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Research Article

Examining the impact of teachers' knowledge on the integration of dynamic mathematics software into constructivist pedagogy

Mailizar Mailizar[1], Khairul Umam[2] and Elisa Elisa[3]

[1]*Universitas Syiah Kuala, Indonesia (ORCID: 0000-0003-4084-311X)*
[2]*Universitas Syiah Kuala, Indonesia (ORCID: 0000-0003-3884-181X)*
[3]*Universitas Syiah Kuala, Indonesia (ORCID: 0009-0004-0596-2257)*

This study investigates the impact of teachers' knowledge on the integration of dynamic mathematics software into constructivist pedagogy, focusing on pre-service mathematics teachers' use of Mathematics Analysis Software. Using a quantitative research design and a cross-sectional survey, data were collected from 124 lower secondary mathematics teachers during the preliminary phase of the study. The survey, adapted from the Technological Pedagogical Content Knowledge framework, assessed teachers' technological knowledge, content knowledge, pedagogical knowledge, and their intersections, including pedagogical content knowledge, technological content knowledge, technological pedagogical knowledge, and technological pedagogical content knowledge. Teachers' classroom practices with dynamic mathematics software were analyzed at the classroom, task, and subject levels, while their professional development needs were explored through open-ended questions. The findings reveal significant relationships between various Technological Pedagogical Content Knowledge constructs and their influence on classroom practices. Notably, teachers' integrated knowledge across technology, pedagogy, and content was found to be a strong predictor of their ability to use dynamic mathematics software in classroom, subject, and task-level teaching. However, some relationships, such as content knowledge to technological content knowledge, were not significant. The study highlights the importance of professional development in enhancing teachers' Technological Pedagogical Content Knowledge and their effective use of dynamic mathematics software in constructivist teaching. These findings provide valuable insights for improving mathematics education and inform future research on integrating technology into pedagogy.

Keywords: Constructivist pedagogy; Dynamic mathematics software; Mathematics teachers; Technology integration; TPACK

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1. Introduction

The integration of technology into education has become a critical focus in recent years, particularly in mathematics education, where dynamic mathematics software [DMS] has shown significant potential to enhance teaching and learning. DMS, such as GeoGebra, Desmos, and other Mathematics Analysis Software [MAS], provides interactive tools that allow students to explore

Address of Corresponding Author

Mailizar Mailizar, PhD, Syiah Kuala University, Kota Banda Aceh, Aceh 23111, Indonesia.

armiati@fe.unp.ac.id

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mathematical concepts dynamically, fostering deeper understanding and engagement (Bakar et al., 2018; Drijvers et al., 2010). However, the effective use of such tools in classrooms depends on teachers' knowledge and their ability to integrate technology into pedagogy. This study examines the role of teachers' knowledge, particularly their Technological Pedagogical Content Knowledge [TPACK], in the integration of DMS into constructivist teaching practices.

The use of technology in mathematics education has been widely recognized as a means to improve students' conceptual understanding, problem-solving skills, and engagement (Pierce & Stacey, 2010; Ruthven, 2012). Dynamic mathematics software, in particular, enables students to visualize abstract mathematical concepts, manipulate variables, and observe real-time changes, which aligns with the principles of constructivist learning (Hohenwarter et al., 2009). Constructivist pedagogy emphasizes active learning, where students construct their own understanding through exploration and interaction with the material (Vygotsky, 1978). DMS supports this approach by providing interactive and exploratory environments that encourage students to experiment and discover mathematical relationships (Mostert & Clark-Wilson, 2016).

Despite the potential benefits of DMS, its effective implementation in classrooms remains a challenge. Research has shown that many teachers struggle to integrate technology into their teaching due to a lack of knowledge, confidence, or training (Ertmer & Ottenbreit-Leftwich, 2010; Mishra & Koehler, 2006). This highlights the importance of understanding the factors that influence teachers' ability to use DMS effectively, particularly their technological, pedagogical, and content knowledge.

The TPACK framework, developed by Mishra and Koehler (2006), provides a comprehensive model for understanding the knowledge required for effective technology integration in teaching. TPACK extends Shulman's (1986) concept of Pedagogical Content Knowledge by incorporating technological knowledge as a critical component. The framework consists of seven constructs: Technological Knowledge [TK], Content Knowledge [CK], Pedagogical Knowledge (PK), Pedagogical Content Knowledge [PCK], Technological Content Knowledge [TCK], Technological Pedagogical Knowledge [TPK], and Technological Pedagogical Content Knowledge. These constructs represent the intersections of technology, pedagogy, and content, emphasizing the need for teachers to integrate all three domains to create effective learning experiences (Koehler & Mishra, 2009).

Several studies have demonstrated the importance of TPACK in technology integration. For example, Chai et al. (2013) found that teachers with higher TPACK levels were more likely to use technology effectively in their classrooms. Similarly, Voogt et al. (2013) highlighted the role of TPACK in supporting teachers' ability to design technology-enhanced learning activities. In the context of mathematics education, TPACK is particularly relevant, as it enables teachers to select and use appropriate technological tools to support the teaching of complex mathematical concepts (Niess, 2005; Polly et al., 2010).

While the TPACK framework provides a useful lens for understanding teachers' knowledge, the integration of DMS into constructivist pedagogy presents unique challenges. Constructivist teaching requires teachers to create learning environments that encourage exploration, collaboration, and critical thinking (Jonassen, 1999). However, many teachers face difficulties in aligning their pedagogical practices with constructivist principles, particularly when using technology (Ertmer & Simons, 2006). For instance, teachers may lack the confidence or skills to design open-ended tasks that leverage the capabilities of DMS (Drijvers et al., 2010). Additionally, the use of DMS often requires significant changes to traditional teaching practices, which can be a barrier for teachers who are accustomed to more teacher-centered approaches (Pierce & Stacey, 2010).

Professional development has been identified as a key factor in addressing these challenges. Research has shown that targeted professional development programs can enhance teachers' TPACK and their ability to integrate technology into constructivist teaching (Lawless & Pellegrino, 2007; Polly et al., 2010). For example, Niess (2005) emphasized the importance of providing teachers with opportunities to explore and experiment with technology in a supportive environment. Similarly, Koehler et al. (2013) highlighted the need for professional development programs to focus on the integration of technology, pedagogy, and content, rather than treating them as separate domains.

