediates the relationship between CK and TPACK, while TCK and TPK mediate links from CK, PK, and TK to TPACK in various technology-rich environments (Imaduddin & Astuti, 2022; Ripsam & Nerdel, 2024). Nonetheless, it remains unclear which mediating paths are most salient when the technology in question is AR, and the subject is chemistry.

Mediating relationships within the TPACK framework

Building on this literature, the present study conceptualizes TCK, PCK, and TPK as key mediating mechanisms through which CK, PK, and TK are translated into integrated TPACK for AR-enhanced chemistry teaching. Specifically, strong CK is expected to foster both PCK and TCK, as teachers who deeply understand chemistry are better positioned to design AR-embedded explanations and evaluate the appropriateness of AR models. In turn, PCK and TCK should contribute to higher TPACK, as they reflect teachers' ability to align AR-based representations with curricular goals and learners' conceptual difficulties.

Similarly, PK is theorized to influence PCK and TPK; teachers with well-developed pedagogical repertoires can more readily adapt teaching strategies and classroom structures when AR is introduced, thereby strengthening their TPACK. TK is hypothesized to support TCK and TPK by enabling teachers to explore AR tools, recognize their affordances, and integrate them into instruction. However, prior studies suggest that TK may exert weaker or more indirect effects than CK and PK, particularly when teachers are already familiar with digital technologies more broadly (Ertmer & Ottenbreit-Leftwich, 2010; Graham et al., 2012).

By explicitly modelling these mediating relationships, this study moves beyond treating TPACK as a monolithic construct and examines how different knowledge domains interact to produce effective AR integration. This approach aligns with recent calls in the literature to employ structural equation modelling to clarify the causal pathways within TPACK and to identify leverage points for professional development (Benton-Borghi, 2014; Chai et al., 2013).

RESEARCH MODEL AND HYPOTHESES

CONCEPTUAL MODEL

Drawing on the TPACK framework and prior research on AR-supported instruction, the present study conceptualizes chemistry teachers' knowledge for AR integration as a network of interrelated knowledge domains rather than a single, undifferentiated construct. In this network, three foundational domains- CK, PK, and TK-are treated as exogenous latent variables that provide the disciplinary, pedagogical, and technological bases for teaching. Their influence on teachers' overall TPACK is theorized to be transmitted primarily through three intersection domains: PCK, TCK, and TPK.

In other words, the model assumes that chemistry teachers do not move directly from CK, PK, and TK to fully integrated TPACK. Instead, they first develop content-pedagogy integration (PCK), content-technology integration (TCK), and technology-pedagogy integration (TPK), which then combine to form a coherent capacity to design, enact, and evaluate AR-enhanced chemistry lessons. This perspective is consistent with theoretical arguments that intersection domains act as "bridges" between core knowledge and enacted practice, and with empirical studies showing that PCK, TCK, and TPK are often stronger predictors of classroom integration than CK, PK, or TK alone.

In the specific context of AR-enhanced chemistry teaching, the model posits that:

- CK is crucial for identifying chemistry concepts suitable for AR visualization and for evaluating the scientific accuracy of AR representations, thereby strengthening both PCK and TCK.
- PK supports the design of inquiry-oriented, collaborative AR activities and the use of formative assessment strategies around AR tasks, thereby enhancing both PCK and TPK.
- TK enables teachers to explore, select, and operate AR tools, thereby supporting the development of both TCK and TPK.

PCK, TCK, and TPK, in turn, are expected to exert direct effects on TPACK, since they reflect increasingly integrated forms of knowledge that are closer to actual teaching practice with AR. The conceptual model is summarised in Figure 1 (revised version of the original research framework), in which CK, PK, and TK feed into PCK, TCK, and TPK, and these intersection domains collectively predict teachers' overall TPACK for AR-enhanced chemistry instruction.

This model directly addresses the study's overarching goal of exploring mediating relationships within the TPACK framework in the context of AR. Rather than merely confirming that CK, PK, and TK correlate with TPACK, the study examines *how* these domains influence TPACK through PCK, TCK, and TPK, and which pathways are most salient for in-service chemistry teachers who already have experience using AR in their teaching.

DIRECT EFFECTS OF CK, PK, AND TK ON INTERSECTION DOMAINS

Content knowledge and PCK/TCK

Teachers with strong CK are better able to anticipate students' misconceptions, select conceptually critical topics for AR support, and design explanations that connect macroscopic, symbolic, and microscopic representations. In chemistry, CK is particularly important for identifying phenomena that genuinely require 3D visualization (e.g., molecular geometry, orbital overlap, intermolecular forces) and for ensuring that AR models do not misrepresent scientific ideas. As teachers refine these content-focused decisions in their practice, their PCK-the ability to transform content into teachable forms-is likely to improve. At the same time, deep CK should facilitate the development of TCK, since teachers must draw on content expertise to judge whether specific AR tools and resources are appropriate for representing complex chemical processes.

Accordingly, the following hypotheses are proposed:

H1: CK has a positive effect on PCK.

H2: CK has a positive effect on TCK.

Pedagogical knowledge and PCK/TPK

PK underpins teachers' capacity to design coherent instructional sequences, manage classroom interactions, and use assessment to guide learning. In AR-enhanced chemistry teaching, teachers with strong PK are more likely to embed AR within meaningful inquiry cycles, collaborative tasks, or problem-solving activities rather than treating it as a superficial visual aid. Such pedagogical sophistication should reinforce PCK, as teachers learn to align AR-supported explanations and tasks with learners' prior knowledge and difficulties.

Furthermore, PK is expected to contribute to TPK because integrating AR requires teachers to adapt their pedagogical strategies to new technological affordances and constraints, such as coordinating students' physical movement around AR markers, structuring group work around shared devices, and integrating AR-based observations into feedback. As teachers experiment with these adaptations, their understanding of how technology reshapes pedagogy should deepen.

Thus, the following hypotheses are proposed:

H4: PK has a positive effect on PCK.

H5: PK has a positive effect on TPK.

Direct effects of intersection domains on TPACK

The intersection domains are expected to be proximal predictors of overall TPACK in AR-enhanced chemistry teaching.

PCK → TPACK. Teachers with strong PCK can design AR-supported explanations, analogies, and tasks that address known misconceptions and make abstract chemical ideas accessible. Their ability to connect content and pedagogy provides a foundation for full TPACK, where technology is integrated in ways that are both conceptually meaningful and pedagogically sound.

