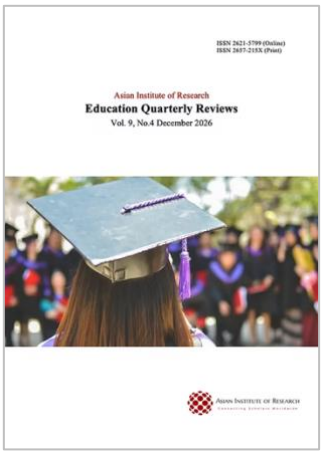


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Developing and Validating a TPACK-based Knowledge Model of Pre-service Teachers for STEM Instruction

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Abstract
STEM instruction in the digital era places complex knowledge demands on science teachers, yet few theoretically grounded STEM-TPACK models have been developed to support pre-service teacher preparation. To address the new requirements of technology-enhanced teaching, this study aimed to develop and validate an instrument assessing pre-service science teachers' knowledge for STEM teaching based on the TPACK framework. Drawing on the original theoretical framework of TPACK, a knowledge model for STEM instruction with eight dimensions was constructed. Survey data from 195 Chinese pre-service science teachers were analyzed using exploratory factor analysis (EFA) to identify the latent factor structure. A separate sample of 208 pre-service science teachers was used for confirmatory factor analysis (CFA) to examine scale reliability and validity. The results supported an eight-factor, a 28-items model with acceptable internal consistency, convergent validity and model fit. This study provides a model for understanding and measuring pre-service teachers' multidimensional knowledge for STEM teaching and identifying their preparation needs, thereby informing targeted teacher education activities.

Keywords: TPACK, STEM Instruction, Pre-Service Teachers, Science Teachers, Measurement Development

1. Introduction

To effectively organize STEM instruction, teachers should connect ideas across disciplines and design activities in which scientific explanations, mathematical reasoning, technology, and engineering design contribute to solving a problem (Nipyrakis et al., 2025), which requires attention to disciplinary connections and to how those connections become teachable activities (Stevenson et al., 2026). Examining the structure of teachers' knowledge for STEM instruction and assessing that knowledge are therefore essential for identifying gaps in teacher preparation, guiding targeted professional learning, and supporting sustained improvements in the quality of STEM education. In China, teachers implementing STEM instruction may face challenges arising from a limited understanding of interdisciplinary STEM concepts and connections, making it difficult to move beyond subject-specific knowledge and design integrated learning activities (Dong et al., 2020).

Technology can address these challenges by making connections across STEM disciplines more visible and supporting learning activities that bring together otherwise isolated subject knowledge. Before digital technologies became widespread in schools, STEM education already treated technological literacy as part of scientific literacy. Today, digital tools offer new ways to visualize scientific phenomena, collect data, and test solutions in STEM instruction (Kruse et al., 2025). Thus, teachers must decide which tool helps students understand a concept and how to use it within a learning activity (Aumann et al., 2023). The technological pedagogical content knowledge (TPACK) framework provides a basis for examining these decisions. It describes how teachers combine knowledge of technology, pedagogy, and subject matter (Mishra & Koehler, 2006).

Although recent studies have examined TPACK-based interventions and technology integration in STEM teacher education (Chai et al., 2020; Mansour et al., 2024), limited attention has been paid to developing and empirically validating a knowledge model that explicitly incorporates interdisciplinary STEM content knowledge and the preparation needs of pre-service science teachers. The pre-service stage is particularly important because the knowledge developed during teacher preparation provides a foundation for teachers' subsequent instructional decisions and their capacity to design and implement integrated STEM learning activities (Dökme & Ünlü, 2024). Therefore, to clarify the knowledge required for integrated STEM instruction, this study aims to develop and validate a TPACK-based knowledge model that explicitly incorporates interdisciplinary STEM content knowledge and pre-service teacher training knowledge. We propose two research questions: (1) What knowledge dimensions constitute a TPACK-based model of pre-service teachers' knowledge for integrated STEM teaching? (2) What are the relationships among the knowledge dimensions in the proposed model?

2. Theoretical framework of this study

This study draws on two complementary theoretical perspectives: TPACK and a situated perspective on teacher learning. TPACK identifies the technological, pedagogical and content knowledge involved in teaching with technology and provides the structure of the proposed knowledge model (Mishra & Koehler, 2006). Korthagen's (2010) perspective emphasizes the relationship between theoretical knowledge and practical teaching experiences in teacher preparation. Drawing on this perspective, the present study extends TPACK to include preparation-related knowledge, focusing on how pre-service teachers connect coursework with lesson planning, learn from classroom observations, and use feedback to improve their teaching designs.