Building on this body of research, the present study aims to investigate the impact of teachers' TPACK on their use of DMS in constructivist teaching practices. Specifically, the study focuses on pre-service mathematics teachers and examines the relationships between the different TPACK constructs and their classroom practices. By identifying the key factors that influence teachers' ability to integrate DMS into their teaching, this study seeks to provide insights into how professional development programs can be designed to support teachers in using technology effectively.

This study contributes to the growing body of literature on technology integration in education by providing empirical evidence on the role of TPACK in the use of DMS. The findings have implications for teacher education programs, policymakers, and researchers. For teacher education programs, the study highlights the need to incorporate TPACK-based training into the curriculum to prepare pre-service teachers for the challenges of technology integration. For policymakers, the study underscores the importance of investing in professional development programs that focus on the integration of technology, pedagogy, and content. Finally, for researchers, the study provides a framework for exploring the relationships between TPACK constructs and classroom practices, paving the way for future research on technology integration in mathematics education.

2. Related Literature and Conceptual Framework

The integration of technology has become a focus of research in mathematics education, particularly with the emergence of dynamic mathematics software such as GeoGebra, Desmos, and other mathematics analysis software. These tools have been shown to enhance students' understanding of mathematical concepts, improve engagement, and foster problem-solving skills (Hohenwarter et al., 2009; Pierce & Stacey, 2010). However, the effective use of DMS in classrooms depends on teachers' knowledge and their ability to integrate technology into their pedagogical practices (Drijvers et al., 2010; Niess, 2005).

A widely used model for understanding the knowledge required for effective technology integration is the Technological Pedagogical Content Knowledge framework, introduced by Mishra and Koehler (2006). TPACK extends Shulman’s (1986) concept of Pedagogical Content Knowledge by incorporating Technological Knowledge as a critical component. The framework emphasizes the interplay between technology, pedagogy, and content, highlighting the need for teachers to integrate all three domains to create effective learning experiences (Koehler & Mishra, 2009).

2.1. Dynamic Mathematics Software in Mathematics Education

DMS provides interactive tools that allow students to explore mathematical concepts dynamically, enabling them to visualize and manipulate variables in real time. This approach aligns with constructivist learning theories, which emphasize active engagement and the construction of knowledge through exploration and interaction (Jonassen, 1999; Vygotsky, 1978). Research has shown that DMS can support students in developing a deeper understanding of abstract mathematical concepts, such as geometry, algebra, and calculus (Mostert & Clark-Wilson, 2016; Ruthven, 2012).

Despite its potential, integrating DMS into classroom practice remains challenging. Teachers often face barriers such as a lack of technological knowledge, limited access to resources, and insufficient professional development opportunities (Ertmer & Ottenbreit-Leftwich, 2010; Polly et al., 2010). These challenges highlight the importance of understanding the factors that influence teachers' ability to use DMS effectively, particularly their TPACK.

Recent literature highlights that DMS is most effective when used to foster active, student-centered learning environments, supporting the core principles of constructivist pedagogy. A comprehensive meta-analysis by Ji et al. (2024) found that DMS significantly improves students' mathematical performance across educational levels, with the greatest effects observed when software is used to support inquiry-based and collaborative learning. This finding aligns with earlier studies by Zengin and Tatar (2017), who reported that GeoGebra enhances both motivation and conceptual understanding in mathematics classrooms.

Furthermore, the role of DMS in supporting personalized and adaptive learning has gained more attention in the AI era. Recent studies suggest that AI-driven and adaptive learning systems, when integrated with teacher facilitation, can support learner engagement and agency by enabling more responsive and personalized learning environments. However, research also highlights that the educational value of such technologies depends largely on teachers' experience, pedagogical alignment, and instructional decision-making, rather than on the technological tools themselves (Acuyo Cespedes, 2025; Hang, 2024). Accordingly, scholars caution that while AI-based systems may offer pedagogical opportunities, effective integration is contingent upon teacher expertise and sound instructional design (Bilgin & Güngören, 2025).

The transformation of mathematics teaching, learning, and assessment in the digital age is well documented. Borba et al. (2024) highlight that digital technology, including DMS, is reshaping classroom practices, enabling more flexible, interactive, and student-driven learning experiences.

The integration of DMS into mathematics education is deeply intertwined with constructivist teaching, where technology is not merely a tool but a mediator of mathematical meaning and learning. Hoyles and Noss (2009) argue that mathematical knowledge and pedagogy are inextricably linked to the tools. They emphasize that the design of both the tools and the learning activities in which they are embedded fundamentally shapes mathematical cognition. This perspective is echoed in recent systematic reviews, which highlight that DMS such as GeoGebra and Desmos enable students to construct, manipulate, and visualize mathematical objects, supporting deeper conceptual understanding and active engagement (Ji et al., 2024; Zengin & Tatar, 2017).

Borba and Villarreal (2005) extend this argument by introducing the concept of "humans-with-media," positing that mathematical thinking is reorganized through interactions with information and communication technologies. They contend that modeling, visualization, and experimentation are not just enhanced by technology but are fundamentally reorganized by it, leading to new forms of mathematical reasoning and learning. This theoretical lens has been influential in framing recent research on the affordances and challenges of DMS in mathematics education. For example, Cevikbas et al. (2023) found that digital technologies in mathematical modeling education offer significant cognitive, social, and pedagogical enhancements, but also introduce challenges such as "black-box" effects and the need for new teacher competencies.

Recent literature further underlines the importance of teacher beliefs and knowledge in realizing the constructivist potential of DMS. Thurm and Barzel (2022) show that teachers' self-efficacy and epistemological beliefs are central to the integrated and constructivist use of technology in mathematics classrooms. Similarly, Li et al. (2024) highlight that teachers' TPACK is a key factor in leveraging DMS for student-centered, inquiry-based learning. Engelbrecht and Borba (2024) also note that the rapid evolution of digital tools requires teachers to continuously adapt their pedagogical strategies, with constructivist approaches being particularly well-suited to the affordances of DMS.

The theoretical and empirical consensus is that DMS, when used within a constructivist framework, can transform mathematics education by enabling new forms of exploration, collaboration, and meaning-making. However, as Hoyles and Noss (2009) and Borba and Villarreal (2005) caution, the effectiveness of these technologies depends on thoughtful design and the active mediation of teachers.