TCK → TPACK. Teachers with strong TCK understand how AR can best be used to represent complex structures and processes and can align specific AR tools with particular chemistry topics. This content–technology alignment is essential for designing AR-enhanced lessons that are scientifically accurate and instructionally effective.

TPK → TPACK. Teachers with strong TPK can adapt their teaching strategies to AR's affordances and constraints, managing classroom flow, scaffolding inquiry, and integrating AR activities into broader learning sequences. This technology–pedagogy alignment is crucial for moving beyond technologically simplistic uses of AR (e.g., "show-and-tell" visualizations) toward more sophisticated integration.

Based on this reasoning, the following hypotheses are proposed:

H3: PCK has a positive effect on TPACK.

H6: TCK has a positive effect on TPACK.

H9: TPK has a positive effect on TPACK.

MEDIATING ROLES OF PCK, TCK, AND TPK

A central contribution of this study is the examination of indirect effects within the TPACK framework, specifically the mediating roles of PCK, TCK, and TPK. Rather than assuming that CK, PK, and TK exert direct, independent influences on TPACK, the model posits that these foundational domains operate largely *through* intersection domains.

PCK as a mediator

Given that PCK embodies the transformation of disciplinary content into teachable forms, it is reasonable to expect that the effects of both CK and PK on TPACK are mediated by PCK. Teachers with strong CK but weak PCK may know chemistry well but struggle to design AR-supported tasks that make that knowledge accessible. Likewise, teachers with strong PK but weak PCK may be skilled in general pedagogy but unable to tailor strategies to the specific conceptual demands of chemistry. When CK and PK jointly support PCK, teachers are better positioned to integrate AR in ways that are coherent with both the content and students' learning needs.

Thus, the following mediating hypotheses are proposed:

H10: PCK mediates the relationship between CK and TPACK.

H11: PCK mediates the relationship between PK and TPACK.

TCK as a mediator

TCK captures teachers' understanding of how technology can represent and transform disciplinary content. In AR-enhanced chemistry teaching, TCK is likely to channel the effects of both CK and TK toward TPACK. Teachers with strong CK but limited TCK may analyze chemistry concepts deeply yet fail to identify AR visualizations that accurately and meaningfully represent those concepts. Conversely, teachers with strong TK but limited CK may know how to operate AR tools but struggle to evaluate their scientific adequacy. When CK and TK combine to strengthen TCK, teachers can choose and adapt AR resources that align with curricular goals and learners' conceptual difficulties, thereby contributing to higher TPACK.

Accordingly, the following hypotheses are proposed:

H12: TCK mediates the relationship between CK and TPACK.

H13: TCK mediates the relationship between TK and TPACK.

TPK as a mediator

Finally, TPK is expected to mediate the effects of PK and TK on TPACK. Teachers with strong PK but weak TPK may be proficient in traditional pedagogies yet uncertain about how to adapt those methods when AR is introduced. Teachers with strong TK but weak TPK may be technologically confident but lack strategies for embedding AR in conceptually rich, student-centred learning experiences. By contrast, teachers who develop TPK can orchestrate AR activities that exploit technological affordances while maintaining pedagogical coherence, thereby achieving higher levels of TPACK for AR integration.

Thus, the following mediating hypotheses are proposed:

H14: TPK mediates the relationship between PK and TPACK.

H15: TPK mediates the relationship between TK and TPACK.

Alignment with research questions

Taken together, the direct and mediating hypotheses address the study's overarching research questions:

- Which knowledge factors are involved in chemistry teachers' TPACK for AR-enhanced instruction (addressed through the inclusion of CK, PK, TK, PCK, TCK, TPK, and TPACK)?
- How are these factors structurally represented within the TPACK framework in the context of AR (addressed through the direct paths H1–H9)?
- How the influences of CK, PK, and TK on TPACK are illustrated through mediating mechanisms (addressed through the indirect paths H10–H15).

By testing this structural model with data from in-service chemistry teachers who have experience using AR, the study seeks to refine theoretical understanding of TPACK in AR-enhanced chemistry education and to identify leverage points for targeted professional development.

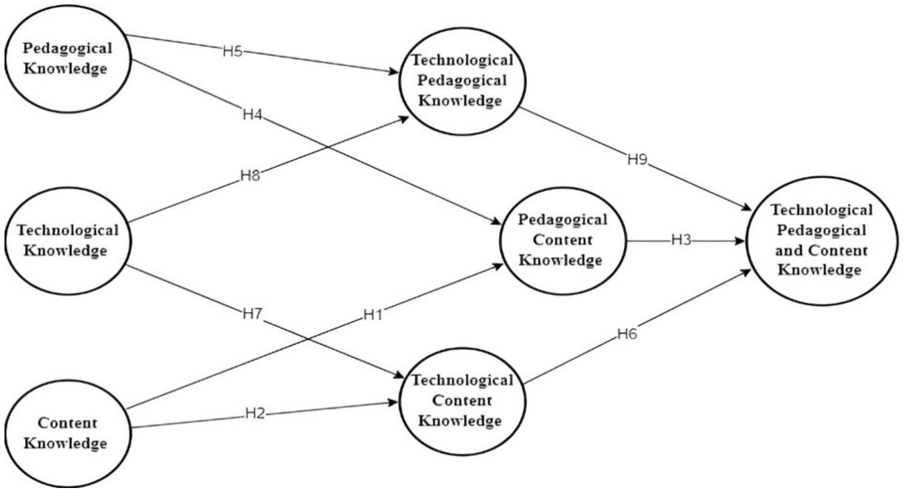

Figure 2. Research framework of the study

METHOD

RESEARCH DESIGN

This study employed a cross-sectional survey design using self-report questionnaires to examine the structural relationships among TPACK components in the context of augmented reality (AR)–enhanced chemistry teaching. The choice of a survey design was guided by the aim of capturing in-service chemistry teachers perceived knowledge across multiple TPACK domains and modelling the direct and indirect effects among these domains using structural equation modelling. The design is appropriate for testing theoretically grounded relationships among latent constructs in a relatively large sample of practising teachers within authentic school contexts.

The research questions and hypotheses derived from the literature review explicitly informed the design of the instrument, sampling strategy, and analytic approach. In particular, the focus on mediating relationships within the TPACK framework required a design that could simultaneously estimate multiple paths among CK, PK, TK, PCK, TCK, TPK, and TPACK using a single structural model.

