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Understanding the Development of Mathematics Pre-service Teachers' TPACK: A Professional Learning Pathway Perspective

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Abstract: *The integration of digital technologies into mathematics education has created new demands for teachers' professional knowledge. Although Technological Pedagogical Content Knowledge (TPACK) has been widely recognized as an essential framework for understanding technology integration, limited attention has been given to the developmental mechanisms through which mathematics pre-service teachers construct TPACK. This study proposes a professional learning pathway model to explain TPACK development by examining the relationships among digital literacy, technology self-efficacy, teaching reflection, and TPACK. Data were collected from 386 mathematics pre-service teachers, and structural equation modeling was employed to test the proposed model. The results indicate that digital literacy contributes to TPACK both directly and indirectly. Specifically, technology self-efficacy and teaching reflection sequentially mediate the relationship between digital literacy and TPACK, while technology self-efficacy also independently mediates this relationship. Among the predictors, teaching reflection exerts the strongest direct effect on TPACK, highlighting its critical role in transforming technology-related experiences into integrated professional knowledge. These findings suggest that TPACK development is not simply a consequence of technological capability but a progressive professional learning process in which digital literacy strengthens technological confidence and teaching reflection facilitates the development of integrated professional knowledge. This study contributes to TPACK research by shifting attention from identifying factors associated with TPACK toward explaining how TPACK develops through a professional learning pathway. The findings also provide practical implications for mathematics teacher education by emphasizing integrated professional learning experiences rather than isolated technology skills training.*

Keywords: *TPACK; Mathematics Pre-service Teachers; Digital Literacy; Technology Self-efficacy; Teaching Reflection; Professional Learning Pathway*

1. Introduction

1.1 Digital Transformation, TPACK, and Mathematics Teacher Education

The rapid advancement of digital technologies has fundamentally transformed education, creating new opportunities for teaching and learning. In mathematics education, technologies such as dynamic geometry software, computer algebra systems, and online learning platforms have enriched mathematical representation, visualization, and problem solving, enabling students to explore abstract concepts through dynamic manipulation and interactive inquiry.

However, the educational value of these technologies ultimately depends on teachers' ability to integrate them meaningfully into instructional practice. Technology does not automatically improve learning outcomes; its effectiveness relies on teachers' capacity to align technological resources with pedagogical practices and mathematical content[1][2]. Consequently, preparing future mathematics teachers to integrate technology effectively has become a central objective of teacher education worldwide.

Although teacher education programs have increasingly incorporated digital technologies, many beginning teachers continue to experience difficulties translating technological knowledge into effective classroom practice. Despite familiarity with digital tools, they often lack the professional competence required to integrate technology effectively with instructional design and mathematics-specific pedagogy[3]. These challenges suggest that developing technology integration competence involves more than acquiring technological skills and requires sustained professional learning.

Among the theoretical frameworks proposed to explain teachers' technology integration competence, the Technological Pedagogical Content Knowledge (TPACK) framework has become one of the most influential[1]. Building on Shulman's concept of Pedagogical Content Knowledge (PCK)[4], TPACK posits that effective technology integration requires teachers to coordinate technological knowledge, pedagogical knowledge, and content knowledge rather than relying on any single knowledge domain. Within mathematics education, TPACK has provided an important conceptual lens for understanding technology integration, generating substantial research on measurement, influencing factors, and professional development.

Despite these contributions, existing research has largely emphasized identifying variables associated with TPACK—such as technology experience, digital competence, or professional development opportunities—while comparatively less attention has been devoted to explaining the developmental process through which pre-service teachers gradually develop TPACK. As a result, TPACK has frequently been treated as a measurable outcome rather than as an evolving form of professional knowledge. This limitation is particularly important in mathematics teacher education because learning to integrate technology is not a single event but a continuous process of professional growth. Understanding how TPACK develops is therefore likely to provide more meaningful guidance for mathematics teacher education than merely identifying factors associated with higher levels of TPACK.

1.2 Research Gap: Understanding How TPACK Develops

Although previous studies have generated substantial knowledge regarding teachers' TPACK, several important research gaps remain. First, existing research has predominantly adopted a predictor-oriented perspective, providing limited explanation of how TPACK develops over time and leaving the developmental mechanisms underlying TPACK construction insufficiently understood. Second, relatively few studies have investigated TPACK development from a professional learning perspective; technology integration competence should be viewed as an evolving form of professional learning rather than merely the result of technological training. Third, although digital literacy, technology self-efficacy, and teaching reflection have been recognized as important contributors to teacher professional learning, these three constructs have often been investigated independently, with limited research explaining how they interact within a unified theoretical framework.