2.2. The TPACK Framework and Teacher Knowledge

The TPACK framework provides a comprehensive model for understanding the knowledge required for technology integration. It consists of seven constructs: Technological Knowledge, Content Knowledge, Pedagogical Knowledge, Pedagogical Content Knowledge, Technological Content Knowledge, Technological Pedagogical Knowledge, and Technological Pedagogical Content Knowledge (Mishra & Koehler, 2006). Each construct represents a specific intersection of technology, pedagogy, and content, emphasizing the need for teachers to integrate these domains to create effective learning experiences.

Several studies have highlighted the importance of TPACK in supporting teachers' ability to integrate technology into their teaching. For example, Chai et al. (2013) found that teachers with higher TPACK levels were more likely to use technology effectively in their classrooms. Similarly, Voogt et al. (2013) emphasized the role of TPACK in enabling teachers to design technology-enhanced learning activities. In the context of mathematics education, TPACK is particularly relevant, as it enables teachers to select and use appropriate technological tools to support the teaching of complex mathematical concepts (Niess, 2005; Polly et al., 2010).

Teachers' knowledge plays a critical role in shaping their classroom practices, particularly in the use of technology. Research has shown that teachers with strong TPACK are more likely to integrate technology into their teaching in meaningful ways (Drijvers et al., 2010; Koehler et al., 2013). For instance, teachers with high levels of Technological Content Knowledge are better equipped to select and use technological tools that align with the content they are teaching (Niess, 2005). Similarly, teachers with strong Technological Pedagogical Knowledge are more likely to design learning activities that leverage the affordances of technology to support student learning (Chai et al., 2013).

In the context of DMS, teachers' knowledge influences their ability to design and implement tasks that align with constructivist principles. For example, Drijvers et al. (2010) found that teachers with strong TPACK were more likely to use DMS to create exploratory tasks that encourage students to experiment and discover mathematical relationships. However, many teachers struggle to align their pedagogical practices with constructivist principles, particularly when using technology (Ertmer & Simons, 2006). This highlights the need for professional development programs that focus on enhancing teachers' TPACK and their ability to integrate DMS into constructivist teaching.

2.3. Professional Development and TPACK

Professional development has been identified as a key factor in supporting teachers' ability to integrate technology into their teaching. Research has shown that targeted professional development programs can enhance teachers' TPACK and their ability to use technology effectively (Lawless & Pellegrino, 2007; Polly et al., 2010). For example, Niess (2005) emphasized the importance of providing teachers with opportunities to explore and experiment with technology in a supportive environment. Similarly, Koehler et al. (2013) highlighted the need for professional development programs to focus on the integration of technology, pedagogy, and content, rather than treating them as separate domains.

In the context of DMS, professional development programs should focus on helping teachers develop the skills and knowledge needed to design and implement constructivist tasks. For instance, teachers should be trained to use DMS to create tasks that encourage students to explore and discover mathematical concepts dynamically (Mostert & Clark-Wilson, 2016). Additionally, professional development programs should provide teachers with opportunities to collaborate and share best practices, as this can help them overcome barriers to technology integration (Ertmer & Ottenbreit-Leftwich, 2010).

2.4. Conceptual Framework

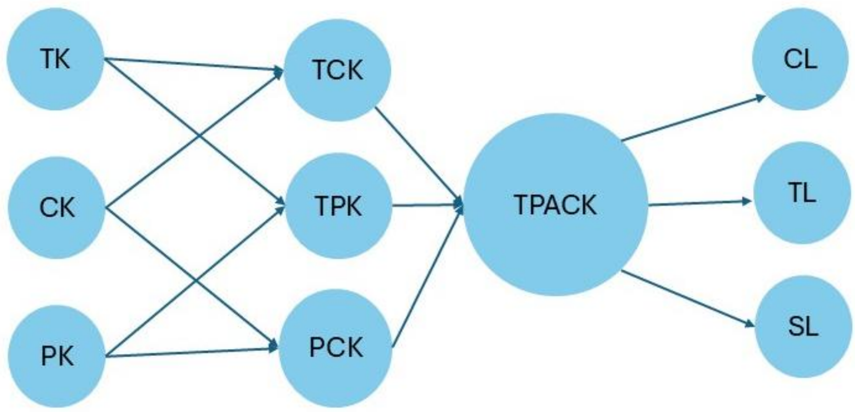
The conceptual framework for this study is based on the TPACK model, which provides a comprehensive lens for understanding the knowledge required for technology integration. The framework emphasizes the interplay between technology, pedagogy, and content, highlighting the need for teachers to integrate these domains to create effective learning experiences (Mishra & Koehler, 2006). In the context of this study, the TPACK framework is used to examine the impact of teachers' knowledge on their use of DMS in constructivist teaching practices.

The study focuses on all aspects of teachers’ Technological Pedagogical Content Knowledge, encompassing Technological Knowledge, Pedagogical Knowledge, Content Knowledge, and their intersections: Technological Content Knowledge, Pedagogical Content Knowledge, Technological Pedagogical Knowledge, and the integrative TPACK construct itself. These comprehensive constructs are used to examine the relationships between teachers’ knowledge and their classroom practices, including their use of DMS at the classroom level, task level, and subject level, as outlined in the Pedagogical Map of MAS framework (Pierce & Stacey, 2010).

2.5. Hypothetical Model

Based on our review of how dynamic mathematics software and constructivist pedagogy intersect with teachers’ knowledge domains, we propose a hypothetical model in which Technological Knowledge, Content Knowledge, and Pedagogical Knowledge interact to drive effective Mathematics Analysis Software integration. Drawing on Niess (2005) and Voogt et al. (2013), we assume that TK directly strengthens both Technological Content Knowledge and Technological Pedagogical Knowledge, enabling teachers to select appropriate software features and design technology-mediated instructional strategies (Chai et al., 2013). Likewise, CK informs TCK (Koehler & Mishra, 2009; Mostert & Clark-Wilson, 2016) and Pedagogical Content Knowledge (Niess, 2011; Shulman, 1986), guiding the choice of mathematical representations and sequencing of concepts. General pedagogical expertise further shapes PCK (Polly et al., 2010; Shulman, 1986) and supports the use of DMS-based tasks (Angeli & Valanides, 2009; Drijvers et al., 2010) reflected in TPK. These three intersection domains—TCK, PCK, and TPK—then jointly promote integrated Technological Pedagogical Content Knowledge (Koehler et al., 2013; Mishra & Koehler, 2006). Finally, it is this holistic TPACK that we expect to integrate into MAS implementation across classroom-level, subject-specific, and task design, as presented in the Pedagogical Map of MAS (Pierce & Stacey, 2010). Figure 1 visualizes these hypothesized relationships.