PARTICIPANTS AND CONTEXT

Participants were in-service chemistry teachers working at lower- and upper-secondary schools in several provinces representing different educational contexts (urban and non-urban) within the national school system. Schools were selected in collaboration with local education authorities to ensure variation in school type and location while maintaining the feasibility of access.

Questionnaires were distributed to chemistry teachers at these schools using a combination of on-site and online formats. To ensure responses reflected experience with AR in chemistry teaching, the first section of the questionnaire included a screening item asking teachers whether they had ever used AR-based tools or applications in their chemistry lessons (e.g., mobile AR apps, AR textbooks, or marker-based AR materials). Only teachers who answered "yes" and completed the full questionnaire were retained for analysis.

After data screening, a total of N = 337 valid responses were included in the study. The sample size satisfies common rules of thumb for structural equation modelling (Hair et al., 2019), including both the minimum sample size of 200 and the "10-times rule" based on the maximum number of arrows pointing to a latent construct in the structural model. Descriptive statistics (reported in the Results section) indicate that the sample varied in gender, years of teaching experience, academic degree, and school type, supporting the generalizability of the findings to in-service chemistry teachers who have begun to integrate AR into their instruction.

Participation was voluntary, and teachers were informed of the study's purpose and the confidentiality of their responses before completing the questionnaire. No identifying information was collected, and data were analysed only in aggregate form.

Based on the demographic information provided in Table 1, the surveyed teachers demonstrated a diverse range of teaching experience, with 53.7% having more than 10 years of experience, 20.7% with 5-10 years, 13.4% with 3-5 years, and 6.2% with less than 3 years. Additionally, the majority of the teachers held a master's degree (53.4%), followed by bachelor's degree holders (45.1%). Regarding their work units, the majority of the surveyed teachers were employed in public schools (80.1%), followed by those working in private schools (16.3%) and international schools (3.6%).

Table 1. Demographic information of respondents

General information		Number	Percentage of respondents
Gender	Male	119	35.3
	Female	218	64.7
Years since graduation	Less than 3 years	21	6.2
	3 – 5 years	45	13.4
	5 – 10 years	90	20.7
	More than 10 years	181	53.7
	Bachelor's Degree	152	45.1
	Master's Degree	180	53.4
	Doctor of Philosophy	5	1.5
Work unit	Private	55	16.3
	Public	270	80.1
	International	12	3.6
Total		**337**	**100**

DATA COLLECTION

The data was collected from high schools in Hanoi, Nghe An, Thai Nguyen, and Ha Nam provinces. Chemistry teachers were invited to complete the survey. The spread in regions allows for more diverse answers, giving more trustworthy statistics. Specifically, the first question in the survey, which asked, "Have you ever used mobile technology, especially AR, to teach Chemistry before?", was used to screen participants who did not have experience with AR on devices. This is an act to ensure that only those who are reliable and can provide meaningful answers to statistical questions will continue with the survey. A total of 520 surveys were distributed to chemistry teachers, and the total number of usable responses was 337. This implies that the majority of the respondents have used AR to teach Chemistry before, while only a small number had not used AR.

INSTRUMENTATION

To evaluate key variables, survey items were drawn from various reports on the effects of the TPACK model with AR on chemistry teachers. As shown in Table 2, a 5-point Likert scale, which ranged from "1 = strongly disagree" to "5 = strongly agree", was employed to assess different constructs in this research. The survey items were built based on the article by Lin et al. (2013). By using constructs that were based on an existing paper, the viability of the instrumentation is ensured. For the given consideration of identifying a suitable instrument to elicit these chemistry teachers' perceptions of TPACK, this study intended to apply a survey targeting similar samples. A total of 35 items were included in the survey, with all constructs (TK, PK, CK, TPK, TCK, PCK, TPACK).

RESULTS

PRELIMINARY ANALYSES AND SAMPLE CHARACTERISTICS

All 337 cases retained for analysis were complete and satisfied the inclusion criterion of having prior experience with augmented reality (AR) in chemistry teaching. Visual inspection of histograms and skewness–kurtosis statistics indicated that item distributions did not deviate severely from normality; given the use of a variance-based structural equation modelling approach, minor non-normality was not considered problematic. No multivariate outliers with undue influence on the model were identified.

Descriptive statistics for the demographic variables (Table 1) show that the sample comprised both male and female teachers, with a broad range of teaching experience from early career to highly experienced teachers. Participants held different academic degrees and were employed at a variety of school types (e.g., lower-secondary, upper-secondary, and specialized schools). These characteristics suggest that the sample reflects a diverse group of in-service chemistry teachers who have begun to use AR in their classrooms.

Mean scores across the seven TPACK-related constructs were generally above the scale midpoint, indicating that participants perceived themselves as having moderate to high levels of knowledge of AR-enhanced chemistry teaching. However, variability within each construct suggests room for further development, supporting the relevance of modelling relationships among the knowledge domains.

MEASUREMENT MODEL

The measurement model was evaluated prior to testing the structural relationships among the constructs. The goal of this step was to ensure that the latent variables-CK, PK, TK, PCK, TCK, TPK, and TPACK-were measured reliably and validly by their respective indicators.

INDICATOR RELIABILITY

Standardized factor loadings were examined for all items (Table 2). Most indicators loaded strongly on their intended constructs, with loadings exceeding the recommended threshold of 0.70. A small number of items exhibited lower loadings. Following Hair et al. (2019), items with clearly insufficient loadings and limited conceptual contribution were removed from the model. In particular, two items from the original TPACK scale were dropped because they displayed weak factor loadings and ambiguous wording related to immersive technologies; these items did not explicitly refer to augmented reality and risked conflating AR with other technologies. After removing these items, all remaining indicators demonstrated satisfactory loadings on their target constructs, providing initial support for indicator reliability.