To address these gaps, the present study proposes and empirically tests a professional learning pathway model that integrates TPACK theory, Social Cognitive Theory, and Reflective Practice Theory to explain how mathematics pre-service teachers progressively develop technology integration competence. Specifically, digital literacy is proposed as the foundational capability that strengthens technology self-efficacy, which in turn facilitates teaching reflection and ultimately contributes to TPACK development. In addition to this sequential pathway, digital literacy, technology self-efficacy, and teaching reflection are also expected to exert direct effects on TPACK. Thus, the proposed model conceptualizes TPACK development as a dynamic professional learning process rather than a static outcome.

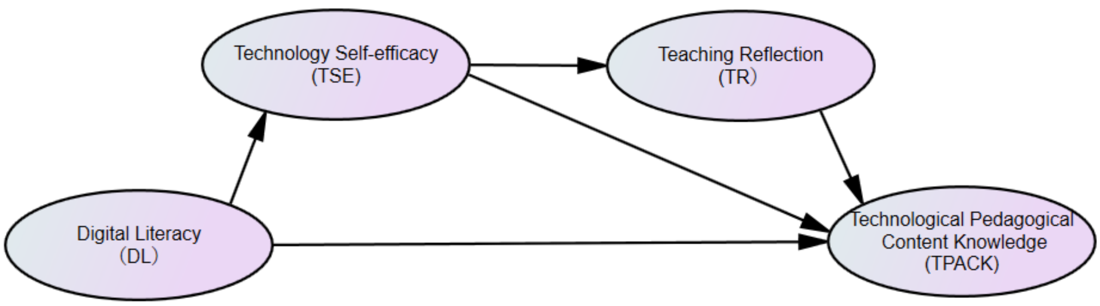

Figure 1: Proposed Professional Learning Pathway Model

Accordingly, this study addresses the following research questions:

RQ1: How does digital literacy (DL) contribute to the development of mathematics pre-service teachers' TPACK?

RQ2: To what extent do technology self-efficacy (TSE) and teaching reflection (TR) sequentially

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mediate the relationship between digital literacy (DL) and TPACK, and does technology self-efficacy also independently mediate this relationship?

To answer these questions, this study develops and empirically tests a theoretical model explaining TPACK development among mathematics pre-service teachers. By shifting attention from identifying factors associated with TPACK to explaining its developmental mechanisms through a professional learning pathway, this study contributes to the literature on TPACK and provides practical implications for the design of mathematics teacher education programs.

2. Literature Review and Theoretical Framework

2.1 TPACK as a Dynamic Professional Knowledge Framework

Since its introduction by Mishra and Koehler[1], the Technological Pedagogical Content Knowledge (TPACK) framework has become one of the most influential theoretical perspectives for understanding teachers' technology integration competence. Building on Shulman's [4] concept of Pedagogical Content Knowledge (PCK), TPACK posits that effective technology integration requires the coordination of technological, pedagogical, and content knowledge. Within mathematics education, this framework is particularly significant because digital technologies influence mathematical representation, conceptual visualization, and problem-solving processes[5].

However, existing research has predominantly treated TPACK as a static knowledge structure to be measured or described, providing limited explanation of how it is progressively developed through professional learning[6]. The present study adopts a developmental perspective, conceptualizing TPACK as an evolving form of professional knowledge that emerges through continuous professional learning and reflective practice rather than as a fixed body of knowledge.

2.2 Digital Literacy as the Foundation of Professional Learning

Digital literacy is conceptualized as a multidimensional competence involving the ability to access, evaluate, create, and apply digital information within educational contexts[7][8]. For mathematics pre-service teachers, it extends beyond technical operation to include understanding the educational affordances of mathematical technologies and selecting appropriate digital resources to support mathematical reasoning.

Nevertheless, possessing technological knowledge does not ensure effective classroom integration. Previous studies have shown that many teachers with adequate technical skills struggle to design technology-supported learning activities or adapt digital tools to pedagogical objectives[3][9]. These findings suggest that digital literacy serves as the foundation upon which more sophisticated professional knowledge is constructed, providing the foundation for subsequent professional learning rather than representing the endpoint of technology integration competence.