Figure 1
Hypothetical Model



Hypotheses:

H1. Technological Knowledge (TK) has a significant and positive effect on Technological Content Knowledge (TCK) in the context of MAS use.

H2. Content Knowledge (CK) has a significant and positive effect on Technological Content Knowledge (TCK) in the context of MAS use.

H3. Technological Knowledge (TK) has a significant and positive effect on Technological Pedagogical Knowledge (TPK) in the context of MAS use.

H4. Pedagogical Knowledge (PK) has a significant and positive effect on Technological Pedagogical Knowledge (TPK) in the context of MAS use.

H5. Pedagogical Knowledge (PK) has a significant and positive effect on Pedagogical Content Knowledge (PCK) in the context of MAS use.

H6. Content Knowledge (CK) has a significant and positive effect on Pedagogical Content Knowledge (PCK) in the context of MAS use.

H7. Technological Content Knowledge (TCK) has a significant and positive effect on Technological Pedagogical Content Knowledge (TPACK) for MAS integration.

H8. Technological Pedagogical Knowledge (TPK) has a significant and positive effect on Technological Pedagogical Content Knowledge (TPACK) for MAS integration.

H9. Pedagogical Content Knowledge (PCK) has a significant and positive effect on Technological Pedagogical Content Knowledge (TPACK) for MAS integration.

H10. Technological Pedagogical Content Knowledge (TPACK) for MAS integration has a significant and positive effect on teaching practice at the Classroom Level (CL).

H11. Technological Pedagogical Content Knowledge (TPACK) for MAS integration has a significant and positive effect on teaching practice at the Task Level (TL).

H12. Technological Pedagogical Content Knowledge (TPACK) for MAS integration has a significant and positive effect on teaching practice at the Subject Level (SL).

3. Method

3.1. Research Design

This study employed a quantitative research design with a cross-sectional survey approach, as outlined by Fraenkel et al. (2011). The use of a questionnaire allowed for the collection of standardized responses from a large sample, ensuring reliable, valid, and generalizable findings. Hypothesis testing was employed as a key analytical tool, following the guidelines of Shank and Brown (2013), to explore the relationships between TPACK constructs and classroom practices. This approach provided valuable insights into how TPACK influences the effective use of MAS in mathematics education.

3.2. Participants

The participants in this study were 124 lower secondary mathematics teachers. In this study, the focus was on evaluating their classroom practices with MAS and their perceptions of the impact of TPACK on their teaching. These teachers were selected to provide a representative sample of lower secondary mathematics educators who use MAS in their classrooms.

3.3. Instruments

To measure teachers' knowledge and classroom practices, the study utilized an adapted version of the mathematics TPACK questionnaire developed by Zelkowski et al (2013). The original instrument was specifically designed and validated for secondary mathematics teachers, addressing the need for a reliable, domain-specific measure of Technological Pedagogical Content Knowledge in mathematics education (Zelkowski et al., 2013). This instrument assessed seven constructs: Technological Knowledge, Content Knowledge, Pedagogical Knowledge, Pedagogical Content Knowledge, Technological Content Knowledge, Technological Pedagogical Knowledge, and Technological Pedagogical Content Knowledge. Teachers' classroom practices with MAS were evaluated using a framework based on the pedagogical map of MAS (Pierce & Stacey, 2010), which examines practices at three levels: classroom, task, and subject.

3.4. Data Collection and Analysis

An online survey was administered to the participants during the assessment phase. The data collected included both quantitative responses from the TPACK questionnaire and qualitative responses to open-ended questions. The data were analyzed using Structural Equation Modeling [SEM] with the Partial Least Squares [PLS] approach, conducted through SmartPLS 3.0 software. This method was chosen for its ability to handle complex relationships between latent variables and its suitability for small to medium sample sizes. The analysis followed a two-step process: (1) Measurement Model Assessment, which evaluated reliability and validity through Cronbach's alpha, composite reliability [CR], average variance extracted [AVE], and discriminant validity using the Fornell-Larcker criterion and HTMT ratio; and (2) Structural Model Assessment, which tested the hypothesized relationships between constructs using path coefficients, R^2 values, effect sizes (f^2), and predictive relevance (Q^2). Bootstrapping with 5,000 resamples was used to assess the significance of path coefficients.

3.4. Data Collection and Analysis

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4. Results

This section presents the findings of the study, which aimed to examine the impact of teachers' Technological Pedagogical Content Knowledge on their integration of Mathematics Analysis Software into constructivist teaching practices. The results are based on data collected from 124 lower secondary mathematics teachers during the assessment phase of the research. Using Structural Equation Modeling with Partial Least Squares [SEM-PLS] in SmartPLS 3.0, the study evaluated the relationships between TPACK constructs and classroom practices at the classroom level [CL], task level [TL], and subject level [SL]. The analysis included the assessment of the measurement model for reliability and validity, as well as the structural model to test the hypothesized relationships. Key findings, including the significance of path coefficients, R^2 values, and predictive relevance (Q^2), are discussed to provide insights into the role of TPACK in effective MAS integration.

4.1. Measurement Model

4.1.1. Indicator loadings and internal consistence reliability

Table 1 presents the reflective indicator loadings and internal consistency reliability for each construct measured in the study. This table is important for establishing the reliability and validity of the measurement model, ensuring that each construct is accurately represented by its indicators.

The measurement model was assessed for reliability and validity. Table 1 shows that all indicator loadings exceeded the recommended threshold of 0.70 (Hair et al., 2017), indicating that the items strongly represent their respective constructs. For example, the loadings for Content Knowledge ranged from 0.729 to 0.903, while Pedagogical Knowledge ranged from 0.864 to 0.934. Similarly, other constructs, such as Technological Knowledge, Pedagogical Content Knowledge, Technological Content Knowledge, and Technological Pedagogical Knowledge, also demonstrated high loadings, confirming the adequacy of the indicators.