Table 2. Measurement model values

Constructs	Codes	Measurement items	Factor loading	Source
Technological Knowledge (TK)	TK1	I am successful at work using AR software and applications.	0.704	(Ali et al., 2023; Belda-Medina & Calvo-Ferrer, 2022; Perifanou et al., 2022)
	TK2	I regularly explore new AR technologies for potential uses in my teaching.	0.763	
	TK3	I feel comfortable solving technical problems related to AR tools.	0.825	
	TK4	I have been going through expert development sessions with reference to AR technology.	0.645	

Constructs	**Codes**	**Measurement items**	**Factor loading**	**Source**
	TK5	I am sure about how my work integrates AR technology with my tech skill set.	0.750	
Pedagogical Knowledge (PK)	PK1	I integrate AR into lesson plans to support and enhance students' learning	0.710	(Hsu, 2017; Schmid et al., 2021; Sofwan et al., 2023)
	PK2	I can flexibly adjust my teaching style to suit different teaching methods.	0.819	
	PK3	I analyze the effectiveness of my teaching methods during instruction.	0.750	
	PK4	I feel comfortable using AR as a learning tool in my classroom.	0.748	
	PK5	I often take feedbacks from students after each lesson.	0.809	
Content Knowledge (CK)	CK1	I regularly update my chemistry knowledge to include new concepts.	0.772	(Imaduddin & Astuti, 2022)
	CK2	I have a solid understanding of chemistry content that I believe can be supported by advanced teaching methods.	0.801	
	CK3	I am assured of my ability to integrate intricate chemistry concepts into my instructional strategies.	0.800	
	CK4	I feel confident in incorporating the AR to intricate concepts of chemistry.	0.710	
	CK5	I enhance the subject content with practical relevance and real-life applications by using advanced teaching techniques.	0.721	
Technological Pedagogical Knowledge (TPK)	TPK1	I have changed my teaching approach to improve students' understanding.	0.789	(Imaduddin & Astuti, 2022; Ripsam & Nerdel, 2024)
	TPK2	I have a high level of confidence in my ability to teach chemical principles.	0.794	
	TPK3	I evaluate students' performance concerning learning chemistry lessons.	0.812	
	TPK4	I feel comfortable using teaching methods to enhance students' interest in chemistry.	0.848	
	TPK5	I always ask my students about the usefulness of my teaching methods.	0.810	
Technological Content Knowledge (TCK)	TCK1	I use AR to explain and visualize complex chemistry concepts.	0.831	(Bower et al., 2014; Yamtinah et al., 2023)
	TCK2	I am quite sure that I can select the most suitable AR tools to explore certain chemistry subjects.	0.671	
	TCK3	I update the AR content that I develop with chemistry subjects that I teach frequently.	0.830	
	TCK4	I include AR into my knowledge evaluations of chemistry.	0.878	
	TCK5	I am comfortable using AR to show actual chemical reaction.	0.820	
Pedagogical Content	PCK1	I changed the way I taught to include AR to improve pupils' understanding.	0.760	(Imaduddin & Astuti, 2022;

Constructs	Codes	Measurement items	Factor loading	Source
Knowledge (PCK)	PCK2	I possess a high level of assurance in my capacity to instruct chemical principles utilizing AR.	0.751	Yamtinah et al., 2023)
	PCK3	I evaluate students' performance with regard to learning chemistry lessons that contain AR.	0.743	
	PCK4	I am at ease in using AR for improving students' interest in chemistry.	0.772	
	PCK5	I always ask my students about the usefulness of AR in my teaching.	0.656	
Technological Pedagogical Content Knowledge (TPACK)	TPACK1	I am comfortable combining instructional techniques and chemical information with AR technology.	0.696	(Bullock & Huwer, 2024; Yamtinah et al., 2023)
	TPACK2	I develop thorough lesson plans that combine teaching and subject-matter expertise with AR.	0.596	
	TPACK3	I possess the ability to effectively align AR technologies with learning objectives and course requirements.	0.507	
	TPACK4	I consistently evaluate the efficacy of virtual reality in enhancing student learning.	0.582	
	TPACK5	I am a member of professional learning communities that discuss the potential applications of virtual reality in educational settings.	0.607	

Moving on to Table 3, several important measures are presented, including Cronbach's alpha, composite reliability (rho_a and rho_c), and the average variance extracted (AVE). The confirmatory factor analysis findings provide a strong statistical foundation for validating the internal consistency and dependability of the measured components.

Table 3. Confirmatory factor analysis

Items	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
TK	0.929	0.93	0.946	0.779
PK	0.816	0.934	0.89	0.667
CK	0.92	0.921	0.94	0.758
TPK	0.94	0.942	0.955	0.808
TCK	0.898	0.903	0.925	0.712
PCK	0.908	0.91	0.931	0.731
TPACK	0.935	0.937	0.951	0.794

All constructions have quite high Cronbach's alpha values. TK has an astounding alpha of 0.935, which denotes outstanding internal consistency. In addition, the composite reliability (rho_a and rho_c) of TK is 0.937 and 0.951, respectively, providing additional evidence of the variables' reliability. The AVE for TK is 0.794, indicating that a significant portion of the variability in the observable variables is explained by the construct.

However, the PCK construct has a slightly lower Cronbach's alpha value of 0.816, which, while deemed acceptable, is the lowest among the constructions. However, the composite reliability metrics for this remain strong, with a rho_a of 0.934 and a rho_c of 0.890, indicating consistent and dependable internal consistency. The AVE for PCK at 0.667 is the lowest among the constructs, yet it's still above the widely recognized criterion of 0.5. This indicates a reasonable degree of variation explained.

The findings highlight the strong psychometric qualities of the scales used to assess the various aspects of TPACK in the context of AR in chemistry teaching. The robust reliability indices indicate that the constructs are well specified and successfully include the many dimensions of instructors' skills in using AR technology in their teaching methods.

Table 4 displays the results of the exploratory factor analysis (EFA) for several components linked to the investigation. Every collected data point and the scientific basis of the TPACK model exhibit a strong alignment, as shown by the very high factor loadings across all constructs. To be more specific, the TCK construct has the highest loadings. Especially, TCK4 ("I include AR into my knowledge evaluations of chemistry."), has the highest factor loading of 0.933. The significant statistic reveals the crucial role of AR in enabling chemistry educators to integrate technology with their expertise in the topic.