2.3 Technology Self-efficacy as the Psychological Mechanism of Professional Learning

According to Social Cognitive Theory, self-efficacy—individuals' confidence in their ability to perform specific tasks—plays a central role in shaping motivation, persistence, and performance[10]. Within technology-enhanced education, technology self-efficacy refers to teachers' confidence in employing digital technologies for instructional purposes. Teachers with stronger self-efficacy are more likely to experiment with new approaches, overcome technological difficulties, and adopt innovative practices[11][12].

From a professional learning perspective, technology self-efficacy functions as the motivational mechanism connecting technological capability with instructional action. Digital literacy provides opportunities to acquire technological competence, whereas self-efficacy determines whether these capabilities are translated into active experimentation, sustained technology use, and ultimately effective instructional practice.

2.4 Teaching Reflection as the Mechanism of Professional Knowledge Construction

Reflection has long been regarded as a defining characteristic of teacher professional learning. Dewey[13] described reflection as the deliberate examination of experience, while Schön[14] emphasized

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it as a process through which professionals reconstruct knowledge through practice. Rather than passively accumulating experience, teachers develop expertise by critically evaluating instructional decisions and continuously refining future practice.

For mathematics teachers, reflection is particularly important because digital technologies influence students' mathematical representations, conceptual understanding, and problem-solving strategies. Technology-supported experiences become meaningful professional knowledge only when teachers critically interpret their instructional effectiveness. Despite its importance, the role of reflection in TPACK development has received comparatively limited attention. This study conceptualizes teaching reflection as the mechanism through which technology-supported experiences are analyzed, interpreted, and integrated into the development of TPACK. Consequently, teaching reflection serves as the critical mechanism through which technology-supported experiences are transformed into integrated professional knowledge.

2.5 A Professional Learning Pathway Perspective of TPACK Development

No single theoretical perspective fully explains how TPACK develops. TPACK theory identifies the knowledge required but offers limited explanation of developmental processes. Social Cognitive Theory explains how beliefs influence behavior but does not specify how technological knowledge becomes integrated professional competence. Reflective practice theory emphasizes learning through experience but pays comparatively less attention to technology integration.

To address these limitations, the present study integrates the three perspectives into a professional learning pathway model. Within this framework, digital literacy provides the technological foundation for professional learning; successful technology-related experiences strengthen technology self-efficacy; and continuous teaching reflection integrates technological experiences with pedagogical reasoning and mathematical content knowledge. Together, these three stages conceptualize TPACK development as a dynamic professional learning process through which mathematics pre-service teachers progressively develop technology integration competence.

3. Research Model and Hypothesis Development

3.1 Proposed Research Model

Based on the professional learning pathway perspective developed in the preceding section, this study proposes a sequential mediation model (Figure 1) in which digital literacy (DL) contributes to TPACK both directly and indirectly through technology self-efficacy (TSE) and teaching reflection (TR). The theoretical rationale and hypothesized relationships are presented below.

3.2 Hypothesis Development

3.2.1 Digital Literacy and TPACK

Digital literacy provides the technological foundation for integrating technology with pedagogy and disciplinary knowledge[7][8]. Teachers with higher digital literacy are more capable of recognizing instructional affordances, selecting appropriate resources, and adapting tools to support mathematics teaching. Empirical evidence consistently demonstrates a positive association between digital competence and TPACK[15]. Within the proposed pathway, digital literacy represents the initial capability enabling participation in technology-supported professional learning.

H1: Digital literacy (DL) positively predicts mathematics pre-service teachers’ TPACK.

3.2.2 Digital Literacy and Technology Self-efficacy

According to Social Cognitive Theory, self-efficacy develops primarily through successful performance experiences[10]. Digital literacy provides the knowledge and skills necessary for successful interaction with educational technologies; as pre-service teachers become more proficient, they experience greater success in technology-related activities, reinforcing confidence in their ability to use technology effectively[11]. Technology self-efficacy thus functions as the motivational mechanism transforming competence into confidence.

H2: Digital literacy (DL) positively predicts technology self-efficacy (TSE).