Table 1
Reflective indicator loadings and internal consistency reliability

Item	*Loading*	*α*	*CR*	*AVE*
CK2	0.816	.918	.923	.673
CK3	0.729			
CK4	0.834			
CK5	0.808			
CK6	0.782			
CK7	0.858			
CK8	0.903			
PK1	0.864	.917	.921	.800
PK2	0.934			
PK3	0.889			
PK4	0.890			
TK1	0.858			
TK2	0.845			
TK3	0.805			
TK4	0.789			
TK5	0.835			
PCK1	0.843	.934	.938	.753
PCK2	0.869			
PCK3	0.907			
PCK4	0.868			
PCK5	0.902			
PCK6	0.814			
TCK1	0.898	.935	.938	.798
TCK2	0.896			
TCK3	0.773			
TCK4	0.941			
TCK5	0.948			
TPK1	0.917	.934	.947	.793
TPK2	0.881			
TPK3	0.921			
TPK4	0.928			
TPK5	0.799			
CL1	0.890	.971	.971	.875
CL2	0.923			
CL3	0.932			
CL4	0.952			
CL5	0.961			
CL6	0.953			
SL1	0.923	.955	.957	.848
SL2	0.854			
SL3	0.953			
SL4	0.950			
SL5	0.922			
TL1	0.842	.954	.958	.846
TL2	0.918			
TL3	0.950			
TL4	0.950			
TL5	0.933			

Table 1 also shows Internal consistency reliability which was evaluated using Cronbach's alpha (α) and Composite Reliability. All constructs exceeded the threshold of 0.70 for Cronbach's alpha and 0.70 for CR, indicating strong internal consistency. For instance, CK had α = .918 and CR = .923, while PK had α = .917 and CR = .921. These results confirm that the constructs are reliable and consistent in measuring their respective dimensions.

4.2. Convergent Validity

Convergent validity was assessed using the Average Variance Extracted. All constructs achieved AVE values above the recommended threshold of .50 (Fornell & Larcker, 1981), indicating that the constructs explain a substantial portion of the variance in their indicators. For example, CK had an AVE of .673, PK had an AVE of .800, and TPACK had an AVE of 0.878. These results confirm that the constructs exhibit adequate convergent validity.

4.3. Discriminant Validity

Discriminant validity was evaluated using the Fornell-Larcker criterion and the Heterotrait-Monotrait [HTMT] ratio. Table 4 shows that the square root of the AVE for each construct (diagonal values) is greater than its correlations with other constructs, satisfying the Fornell-Larcker criterion. For example, the square root of the AVE for CK (.820) is higher than its correlations with other constructs, such as CL (.470) and PCK (.814). This indicates that each construct is distinct from the others.

The HTMT ratio (Table 6) was also used to confirm discriminant validity. All HTMT values were below the threshold of .85 (Henseler et al., 2015), further supporting discriminant validity. For instance, the HTMT value between CK and PK was .803, and between CK and TPACK was .582, both below the threshold. These results confirm that the constructs are distinct and do not overlap significantly.

Table 2 displays the Fornell-Larcker criterion results, which are used to assess discriminant validity among the constructs. This criterion ensures that each construct is distinct from the others in the model.

Table 2
Fornell–Larcker Criterion Results for Discriminant Validity

	CK	*CL*	*PCK*	*PK*	*SL*	*TCK*	*TK*	*TL*	*TPACK*	*TPK*
CK	.820									
CL	.470	.935								
PCK	.814	.497	.868							
PK	.739	.465	.830	.895						
SL	.487	.689	.419	.449	.921					
TCK	.508	.578	.549	.471	.665	.893				
TK	.634	.587	.589	.550	.676	.739	.827			
TL	.540	.843	.501	.476	.774	.603	.656	.920		
TPACK	.548	.763	.555	.510	.710	.774	.677	.843	.878	
TPK	.583	.702	.615	.555	.680	.598	.661	.628	.657	.890

The diagonal values in Table 2 are higher than the correlations with other constructs, satisfying the Fornell-Larcker criterion. This indicates that each construct is sufficiently distinct, supporting the discriminant validity of the measurement model.

Table 3 provides the cross-loading values for all items across constructs. Cross-loadings are examined to further confirm that each item loads highest on its intended construct. The results in Table 3 show that each item's loading is highest on its respective construct compared to others, further supporting the discriminant validity of the measurement model.

Table 3
Cross-Loading Values of Measurement Items Across Constructs

	CK	*CL*	*PCK*	*PK*	*SL*	*TCK*	*TK*	*TL*	*TPACK*	*TPK*
CK2	.816	.450	.731	.755	.407	.414	.539	.492	.472	.531
CK3	.729	.360	.586	.593	.361	.403	.495	.425	.419	.451
CK4	.834	.384	.622	.536	.463	.355	.444	.458	.438	.434
CK5	.808	.366	.693	.602	.364	.451	.662	.448	.475	.549
CK6	.782	.299	.621	.535	.311	.301	.399	.336	.338	.341
CK7	.858	.396	.666	.562	.457	.456	.492	.432	.462	.473
CK8	.903	.424	.735	.636	.428	.508	.575	.493	.522	.536
CL1	.511	.890	.520	.495	.604	.488	.568	.790	.717	.657
CL2	.472	.923	.482	.459	.625	.488	.525	.798	.728	.650
CL3	.420	.932	.441	.400	.654	.556	.507	.779	.717	.649
CL4	.426	.952	.463	.416	.656	.578	.570	.778	.706	.668
CL5	.410	.961	.430	.427	.676	.562	.561	.796	.713	.664
CL6	.392	.953	.450	.409	.651	.575	.564	.791	.699	.651
PCK1	.717	.480	.843	.802	.423	.461	.541	.511	.567	.602
PCK2	.747	.470	.869	.771	.407	.540	.548	.495	.563	.583
PCK3	.686	.357	.907	.715	.293	.375	.422	.396	.430	.483
PCK4	.660	.373	.868	.692	.302	.471	.563	.398	.436	.536
PCK5	.744	.488	.902	.699	.385	.552	.563	.434	.470	.544
PCK6	.673	.400	.814	.611	.355	.446	.409	.346	.390	.427
PK1	.664	.419	.676	.864	.414	.385	.423	.377	.425	.435
PK2	.678	.454	.784	.934	.367	.401	.509	.436	.464	.566
PK3	.593	.453	.726	.889	.424	.434	.505	.481	.492	.500
PK4	.708	.339	.775	.890	.406	.464	.525	.407	.442	.478
SL1	.448	.636	.368	.426	.923	.565	.643	.711	.652	.620
SL2	.452	.607	.404	.411	.854	.639	.670	.634	.594	.658
SL3	.448	.659	.381	.400	.953	.655	.636	.747	.678	.620
SL4	.496	.630	.405	.429	.950	.616	.612	.745	.665	.633
SL5	.405	.641	.376	.403	.922	.592	.563	.723	.677	.610
TCK1	.358	.433	.450	.322	.536	.898	.570	.433	.616	.435
TCK2	.470	.441	.453	.431	.549	.896	.649	.516	.682	.481
TCK3	.535	.599	.588	.554	.696	.773	.711	.618	.669	.672
TCK4	.462	.528	.489	.372	.559	.941	.677	.543	.708	.504
TCK5	.428	.560	.461	.406	.613	.948	.675	.561	.759	.555
TK1	.608	.689	.569	.569	.757	.737	.858	.736	.730	.694
TK2	.585	.558	.511	.467	.635	.674	.845	.627	.677	.568
TK3	.380	.340	.378	.315	.370	.506	.805	.357	.418	.444
TK4	.490	.367	.440	.437	.509	.495	.789	.486	.466	.487
TK5	.510	.376	.498	.436	.431	.583	.835	.414	.418	.482
TL1	.460	.657	.444	.345	.563	.417	.524	.842	.685	.491
TL2	.498	.724	.496	.424	.694	.551	.606	.918	.775	.584
TL3	.519	.828	.456	.469	.753	.589	.596	.950	.791	.585
TL4	.521	.819	.481	.476	.775	.609	.639	.950	.829	.625
TL5	.484	.837	.427	.465	.759	.590	.645	.933	.789	.593
TPACK1	.582	.763	.561	.523	.733	.633	.673	.853	.886	.676
TPACK2	.536	.706	.553	.517	.628	.586	.563	.792	.870	.612
TPACK3	.482	.661	.560	.472	.644	.560	.583	.739	.843	.614
TPACK4	.403	.616	.412	.387	.551	.775	.576	.669	.903	.499
TPACK5	.444	.648	.421	.401	.593	.790	.611	.710	.894	.541
TPACK6	.420	.606	.397	.366	.571	.748	.548	.656	.871	.497
TPK1	.552	.682	.570	.496	.619	.596	.662	.565	.598	.917
TPK2	.522	.590	.638	.535	.512	.488	.511	.482	.502	.881
TPK3	.542	.667	.548	.524	.715	.629	.673	.666	.701	.921
TPK4	.549	.644	.526	.476	.623	.522	.615	.577	.613	.928
TPK5	.414	.522	.459	.441	.531	.387	.441	.478	.472	.799