Table 4. Exploratory factor analysis of the items

Items	**Factor**						
	CK	**PCK**	**PK**	**TCK**	**TK**	**TPACK**	**TPK**
CK1	0.864						
CK2	0.92						
CK3	0.923						
CK4	0.858						
CK5	0.846						
PCK1		0.922					
PCK2		0.92					
PCK3		0.913					
PCK4		0.897					
PCK5		0.011					
PK1			0.857				
PK2			0.872				
PK3			0.866				
PK4			0.862				
PK5			0.896				
TCK1				0.873			
TCK2				0.849			
TCK3				0.912			
TCK4				0.934			
TCK5				0.925			
TK1					0.789		
TK2					0.88		
TK3					0.89		
TK4					0.787		
TK5					0.868		
TPACK1						0.811	
TPACK2						0.874	
TPACK3						0.858	

Items	Factor						
	CK	PCK	PK	TCK	TK	TPACK	TPK
TPCAK4						0.897	
TPACK5						0.832	
TPK1							0.889
TPK2							0.857
TPK3							0.907
TPK4							0.885
TPK5							0.917

The results showed that instructors are effectively integrating technology and subject knowledge with instructional techniques, as seen by the strong factor loadings in the PCK and TPACK constructs. When the loading is 0.923, PCK1 demonstrates that the use of AR effectively aligns instructional methodologies and subject knowledge.

The findings of this study clearly confirm the accuracy and importance of the TPACK model's structures when used for AR applications in chemistry training. The integration of technical, pedagogical, and subject knowledge in AR technology improves the quality of chemistry training. This study offers a numerical basis to substantiate this claim.

Table 5 shows the diagonal elements, which should ideally have higher values than the off-diagonal elements in the same row and column, representing the square root of the average variance extracted (AVE) for each construct. This indicates the extent to which the construct captures variance relative to the variance caused by measurement error. For example, the AVE square root of TK is 0.915, which is more than its correlations with other variables, thus showing its strong discriminant validity. Notably, there are some significant relationships between different constructs. TPACK has an important relationship with PCK (0.849) and TCK (0.852), suggesting a strong association between these areas in the context of using AR to teach chemistry.

Table 5. Discriminant validity

Factor	TK	PK	CK	TPK	TCK	PCK	TPACK
TK	**0.915**						
PK	0.775	**0.901**					
CK	0.861	0.779	**0.906**				
TPK	0.783	0.708	0.813	**0.899**			
TCK	0.837	0.729	0.855	0.876	**0.933**		
PCK	0.795	0.712	0.829	0.841	0.852	**0.919**	
TPACK	0.821	0.755	0.836	0.808	0.852	0.849	**0.926**

After analysing the data, it can be confirmed that each construct in the model is unique, as most constructs have greater square roots of AVE than their corresponding inter-construct correlations. This highlights that while there are notable similarities, particularly in constructs that include many knowledge domains like TPACK, each construct also encompasses distinct features of instructors' skills and use of AR in educational environments.

Table 6 presents compelling evidence of connections between several knowledge domains in the particular setting of AR in chemistry teaching. The path coefficients demonstrate robust positive associations, namely between CK and TCK, with a coefficient of 0.630 and a highly significant p-value of 0.000. This could suggest that CK has a high level of influence on TCK. These results show that by having a complete comprehension of content knowledge, teachers can significantly enhance their ability to make use of AR in the context of chemistry education. The relationship between PK and TPK is highly significant, as evidenced by a coefficient of 0.691, suggesting that a strong pedagogical foundation greatly enhances the capacity to integrate technology into instructional practices successfully.

Table 6. Path coefficient results of the proposed model

Hypothesis	Path relations	Original sample (O)	Sample mean (M)	Standard deviation (SD)	T statistics	P values	Results
H1	CK->PCK	0.326	0.328	0.082	3.956	0.000	Significant
H2	CK->TCK	0.750	0.747	0.049	15.451	0.000	Significant
H3	PCK->TPACK	0.315	0.313	0.061	5.154	0.000	Significant
H4	PK->PCK	0.579	0.577	0.078	7.392	0.000	Significant
H5	PK->TPK	0.690	0.686	0.061	11.256	0.000	Significant
H6	TCK->TPACK	0.275	0.276	0.094	2.929	0.003	Significant
H7	TK->TCK	0.209	0.211	0.050	4.181	0.000	Significant
H8	TK->TPK	0.225	0.229	0.065	3.476	0.001	Significant
H9	TPK->TPACK	0.325	0.326	0.095	3.426	0.001	Significant

Other significant associations include the impact of PCK on TPACK (coefficient of 0.315) and the influence of TPK on TPACK (coefficient of 0.325), both showing strong statistical significance (p-values). Different findings confirm the integration of domains of knowledge and stress the limited role of PCK and TPK in improving TPACK when using AR systems.

The data support the conceptual tenets of the TPACK model, showing that expertise in content, pedagogy, and technology is crucial for integrating these components in educational settings, especially when this integration is encouraged by the development of modern technologies, such as AR. This study shows the urgency of incorporating AR into learning practices and illustrates how multiple features of teacher competence work together to improve educational outcomes in chemistry.

Figure 3 gives data about the path coefficient results from each part of the proposed model (TPACK). Reviewing this figure provides insights into the model and its components, and how they influence each other within the TPACK scheme. First, PK has a notable positive influence on TPK (path coefficient of 0.024) and on PCK (path coefficient of 0.352). However, the correlation between construct PK and TPACK has little effect, as indicated by a coefficient value of 0.149. Second, TK demonstrates a modest beneficial impact on PCK (coefficient of 0.337) and a statistically significant effect on TPK (coefficient of 0.029). However, the influence of this factor on TPACK is negligible, as evidenced by a value of -0.012, suggesting an indirect correlation. CK significantly impacts TCK, as evidenced by a high path coefficient of 0.846, and it also has a substantial effect on PCK with a coefficient of 0.299. Nevertheless, the impact of CK on TPACK is quite insignificant, with a coefficient value of 0.043. Constructs such as PCK, TPK, and TCK are closely related to TPACK. The coefficient value from PCK to TPACK is the highest (0.769), followed by TPK (0.032) and TCK (0.043).

In conclusion, the approach focuses on the significance of incorporating knowledge constructs to improve overall TPACK. The substantial path coefficient of PCK to TPACK (0.769) indicates that a solid understanding of PCK is necessary for the development of complete TPACK. It is crucial for educators to prioritize integrated knowledge areas to use technology in educational environments effectively.