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3.2.3 Technology Self-efficacy, Teaching Reflection, and TPACK

Individuals with stronger self-efficacy are more likely to persist when facing challenges, adopt innovative practices, and devote greater effort to complex tasks[10]. Confident teachers are more willing to engage with unfamiliar technologies and experiment with innovative approaches, generating richer experiences for reflection[13][14]. They are also more likely to critically evaluate their practices rather than avoid technology-related challenges. Through repeated cycles of action and reflection, teachers progressively refine their understanding of how digital technologies support mathematics teaching.

Furthermore, technology self-efficacy contributes directly to TPACK. Teachers with higher confidence are more willing to explore digital technologies, design technology-supported activities, and integrate resources into instruction[11][15]. As pre-service teachers gain confidence, they are more likely to integrate technological knowledge with pedagogical strategies and mathematical content.

H3: Technology self-efficacy (TSE) positively predicts teaching reflection (TR).

H4: Technology self-efficacy (TSE) positively predicts mathematics pre-service teachers' TPACK.

3.2.4 Teaching Reflection and TPACK

Reflection enables teachers to transform teaching experiences into professional knowledge[13][14]. In technology-enhanced mathematics education, teachers must continuously evaluate whether technological tools effectively support students' conceptual understanding and mathematical reasoning. Through reflective engagement, pre-service teachers gradually integrate technological experiences with pedagogical decision-making and mathematical understanding, reorganizing fragmented experiences into coherent professional knowledge[16][17].

H5: Teaching reflection (TR) positively predicts mathematics pre-service teachers' TPACK.

3.2.5 The Sequential Mediating Roles

The professional learning pathway suggests that TPACK develops through successive stages: digital literacy provides technological competence; mastery experiences strengthen technology self-efficacy; and increased confidence encourages reflective engagement, through which technological experiences are integrated with pedagogical and disciplinary knowledge. This sequential process reflects the combined explanatory power of the three theoretical perspectives. Compared with examining variables independently, the sequential mediation model provides a more comprehensive explanation of how technology integration competence develops during initial teacher education.

H6a: Technology self-efficacy (TSE) mediates the relationship between digital literacy (DL) and mathematics pre-service teachers' TPACK.

H6b: Technology self-efficacy (TSE) and teaching reflection (TR) sequentially mediate the relationship between digital literacy (DL) and mathematics pre-service teachers' TPACK.

4. Research Methodology

4.1 Research Design

This study adopted a quantitative research design to examine the sequential professional learning pathway underlying the development of mathematics pre-service teachers' TPACK. Based on the theoretical model proposed in Chapter 3, structural equation modeling (SEM) was employed to investigate the relationships among DL, TSE, TR, and TPACK. DL was specified as the exogenous variable, TSE and TR as mediating variables, and TPACK as the endogenous variable. Academic year and gender were examined as demographic variables in the preliminary analyses to determine whether they were associated with TPACK.

4.2 Participants

Participants were mathematics pre-service teachers from all four academic years at three normal universities in China. A convenience sampling strategy was employed to capture variations in professional learning experiences across different stages of initial teacher education. Of the 420 questionnaires distributed, 386 valid responses were retained (response rate: 91.9%). The sample comprised 118 males (30.6%) and 268 females (69.4%), distributed as follows: 99 freshmen (25.6%), 106 sophomores (27.5%), 96 juniors (24.9%), and 85 seniors (22.0%). Most participants had completed

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at least one course related to educational technology or digital learning.

4.3 Measures

All constructs included in the proposed model were measured using previously validated instruments that have been widely applied in educational technology research. To ensure the suitability of the instruments for mathematics teacher education, minor wording modifications were made to reflect the context of technology-supported mathematics teaching while preserving the original conceptual meanings of the scales. All questionnaire items were rated on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating stronger agreement with each statement. Table 1 summarizes the instruments.

Table 1: Summary of Measurement Instruments.

Construct	Items	Source	Sample Item
Digital Literacy	6	Adapted from Ng [7] and Falloon[8]	"I can effectively use digital technologies to support mathematics learning"
Technology Self-efficacy	5	Adapted from Wang et al.[18] and Abbitt [11]	"I am confident that I can effectively integrate digital technologies into mathematics teaching"
Teaching Reflection	5	Adapted from Kember et al. [19] and Larrivee [20]	"I regularly reflect on whether digital technologies improve students' mathematical understanding"
TPACK	7	Adapted from Schmidt et al.[21] and Chai et al.[15]	"I can effectively integrate technology, pedagogy, and mathematical content during instruction"

4.4 Data Collection Procedure

Data were collected during the spring semester of 2025. Questionnaires were administered both online and in paper format during teacher education courses under researcher supervision. All responses were screened for missing data and response quality; cases with substantial missing data or obvious response patterns were excluded.