Table 4 presents the Heterotrait-Monotrait ratios, another measure of discriminant validity. HTMT values below .85 indicate that constructs are empirically distinct. All HTMT values in Table 4 are below the .85 threshold, confirming that the constructs do not overlap significantly and that discriminant validity is established.

Table 4
HTMT Ratios for Discriminant Validity Assessment

	CK	*CL*	*PCK*	*PK*	*SL*	*TCK*	*TK*	*TL*	*TPACK*	*TPK*
CK										
CL	.494									
PCK	.874	.518								
PK	.803	.493	.889							
SL	.521	.716	.441	.482						
TCK	.541	.603	.583	.506	.703					
TK	.684	.607	.632	.595	.712	.792				
TL	.575	.874	.525	.507	.807	.631	.687			
TPACK	.582	.794	.581	.545	.745	.825	.714	.884		
TPK	.621	.733	.654	.598	.716	.627	.701	.657	.688	

4.4. Structural Model Assessment

4.4.1. Collinearity issue

Collinearity was assessed using the Variance Inflation Factor [VIF] values. All VIF values were below the threshold of 5.0 (Hair et al., 2017), indicating no significant multicollinearity issues among the constructs. For example, CK had VIF values of 2.200 and 1.671, while PK had VIF values of 2.200 and 1.433. These results confirm that the predictor variables are not highly correlated, ensuring the stability of the structural model

4.4.2. Structural model relationship

Table 5 reports the final results of the structural model, including path coefficients, means, standard deviations, *t*-statistics, *p*-values, and significance for each hypothesized relationship. The structural model was evaluated by analyzing the path coefficients (β), *t*-statistics, and *p*-values (see Table 5). The results indicate several key relationships. Content Knowledge significantly predicts Pedagogical Content Knowledge ($\beta = 0.444$, $p < .001$), suggesting that a strong understanding of content enhances teachers' ability to integrate pedagogy with content. Similarly, Pedagogical Knowledge is a significant predictor of PCK ($\beta = 0.502$, $p < .001$), highlighting the importance of pedagogical expertise in developing PCK. PK also significantly predicts Technological Pedagogical Knowledge ($\beta = 0.275$, $p = .005$), indicating that pedagogical skills contribute to the integration of technology into teaching practices. Technological Knowledge strongly predicts Technological Content Knowledge ($\beta = 0.697$, $p < .001$), emphasizing the role of technological expertise in connecting technology with content, and also significantly predicts TPK ($\beta = 0.510$, $p < .001$), showing that technological skills are essential for integrating technology into pedagogy. Furthermore, TCK significantly predicts Technological Pedagogical Content Knowledge ($\beta = 0.571$, $p < .001$), indicating that the ability to connect technology and content is critical for developing comprehensive TPACK, while TPK also significantly predicts TPACK ($\beta = 0.268$, $p = .032$), further supporting the importance of integrating technology and pedagogy. Finally, TPACK strongly predicts classroom practices at multiple levels, including the classroom level ($\beta = 0.763$, $p < .001$), subject level ($\beta = 0.710$, $p < .001$), and task level ($\beta = 0.843$, $p < .001$), demonstrating its critical role in shaping overall teaching strategies, subject-specific instruction, and the design and implementation of specific teaching tasks.