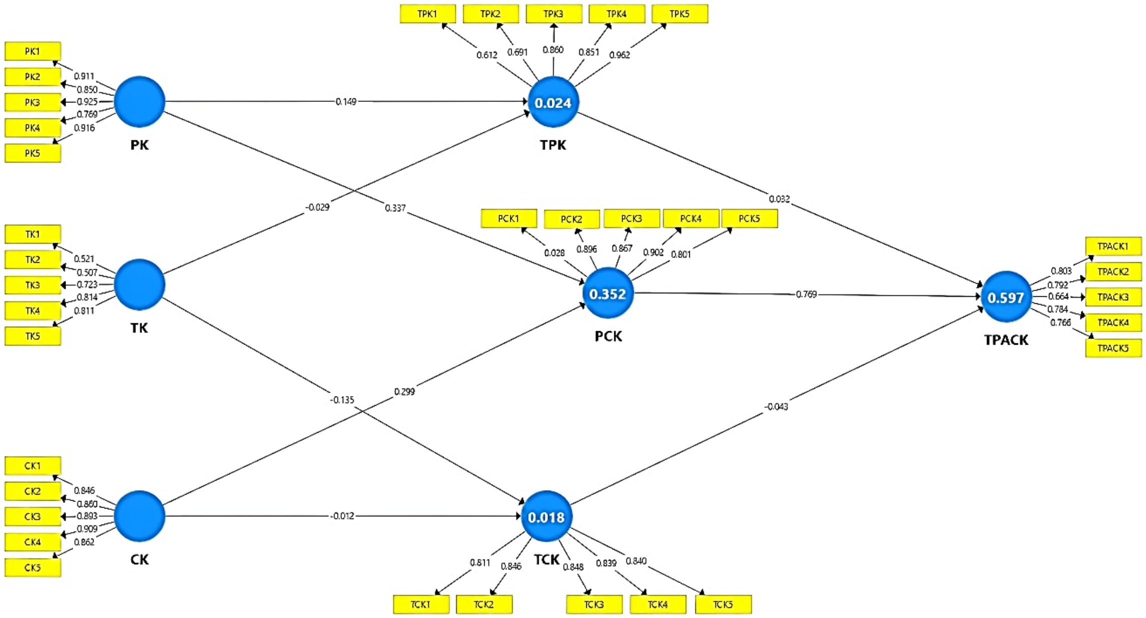

Figure 3. Path coefficient results of the proposed model

The data in Table 7 investigates the connections between several domains of knowledge and how these connections may influence one another through an intermediary domain, ultimately shaping the TPACK domain as a whole. Remarkably, the association between CK and TPACK is mediated by PCK, with an indirect effect size of 0.094.

Table 7. Specific indirect effect

Hypo-thesis	Path relations	Original sample (O)	Sample mean (M)	Standard deviation (SD)	T statistics	P values	Results
H10	CK -> PCK -> TPACK	0.103	0.102	0.030	3.396	0.001	Significant
H11	PK -> PCK -> TPACK	0.183	0.182	0.048	3.839	0.000	Significant
H12	CK -> TCK -> TPACK	0.206	0.204	0.064	3.200	0.001	Significant
H13	TK -> TCK -> TPACK	0.058	0.061	0.030	1.909	0.056	Reject
H14	PK -> TPK -> TPACK	0.225	0.225	0.073	3.080	0.002	Significant
H15	TK -> TPK -> TPACK	0.073	0.074	0.028	2.621	0.009	Significant

This indirect impact is considered strong and highly significant, as shown by a T statistic of 3.033 and a p-value of 0.002. This implies that a strong foundation of understanding in a particular field indirectly enhances the capacity to use technology effectively in teaching, through expertise in teaching methods and subject matter.

Another significant route is from PK to TPK, and finally to TPACK. This route has an indirect impact of 0.225, which is the greatest of the pathways mentioned. The T statistic for this pathway is 3.085, and the p-value is 0.002. This suggests that a strong understanding of teaching methods significantly influences the integration of technology into instruction, which, in turn, improves the overall knowledge framework for technology, teaching, and content.

These results emphasize the complex, interdependent interactions among many elements of the TPACK framework. The statement focuses on the need not only to possess direct expertise in materials, pedagogy, or technology, but also to understand how these areas interact in different ways to improve the efficient use of AR in education. These findings may help shape teacher training programs, highlighting the importance of integrating these areas to optimize the educational benefits of technology-enhanced learning settings.

DISCUSSION

This study examined how chemistry teachers' knowledge components interact within the TPACK framework when they use augmented reality (AR) in their teaching. By testing a model that includes both direct and indirect relationships among CK, PK, TK, PCK, TCK, TPK, and TPACK, the study offers a more fine-grained view of what actually underpins teachers' capacity to design AR-enhanced chemistry lessons, extending recent TPACK work that has employed structural models in STEM contexts.

Knowledge components in AR-enhanced chemistry teaching (RQ1)

The measurement results show that teachers' self-reported knowledge can be meaningfully distinguished into seven domains in the AR context. CK, PK, TK, and the four intersection domains form a coherent structure rather than collapsing into a single broad factor, consistent with recent validation studies of TPACK instruments in science and mathematics education.

At the same time, the descriptive statistics suggest an interesting profile. Teachers generally rated themselves above the midpoint across most domains, but the score distribution is wide, especially for TCK, TPK, and TPACK (Mohamad, 2021). Many teachers, therefore, see themselves as having at least some knowledge of AR integration, yet there is clear variation and room for development. Similar patterns of relatively strong CK/TK, but more heterogeneous ratings in intersection domains, have been reported in other recent STEM-TPACK studies (Mansour et al., 2024; Schmid et al., 2021). This combination of distinct constructs and heterogeneous scores provides a strong basis for exploring how these domains work together in practice.

Direct relationships among TPACK components in an AR context (RQ2)

The structural paths paint a consistent picture of how foundational knowledge feeds into more integrated forms of knowledge as AR enters the classroom, consistent with recent SEM-based analyses of TPACK in STEM teaching (Abebe & Trainin, 2024; Li & Li, 2024).

CK and PK both showed strong links to PCK. In a subject like chemistry, where content is conceptually dense and often counterintuitive, teachers who understand the subject matter well and have a solid grasp of general pedagogy are more likely to develop explanations, representations, and tasks that make difficult topics accessible, with or without AR (Goes & Fernandez, 2023). CK also predicted TCK, suggesting that decisions about which aspects of chemistry can benefit from AR visualisation depend heavily on content expertise-a point that matches emerging AR-in-chemistry work showing that AR tends to be most effective when used for conceptually demanding topics such as molecular structure or green chemistry (Bullock & Huwer, 2024; Khairani & Prodjosantoso, 2023).