5. Results

5.1 Preliminary Analysis

Preliminary analyses were conducted to examine whether TPACK differed across demographic characteristics. A one-way analysis of variance (ANOVA) was performed using academic year as the grouping variable, followed by an independent-samples t-test to examine gender differences.

As shown in Table 2, mean TPACK scores were relatively stable across the four academic years, ranging from 3.76 to 3.81. The ANOVA indicated no statistically significant differences among the four groups, $F(3, 382) = 0.16$, $p = .924$. Likewise, the independent-samples t-test revealed no significant gender difference in TPACK, $t(384) = 0.54$, $p = .591$. Therefore, academic year and gender were not included as control variables in the subsequent structural analyses.

Table 2: Differences in TPACK across Academic Years.

Academic Year	N	Mean	SD
Freshman	99	3.76	0.64
Sophomore	106	3.77	0.60
Junior	96	3.80	0.55
Senior	85	3.81	0.59

5.2 Descriptive Statistics and Correlations

Descriptive statistics and Pearson correlation coefficients for all study variables are presented in Table 3.

Overall, participants reported relatively high levels across all four constructs, with mean scores

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ranging from 3.74 to 3.87 on the five-point Likert scale. Pearson correlation analysis showed that all variables were positively and significantly correlated ($p < .001$), suggesting sufficient associations among the constructs to justify subsequent structural equation modeling.

Table 3: Descriptive Statistics and Correlations.

Variable	Mean	SD	1	2	3	4
1. Digital Literacy (DL)	3.87	0.56	1			
2. Technology Self-efficacy (TSE)	3.74	0.62	.51***	1		
3. Teaching Reflection (TR)	3.81	0.54	.42***	.54***	1	
4. TPACK	3.78	0.60	.51***	.64***	.65***	1

5.3 Measurement Model Assessment

Before testing the structural relationships, confirmatory factor analysis (CFA) was conducted to assess the reliability and validity of the measurement model.

As reported in Tables 4 and 5, all constructs demonstrated satisfactory psychometric properties. Cronbach's alpha coefficients ranged from .88 to .94, composite reliability (CR) values ranged from .89 to .94, and average variance extracted (AVE) values ranged from .61 to .72, all exceeding the recommended thresholds. Standardized factor loadings ranged from .73 to .89 and were all statistically significant. In addition, discriminant validity was established because the square roots of the AVEs exceeded the corresponding inter-construct correlations.

The measurement model also demonstrated a good fit to the data, $\chi^2/df = 2.11$, CFI = .964, TLI = .958, IFI = .964, RMSEA = .054, and SRMR = .043, indicating that the measurement model adequately represented the observed data.

Table 4: Reliability and Convergent Validity.

Construct	Items	Cronbach's α	CR	AVE
Digital Literacy (DL)	6	0.91	0.91	0.63
Technology Self-efficacy (TSE)	5	0.92	0.92	0.65
Teaching Reflection (TR)	5	0.88	0.89	0.61
TPACK	7	0.94	0.94	0.72

Table 5: Discriminant Validity

Construct	DL	TSE	TR	TPACK
Digital Literacy (DL)	0.79			
Technology Self-efficacy (TSE)	0.51	0.81		
Teaching Reflection (TR)	0.42	0.54	0.78	
TPACK	0.51	0.64	0.65	0.85

5.4 Structural Model and Hypothesis Testing

Following validation of the measurement model, the hypothesized structural model was estimated using maximum likelihood estimation in AMOS 24.0.

The structural model demonstrated an excellent fit to the data, $\chi^2/df = 1.273$, CFI = .990, TLI = .989, RMSEA = .027, and SRMR = .018. The standardized path coefficients are summarized in Table 6, and the final structural model is presented in Figure 2.

As shown in Table 6, all hypothesized paths were statistically significant in the expected directions, providing support for H1–H5.

Table 6: Structural Model Results.