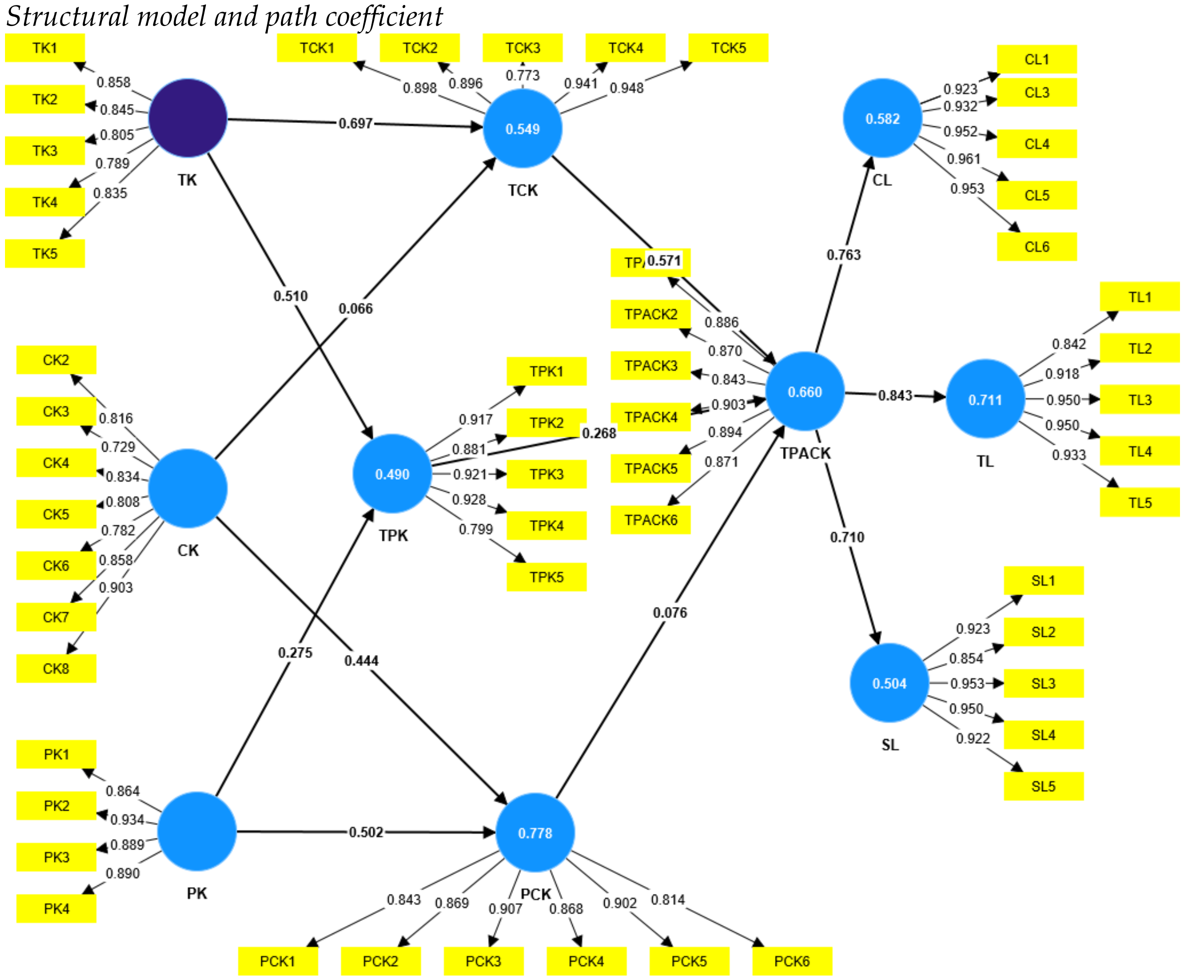
However, the results also reveal some non-significant relationships. Content Knowledge does not significantly predict Technological Content Knowledge ($\beta = 0.066$, $p = .571$), suggesting that content knowledge alone is insufficient to establish meaningful connections between technology and content. Additionally, Pedagogical Content Knowledge does not significantly predict Technological Pedagogical Content Knowledge (β = 0.076, *p* = .323), indicating that the integration of pedagogy and content by itself does not directly lead to the development of comprehensive TPACK.

Table 5
Final results

	β	*Mean*	*SD*	*T-Statistics*	*p-values*	*Significance*
CK → PCK	0.444	0.445	0.088	5.022	<.001	Supported
CK → TCK	0.066	0.074	0.117	0.566	.571	Not supported
PCK → TPACK	0.076	0.069	0.077	0.988	.323	Not supported
PK → PCK	0.502	0.502	0.087	5.743	<.001	Supported
PK → TPK	0.275	0.281	0.097	2.838	.005	Supported
TCK → TPACK	0.571	0.537	0.124	4.593	<.001	Supported
TK → TCK	0.697	0.695	0.073	9.518	<.001	Supported
TK → TPK	0.510	0.511	0.089	5.737	<.001	Supported
TPACK → CL	0.763	0.765	0.065	11.796	<.001	Supported
TPACK → SL	0.710	0.715	0.075	9.469	<.001	Supported
TPACK → TL	0.843	0.845	0.049	17.343	<.001	Supported
TPK → TPACK	0.268	0.307	0.125	2.148	.032	Supported

The results in Table 6 and Figure 2 indicate that several hypothesized relationships are statistically significant, such as TK → TCK and TPACK → TL, while others, like CK → TCK, are not supported. These findings highlight the critical pathways influencing teachers' integration of MAS in constructivist pedagogy.

Figure 2
Structural model and path coefficient



4.4.3. Coefficient of determination (R^2)

Table 6 presents the R-square values for each dependent variable in the model, indicating the proportion of variance explained by the predictors.

Table 6
R-square Results for the Structural Model

	R-square	*Interpretation*
CL	.582	Substantial
PCK	.778	Very Strong
SL	.504	Moderate
TCK	.549	Moderate
TL	.711	Strong
TPACK	.660	Substantial
TPK	.490	Moderate

The R^2 values indicate the proportion of variance explained by the predictor variables for each dependent variable (Table 8). The key findings demonstrate substantial explanatory and predictive power among the studied constructs. Specifically, 66% of the variance in Technological Pedagogical Content Knowledge is explained by its predictors, such as Technological Content Knowledge and Technological Pedagogical Knowledge, indicating a strong model fit (R^2 = .660). For Pedagogical Content Knowledge, 77.8% of the variance is accounted for by Content Knowledge and Pedagogical Knowledge, reflecting very strong predictive power (R^2 = .778). In the case of TCK, 54.9% of its variance is explained by CK and Technological Knowledge, which suggests moderate explanatory power (R^2 = .549). Similarly, 49% of the variance in TPK is explained by PK and TK, also indicating moderate predictive power (R^2 = .490). Regarding classroom practices, TPACK explains 58.2% of the variance at the classroom level, 50.4% at the subject level, and 71.1% at the task level, with the strongest predictive power observed for task-level practices. The R-square values in demonstrate substantial explanatory power for key constructs, with the highest variance explained for PCK (.778) and strong values for TPACK (.660) and TL (.711), supporting the robustness of the model.

4.4.4. Effect size (f^2)

Table 7 shows the effect size (f^2) results, which indicate the contribution of each predictor to the variance explained in the dependent variables.