PK behaved in a slightly different but complementary way. In addition to supporting PCK, it was strongly associated with TPK. This indicates that generic pedagogical knowledge does not remain abstract; when AR is introduced, teachers draw on their existing repertoires to rethink classroom organisation, task design, and feedback (Duc & Quang, 2024; Radianti et al., 2020). Recent TPACK-informed professional development studies similarly show that teachers' pedagogical repertoires are actively reshaped when new tools, such as AR, are integrated into familiar teaching routines (Ilona-Elefteryja et al., 2020; Tondeur et al., 2017). Our results suggest that PK is one of the starting points for teachers to understand how AR changes their teaching, not just what it shows.

TK played a more selective role. It was clearly related to TCK, implying that teachers who are generally comfortable with technology are more likely to explore AR tools and integrate them into chemistry content. However, TK did not significantly predict TPK. Being good with technology does not automatically mean knowing how to reshape pedagogy around AR activities-an issue also highlighted in recent reviews of immersive technologies in STEM education, which caution against equating technical fluency with pedagogical readiness (Garzón et al., 2019).

Turning to the intersection domains, all three-PCK, TCK, and TPK-were positively related to TPACK, but not to the same extent. TPK had the strongest effect, followed by PCK and then TCK. Recent TPACK research employing structural models likewise identifies TPK as a key conduit linking foundational knowledge to overall TPACK in STEM teaching. In an AR-enhanced setting, it seems that knowing how pedagogy must adapt to technology is particularly important. PCK still matters because AR lessons are ultimately about helping students understand chemistry rather than simply manipulating 3D models (Chang & Wu, 2021). TCK also contributes, but its impact on overall TPACK appears smaller than that of the pedagogical intersections. The implication is that in AR-enhanced chemistry teaching, the "engine" of integrated knowledge lies more in how teachers orchestrate learning than in how many tools they know (Jensen & Konradsen, 2017).

Mediating mechanisms and AR-specific dynamics (RQ3)

The mediation results add an additional layer to this picture by clarifying how CK, PK, and TK are incorporated into TPACK. Rather than operating through a simple additive process, foundational knowledge appears to work through the intersection of domains – an assumption that recent TPACK studies have begun to test more explicitly using mediation and path analysis (Mansour et al., 2024).

PCK emerged as an important conduit for both CK and PK. Content specialists who also know how to teach, and general pedagogues who can adapt their strategies to chemistry, both achieve stronger TPACK when they combine these two forms of knowledge (Koehler Mishra, & Cain, 2013). The indirect paths from CK and PK to TPACK through PCK show that much of the impact of foundational domains is realised when teachers design topic-specific explanations, questions, and activities that can incorporate AR in a meaningful way, very much in line with recent AR-chemistry interventions that tie AR explicitly to key conceptual bottlenecks (Wong et al., 2021).

TCK played a more selective mediating role. It transmitted the effect of CK to TPACK, but not the effect of TK. This pattern points to a content-driven logic: teachers seem to start from the chemistry they want to teach and then look for AR tools that fit, rather than starting from the tools they happen to know and trying to fit content into them (Tondeur et al., 2012). Where content understanding is strong, TCK becomes a natural extension and, through TCK, contributes to TPACK. Where TK is strong but content links are weaker, the path to TPACK is less clear. This nuance adds to recent TPACK models that typically emphasise TK and PK as the main precursors of TPACK by foregrounding the role of CK when the technology is highly content-representational, as AR often is in chemistry.

TPK mediated the link between PK and TPACK but not the link between TK and TPACK. This reinforces the idea that pedagogical thinking is central when teachers explore new technologies-a conclusion also drawn from long-term TPACK-guided professional development programmes for STEM teachers (Koehler, Mishra, Kereluik, et al., 2013). Teachers who are already skilled in designing activities, organising group work, and using formative assessment seem better placed to adapt those practices to AR (Voogt & McKenney, 2016). They think in terms of "what students will actually do" with AR and "how learning will be guided", which translates into stronger TPK and, via TPK, into stronger TPACK. Again, TK on its own does not travel far along this route.

Taken together, the mediation results show that PCK and TPK are the dominant pathways from foundational knowledge to integrated knowledge in AR-enhanced chemistry teaching. TCK matters in connection with CK but is less central overall. AR, with its spatial and embodied affordances, appears to magnify the importance of the pedagogical intersections-how content is taught and how technology is woven into pedagogy, rather than technology knowledge by itself (Belda-Medina & Calvo-Ferrer, 2022).

Theoretical implications

To begin with, the results support viewing TPACK as a network rather than as a simple aggregate of CK, PK, and TK. The intersection domains are not peripheral; they carry much of the weight in shaping teachers' readiness to integrate AR. This perspective is consistent with recent TPACK reviews and modelling studies that argue for paying closer attention to PCK-, TCK-, and TPK-like constructs in STEM (Chai et al., 2013). Models that collapse PCK, TCK, and TPK into a single composite risk overlook where change and growth actually occur.

In addition, the dominance of TPK and PCK over TK and even TCK suggests that the TPACK framework may need to be read differently when the technology in question is AR. Because AR activities often involve students moving, manipulating virtual objects, and coordinating multiple representations, much of the complexity lies in classroom orchestration and task design (Dunleavy & Dede, 2013). Recent AR-chemistry interventions underscore this point, showing that learning gains are strongest when AR is tightly embedded in well-structured inquiry tasks rather than used as a stand-alone visualisation. This may explain why PK-linked paths in our model (PK → PCK, PK → TPK → TPACK) were so prominent.

The asymmetry around TCK also nuances the idea of "balanced" TPACK. In AR-enhanced chemistry teaching, balance does not mean equal emphasis on all three primary domains. Instead, content and pedagogy appear to anchor the framework, with technology playing a dependent but powerful role-a view that resonates with recent discussions of immersive technologies and STEM learning. Technology is most productive when it is tightly connected to both what is taught and how it is taught, rather than when it is treated as an independent driver.

Finally, by explicitly modelling and testing mediating paths, the study shows that mediation is not a purely statistical curiosity; it has theoretical meaning. It captures the idea that teachers rarely move directly from basic knowledge to fully integrated expertise. They progress through intermediate, intersectional forms of knowledge that deserve attention in their own right-an insight that recent TPACK work using longitudinal or professional development -focused designs has begun to document more clearly.