Hypothesis	Path	β	S.E.	CR	p	Result
H1	DL → TPACK	.17	.06	3.48	<.001	Supported
H2	DL → TSE	.57	.07	10.11	<.001	Supported
H3	TSE → TR	.60	.05	10.96	<.001	Supported
H4	TSE → TPACK	.34	.06	5.77	<.001	Supported
H5	TR → TPACK	.44	.06	8.17	<.001	Supported

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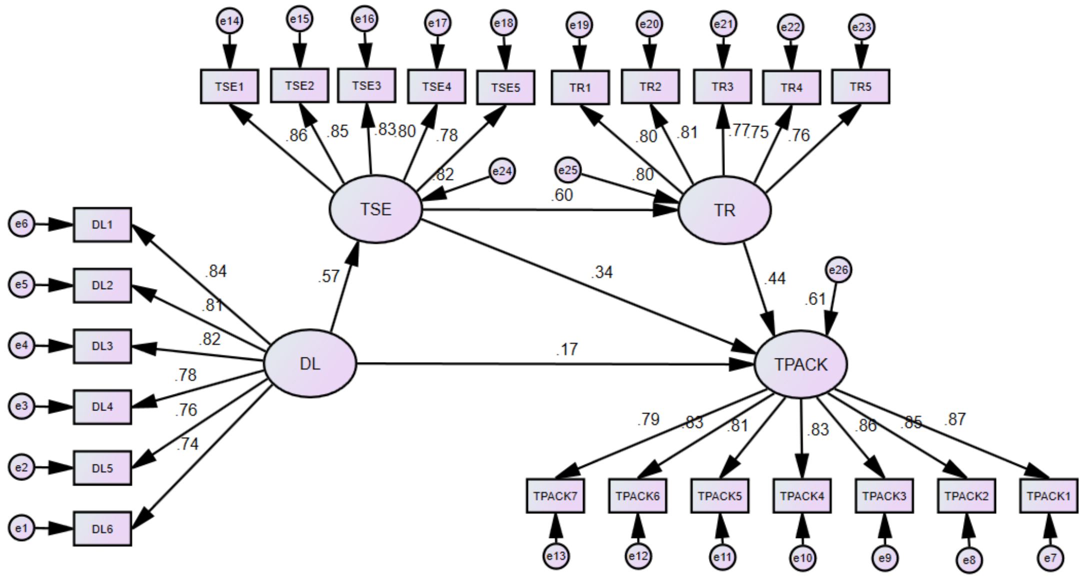

Figure 2 Final Structural Model

5.5 Mediation Analysis

The mediating roles of technology self-efficacy and teaching reflection were examined using bias-corrected bootstrapping with 5,000 resamples. The bootstrap results are presented in Table 7.

Digital literacy exerted both direct and indirect effects on TPACK. Specifically, technology self-efficacy significantly mediated the relationship between digital literacy and TPACK. In addition, the sequential mediation pathway through technology self-efficacy and teaching reflection was also statistically significant. For both indirect effects, the 95% confidence intervals did not include zero, indicating significant mediation. These findings provide support for H6.

Table 7: Bootstrap Test of Mediation Effects.

Hypothesis	Indirect Path	Effect	Boot SE	95% CI	Result
H6a	DL→TSE→TPACK	0.173	0.024	[0.126, 0.220]	Supported
H6b	DL→TSE→TR→TPACK	0.108	0.018	[0.072, 0.144]	Supported

6. Discussion, Implications, and Conclusion

6.1 Discussion of the Major Findings

The primary objective of this study was to explain how mathematics pre-service teachers develop Technological Pedagogical Content Knowledge (TPACK) from a professional learning perspective. Based on the proposed conceptual framework, this study examined the sequential relationships among digital literacy, technology self-efficacy, teaching reflection, and TPACK. The results supported all hypothesized relationships and demonstrated that digital literacy contributes to TPACK both directly and indirectly through technology self-efficacy and teaching reflection. Overall, the findings suggest that TPACK develops through a progressive professional learning pathway in which technological capability, motivational beliefs, and reflective learning jointly facilitate technology integration.

The first major finding is that digital literacy positively predicts TPACK. This result is consistent with previous studies indicating that digital literacy provides the technological foundation necessary for effective technology integration[7][8]. Mathematics pre-service teachers with stronger digital literacy are more capable of selecting appropriate digital tools, evaluating online resources, and applying technology to support mathematics teaching. These competencies facilitate the integration of technological, pedagogical, and content knowledge during instructional planning and implementation.