Table 7
Result of structural model

	CK	*CL*	*PCK*	*PK*	*SL*	*TCK*	*TK*	*TL*	*TPACK*	*TPK*
CK			0.403			0.006				
CL										
PCK									0.010	
PK			0.515							0.103
SL										
TCK									0.567	
TK						0.646				0.356
TL										
TPACK		1.392			1.018			2.463		
TPK									0.111	

The effect size (f^2) indicates the contribution of each predictor variable to the R^2 of the dependent variable. The findings reveal that Technological Knowledge has a large effect on Technological Content Knowledge, with an f^2 value of 0.646, underscoring the critical role of technological expertise in linking technology with content. Technological Pedagogical Content

Knowledge demonstrates a very large effect on task-level practices, with an f^2 of 2.463, highlighting its significant importance in the design and implementation of specific teaching tasks. Additionally, TPACK shows large effects on both classroom-level and subject-level practices, with f^2 values of 1.392 and 1.018 respectively, further confirming its central role in promoting effective teaching across different instructional levels.

The structural model confirms the critical role of TPACK in predicting classroom practices at the classroom, subject, and task levels, with the strongest effect observed at the task level. TK and PK are key predictors of TCK and TPK, respectively, while TCK and TPK significantly contribute to TPACK. However, CK alone does not significantly predict TCK, and PCK does not directly influence TPACK, suggesting that integrating technology is a more complex process requiring multiple knowledge domains. The model demonstrates strong explanatory power (R^2) and predictive relevance (Q^2), providing valuable insights into the relationships between TPACK constructs and teaching practices.

5. Discussion

This study examined how teachers' integrated knowledge of technology, pedagogy, and content influences their use of Mathematics Analysis Software within a constructivist framework. Consistent with foundational research (Chai et al., 2013; Mishra & Koehler, 2006), the findings show that teachers with well-developed TPACK are able to embed MAS into instruction in ways that promote student investigation, conjecture, and collaborative construction of mathematical understanding—key aspects of constructivist pedagogy (Jonassen, 1999; Vygotsky, 1978).

Recent systematic reviews confirm the centrality of the TPACK framework for understanding and improving technology integration in mathematics education. For instance, current research emphasizes the importance of professional development programs that help teachers integrate digital tools effectively, with a focus on contextually relevant training and assessment (Li et al., 2024). This aligns with the present findings, which indicate that teachers' technological knowledge is crucial for selecting and utilizing MAS features, while content knowledge (CK) and pedagogical knowledge guide the design of meaningful, student-centered tasks (Li et al., 2024; Voogt et al., 2013).

The interplay among TCK, TPK, and PCK is essential for effective technology integration. When teachers connect technological skills with content goals (TCK), apply pedagogical practices through digital tools (TPK), and adapt pedagogy to specific mathematical concepts (PCK), they develop a holistic TPACK that enables them to move beyond static lectures to dynamic, student-centered activities (Pierce & Stacey, 2010; Zengin & Tatar, 2017). The strongest impact of TPACK was observed at the task level, where MAS enables teachers to design open-ended activities that allow students to manipulate variables, test conjectures, and receive immediate feedback. Such practices deepen conceptual understanding and foster mathematical discourse and collaboration, as highlighted in recent studies (Li et al., 2024; Zengin & Tatar, 2017).

Contextual factors, including classroom environment, institutional support, and policy, also play a significant role in shaping teachers' ability to integrate technology (Li et al., 2024; Mishra, 2019). In diverse educational settings, access to resources and cultural attitudes toward technology can either facilitate or hinder effective MAS integration. Barriers such as limited access to technology, insufficient training, and lack of institutional support continue to affect the integration of tools like GeoGebra, especially in resource-constrained contexts (Tulu et al., 2024). Studies on innovative visualization tools for spatial reasoning further emphasize the need for ongoing professional development and support networks to help teachers adapt to new technologies (Kurnaz & Yildiz, 2023).

The literature further indicates that DMS should not be viewed as a simple replacement for traditional tools, but as a catalyst for transforming classroom practices toward more student-centered, inquiry-based, and collaborative learning environments (Engelbrecht & Borba, 2024). DMS can support the visualization and manipulation of mathematical concepts, leading to deeper conceptual understanding (Engelbrecht & Borba, 2024; Weinhandl et al., 2020). However, content knowledge alone is not sufficient for effective technology integration; it must be combined with technological and pedagogical skills. This highlights the need for comprehensive professional development that addresses all domains of teacher knowledge.

These findings suggest that professional development should not be limited to isolated technology workshops or generic pedagogy seminars. Instead, teacher education programs should offer integrated experiences that combine technology, pedagogy, and content. Guided practice with MAS, collaborative lesson design, and reflective discussions can help teachers develop authentic TPACK (Li et al., 2024). Collaborative learning communities and mentorship can further reinforce these skills, supporting teachers as they co-design and refine MAS-based lessons (Koehler et al., 2013; Lawless & Pellegrino, 2007).

6. Conclusion and Future Work

This study demonstrates that teachers' integrated TPACK is a key factor in enabling the effective use of Dynamic Mathematics Software to support constructivist mathematics teaching. The results show that TPACK has the greatest impact at the task level, where technology can most directly enhance student engagement, inquiry, and conceptual understanding.

There are several limitations to this study. The cross-sectional design does not allow for causal conclusions, and the focus on pre-service mathematics teachers may limit the generalizability of the findings to in-service teachers or other subject areas. The reliance on self-reported data may also introduce bias.

Future research should consider longitudinal designs to examine how teachers' TPACK develops over time and its long-term impact on teaching practices. Expanding research to include in-service teachers and other subject areas would provide a more comprehensive understanding of TPACK's role in technology integration. Studies that include classroom observations could offer deeper insights into how teachers apply TPACK in real-world settings. Additionally, research on the effectiveness of different professional development models in enhancing TPACK and supporting DMS integration would be valuable.

In summary, this study contributes to the growing literature on TPACK and technology integration in education. The findings offer guidance for improving teacher education and professional development programs and highlight the importance of supporting teachers in leveraging TPACK to create technology-rich, constructivist learning environments that enhance student learning outcomes.

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Data availability: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of interest: The authors declared that there were no potential conflicts of interest.

Ethical statement: Ethical approval was not required for this study in accordance with Syiah Kuala University's guidelines, as participation involved adults (teachers) only and the study posed minimal risk. Informed consent was obtained from all participants.

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