Practical implications

Beyond its theoretical contributions, this study offers several practical implications for teacher professional development and curriculum design in the context of AR–enhanced chemistry teaching. The structural model highlights that intersection domains, particularly TPK and PCK, play a central role in shaping teachers' overall TPACK, whereas TK alone exerts a more limited influence.

From a professional development perspective, the findings suggest that training programmes should move beyond a primary focus on technical skills or tool operation. Instead, professional development initiatives should prioritise helping teachers design and orchestrate AR-supported learning activities that are pedagogically coherent and conceptually grounded. Emphasis should be placed on developing TPK, such as strategies for managing classroom interaction, scaffolding inquiry, and integrating AR-based tasks into formative assessment practices. In parallel, strengthening PCK remains essential, as teachers need support in aligning AR visualisations with common student misconceptions and key conceptual bottlenecks in chemistry.

The results also carry implications for curriculum design. Given that AR is most effective when applied to conceptually demanding and abstract topics, curriculum frameworks should explicitly identify chemistry concepts for which AR can provide added pedagogical value, such as molecular structure, reaction mechanisms, or particulate-level processes. Curriculum designers should ensure that AR activities are embedded within coherent instructional sequences rather than treated as stand-alone enhancements. Clear links between AR tasks, learning objectives, and assessment criteria are necessary to prevent superficial use of technology and to support meaningful conceptual understanding.

Taken together, these implications suggest that effective AR integration in chemistry education depends less on teachers' familiarity with technology per se and more on their ability to connect pedagogy, content, and technology in purposeful ways. Aligning professional development and curriculum design with these priorities may enhance the sustainability and instructional impact of AR-based innovations in school chemistry.

CONCLUSION

This study set out to unpack what stands behind chemistry teachers' TPACK when they integrate augmented reality (AR) into their lessons. Rather than asking only whether teachers "have TPACK", the study examined how CK, PK, and TK connect with the intersection domains PCK, TCK, and TPK, and how these, in turn, relate to overall TPACK in AR-enhanced chemistry teaching.

Survey data from 337 in-service chemistry teachers with prior AR experience point to a clear pattern. CK and PK form a strong foundation, feeding directly into PCK and, in the case of CK, also into TCK. PK is also tied to TPK, reflecting how general pedagogical knowledge is reworked when teachers design and orchestrate AR-based activities. TK does matter, but its influence is concentrated on TCK; it helps teachers link AR tools to chemistry content yet does not automatically lead to changes in pedagogy (TPK).

On the outcome side of the model, PCK, TCK, and especially TPK are closely connected to TPACK. Among these three, TPK exerts the largest effect, with PCK following and TCK playing a more modest role. When these direct effects are considered together with the mediation results, a consistent story emerges: much of the impact of CK and PK on TPACK runs through PCK and TPK, while TCK mainly channels the influence of CK. In other words, integrated forms of knowledge, particularly where content meets pedagogy and where pedagogy meets technology, are the real bridges to TPACK in AR-enhanced chemistry teaching, rather than the isolated domains of CK, PK, or TK.

These findings refine how TPACK can be understood in an AR context. Technology is clearly important, but it is not the starting point. Decisions about how AR is used in chemistry classrooms are anchored in the subject matter and the ways of teaching it; technology becomes powerful when it is woven into those two strands rather than treated as an end in itself.

LIMITATIONS

The conclusions above need to be read with several limitations in mind. The study is based on a cross-sectional survey and self-reported data. Although structural equation modelling allows theoretically grounded relationships to be examined, the design does not warrant strong causal claims. The measures capture teachers' perceptions of their knowledge, not direct observations of how that knowledge is enacted in AR-based lessons. The sample comprises in-service chemistry teachers from a single national system, all of whom reported having used AR in their teaching. This focus helps ensure that questionnaire items are meaningful to respondents, but it also restricts generalisability. The patterns identified here may not fully transfer to other subjects, other countries, or teachers who are only beginning to explore AR. While the measurement model met accepted criteria for reliability and validity, several items needed refinement or removal, particularly those whose wording blurred the distinction between AR and other immersive technologies. There is still room to strengthen instruments that are explicitly tailored to AR-related TPACK.

The study also relies on a single method and source of data. Although initial checks did not suggest that a single factor dominates the variance, common-method bias cannot be ruled out entirely. Multimethod designs would provide a firmer basis for judging the robustness of the relationships found.

Finally, the structural model concentrates on knowledge domains and does not incorporate other potentially important influences such as teachers' beliefs about AR, their technology-related self-efficacy, organisational support, or the design features of specific AR tools. These factors may interact with TPACK components and help explain differences in how teachers actually use AR.

FUTURE DIRECTIONS

One promising direction is to conduct longitudinal or intervention studies that track how TPACK for AR-enhanced chemistry teaching develops over time. Professional development programmes that explicitly focus on designing AR-supported lessons could be used to examine changes in PCK, TCK, TPK, and TPACK before and after participation, and to identify which pathways are most responsive to targeted support.

A second direction is to adopt mixed-methods designs that combine surveys with classroom observations, lesson artefact analysis, and interviews. Such studies would help bridge the gap between self-reported knowledge and actual practice, revealing how TPACK components are expressed in concrete instructional decisions, classroom orchestration, and assessment when AR is in play.

Future research could also expand the model to include additional constructs. Teachers' beliefs about AR, their perceived usefulness and ease of use, technology-related self-efficacy, and school-level conditions may shape how knowledge is mobilised. Including these variables would provide a richer account of why teachers with similar TPACK profiles integrate AR to varying degrees or with varying levels of success.

Comparative work offers another avenue. Studies could investigate whether the patterns observed in chemistry are similar in other subjects where AR is relevant, such as physics, biology, or earth science, or whether discipline-specific differences emerge. Cross-context comparisons across education systems would likewise clarify which aspects of the model are context-bound and which are more general.

Finally, future research might look more closely at different types of AR applications. Tools designed for virtual laboratories, for molecular visualisation, or for situating problems in real-world contexts may call on different configurations of TPACK. Mapping how particular AR designs interact with specific knowledge domains could inform both theoretical refinement of TPACK for immersive technologies and the design of AR tools that better support teachers' instructional goals.

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