More importantly, the mediation analysis revealed that digital literacy influenced TPACK not only directly but also indirectly through technology self-efficacy and teaching reflection. These findings indicate that technological competence alone is insufficient to explain TPACK development. Instead,

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digital literacy appears to function as the starting point of a broader professional learning process through which technological capability is gradually transformed into technology integration competence. The significant direct effect further suggests that additional factors beyond those included in the present model—such as teaching experience, instructional design competence, or institutional support—may also contribute to TPACK development and warrant further investigation.

The second major finding concerns the role of technology self-efficacy. Consistent with Social Cognitive Theory[10], digital literacy significantly enhanced pre-service teachers' confidence in integrating technology into instructional practice. Individuals with stronger technological competence are more likely to believe that they can successfully apply digital technologies in teaching, thereby increasing their willingness to adopt innovative instructional approaches. This finding extends previous research by identifying technology self-efficacy as an important motivational mechanism linking technological competence with professional knowledge. Rather than influencing TPACK directly through technological skills alone, digital literacy strengthens teachers' confidence, which subsequently promotes their professional learning.

The findings further demonstrated that technology self-efficacy positively predicted teaching reflection. Pre-service teachers with greater confidence in technology integration reported engaging more frequently in reflective examination of their technology-supported instructional practices. One possible explanation is that confident teachers are more willing to participate in technology-enhanced learning activities and critically evaluate their instructional decisions. Reflection enables them to recognize instructional strengths and weaknesses, refine teaching strategies, and continuously improve technology-supported learning experiences. Therefore, technology self-efficacy appears to facilitate professional learning not only by encouraging technology use but also by promoting reflective thinking.

One particularly important finding is the prominent role of teaching reflection in TPACK development. Among all direct predictors included in the structural model, teaching reflection exerted the strongest influence on TPACK. This result supports Reflective Practice Theory[14] and is consistent with previous research emphasizing reflection as a key mechanism for transforming teaching experience into professional knowledge[15][17]. Reflection enables pre-service teachers to integrate technological knowledge with pedagogical strategies and mathematical content by critically evaluating the effectiveness of technology-supported instruction. Consequently, reflective learning serves as a key mechanism through which technology-related experiences are transformed into integrated professional knowledge.

Furthermore, the significant sequential mediation effect provides empirical support for the professional learning pathway proposed in this study. Digital literacy first strengthens technology self-efficacy, which subsequently promotes teaching reflection and ultimately contributes to TPACK development. Rather than functioning as independent factors, digital literacy, technology self-efficacy, and teaching reflection operate as interconnected dimensions of teacher professional learning. This sequential process offers a more comprehensive explanation of how mathematics pre-service teachers gradually develop technology integration competence.

Finally, the preliminary analysis indicated that neither academic year nor gender significantly influenced participants' TPACK. This finding suggests that progression through teacher education alone may not guarantee improvements in technology integration competence. Instead, the quality of professional learning experiences appears to be more important than the duration of teacher preparation. Therefore, teacher education programs should provide continuous opportunities for pre-service teachers to develop digital literacy, strengthen technology self-efficacy, and engage in reflective practice throughout the entire preparation process.

In summary, the findings support the proposed professional learning pathway and demonstrate that TPACK development is a dynamic process rather than the simple accumulation of technological knowledge. Digital literacy provides the technological foundation, technology self-efficacy strengthens teachers' confidence, and teaching reflection transforms technology-related experiences into integrated professional knowledge. Together, these dimensions explain how mathematics pre-service teachers progressively develop technology integration competence.

6.2 Theoretical Implications

This study contributes to the literature on TPACK and teacher professional development in three main ways.

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First, it extends the TPACK framework by emphasizing the developmental process through which TPACK is constructed. Previous studies have primarily focused on describing the knowledge domains of TPACK or identifying factors associated with teachers' perceived TPACK. In contrast, the present study proposes and validates a sequential professional learning pathway linking digital literacy, technology self-efficacy, teaching reflection, and TPACK. This perspective shifts attention from what constitutes TPACK to how TPACK develops, thereby providing a developmental complement to the traditional TPACK framework.

Second, the study clarifies the psychological mechanism connecting digital literacy and TPACK. Although previous research has consistently reported positive relationships between digital literacy and technology integration competence, the underlying process has remained unclear. The present findings identify technology self-efficacy as an important motivational mechanism through which technological competence is translated into professional knowledge. These findings extend Social Cognitive Theory by demonstrating that efficacy beliefs facilitate not only technology use but also the development of professional knowledge among mathematics pre-service teachers.

Third, the findings highlight the central role of teaching reflection in technology integration. Teaching reflection exerted the strongest direct effect on TPACK, indicating that reflective learning is a critical mechanism through which technological experiences are transformed into integrated instructional knowledge. This finding reinforces the relevance of Reflective Practice Theory in technology-enhanced teacher education and suggests that reflection should be regarded as a core component of TPACK development rather than a supplementary learning activity. Consequently, the present study complements existing TPACK research by highlighting reflection as an essential mechanism underlying technology integration competence.

Taken together, the proposed model integrates technological, psychological, and reflective perspectives into a coherent explanation of TPACK development. By demonstrating how these dimensions interact during teacher preparation, this study contributes to a more comprehensive understanding of technology integration and provides a useful theoretical foundation for future research on teacher professional learning.

6.3 Practical Implications

The findings of this study provide several practical implications for mathematics teacher education and the design of technology-related professional learning.

First, teacher education programs should position digital literacy as the foundation of TPACK development rather than treating it as an isolated technical skill. Although digital literacy directly contributed to TPACK, the findings demonstrated that its influence was also transmitted through technology self-efficacy and teaching reflection. This finding suggests that technology courses should move beyond teaching software operation and instead emphasize the educational use of digital technologies in authentic mathematics teaching contexts. Activities such as digital lesson design, dynamic mathematics software, classroom case analysis, and technology-supported problem solving can help pre-service teachers connect technological knowledge with pedagogy and mathematical content.

Second, teacher educators should deliberately strengthen technology self-efficacy throughout teacher preparation. The findings indicate that confidence in technology integration serves as an important motivational mechanism for TPACK development. Therefore, teacher education should provide sufficient opportunities for successful technology integration experiences through microteaching, lesson planning, teaching simulations, and practicum activities. Constructive feedback from teacher educators and peers can further reinforce positive learning experiences and encourage pre-service teachers to adopt innovative instructional practices with greater confidence.

Third, the strong influence of teaching reflection highlights the importance of reflective learning in technology-enhanced teacher education. Since teaching reflection emerged as the strongest direct predictor of TPACK, reflective activities should be systematically incorporated into teacher preparation. Reflection can be promoted through teaching journals, reflective portfolios, peer observation, lesson study, and video-based lesson analysis. These activities encourage pre-service teachers to critically evaluate technology-supported instruction, identify areas for improvement, and continuously refine their instructional decision-making. In this way, reflection helps transform technology-related experiences into integrated professional knowledge.

Finally, although no significant differences in TPACK were found across academic years, technology integration competence should still be viewed as a developmental outcome requiring continuous support. Rather than concentrating technology instruction in a single course, teacher education programs should adopt a longitudinal approach that progressively develops digital literacy, technology self-efficacy, and reflective practice across subject methods courses, teaching practicum, and other professional learning experiences. Such an integrated curriculum, rather than isolated technology courses, is more likely to promote sustainable TPACK development among future mathematics teachers.

6.4 Conclusion

This study proposed and empirically validated a professional learning pathway explaining the development of TPACK among mathematics pre-service teachers. The findings demonstrated that digital literacy contributes to TPACK both directly and indirectly through technology self-efficacy and teaching reflection. In particular, technology self-efficacy functioned as an important motivational mechanism, whereas teaching reflection emerged as the strongest direct predictor of TPACK, highlighting the central role of reflective learning in technology integration.

The study extends existing TPACK research by shifting attention from the knowledge structure of TPACK to the developmental process through which it is constructed. By integrating the TPACK framework, Social Cognitive Theory, and Reflective Practice Theory, it provides a coherent explanation of how technological capability, motivational beliefs, and reflective learning jointly promote technology integration among mathematics pre-service teachers.

Overall, the findings suggest that effective technology integration requires more than technological skills alone. Teacher education programs should adopt a developmental approach that systematically cultivates digital literacy, technology self-efficacy, and reflective practice throughout teacher preparation, thereby supporting the sustainable development of TPACK and preparing future mathematics teachers for effective technology integration in increasingly digital learning environments.

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