Grounded in the theoretical framework, this study initially formulated eight knowledge categories as first-level dimensions and preliminarily identified 21 knowledge elements. STEM-CK includes both disciplinary concepts and the connections needed to address an interdisciplinary problem. STEM-PK concerns the organization of inquiry, collaboration, problem solving and iterative design, whereas STEM-TK refers to the functions and limitations of digital tools used in STEM activities. The three paired knowledge domains combine content and pedagogy to teach STEM concepts and interdisciplinary connections (STEM-PCK), content and technology to represent and explore these concepts and connections (STEM-TCK), and pedagogy and technology to support inquiry, collaboration, and engineering design (STEM-TPK). STEM-TPACK integrates all three components to design learning activities that connect STEM disciplines in addressing authentic problems. In addition, the pre-service teacher knowledge domain addresses the transitional and contextual demands specific to initial teacher preparation. It comprises knowledge of translating coursework into practice, bridging theory and authentic classroom application; knowledge of teaching and research, emphasizing evidence-based inquiry and sustained professional development; and knowledge of reflective revision, highlighting the continuous refinement of instructional design and implementation through self-reflection. Figure 1 provides operational definitions to guide item development.

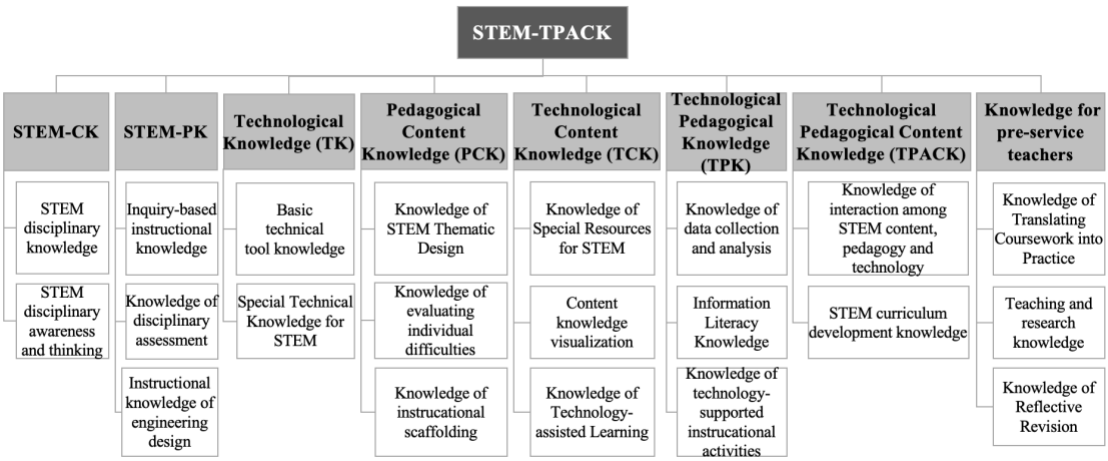


Figure 1: Theoretical framework of STEM-TPACK

3. Research Method

3.1. Instrument Development

This study developed a TPACK-based questionnaire to assess pre-service science teachers' perceived knowledge for integrated STEM teaching. Initial items were constructed according to the proposed knowledge dimensions. Four experts in science education and STEM instruction evaluated the relevance, clarity, and dimensional alignment of the items (Table 1). The scale-level content validity index (S-CVI/Ave) was 0.93, indicating satisfactory content validity (Polit & Beck, 2006). The questionnaire was revised based on their feedback, resulting in 28 items rated on a five-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). Each knowledge element identified in the theoretical framework was operationalized using one or two questionnaire items.

Table 1: Expert characteristics and content validity assessment

Expert	Professional title	Research expertise	S-CVI/Ave
E1	Professor	Science education pre-service teacher education	0.93
E2	Associate professor	STEM education Interdisciplinary curriculum design	0.89
E3	Associate professor	Educational technology	0.96
E4	Senior science teacher	Science instruction School-based STEM practices	0.93

3.2 Population and sampling

Participants were pre-service science teachers from three universities in Zhejiang Province, China. Science teachers play an important role in implementing integrated STEM instruction in Chinese schools. The participants were recruited through random sampling. Participation was voluntary, and informed consent was obtained before data collection. Following data screening, 403 valid responses were randomly divided into an EFA sample of 195 and a CFA sample of 208.

Table 2 presents the demographic characteristics of the EFA and CFA samples, comprising 195 and 208 pre-service science teachers, respectively. Female participants accounted for 51.79% of the EFA sample and 55.77% of the CFA sample. In terms of education level, the EFA sample included 94 undergraduates (48.21%) and 101 postgraduates (51.79%), whereas the CFA sample included 105 undergraduates (50.48%) and 103 postgraduates (49.52%). Both samples showed relatively balanced distributions across gender and education level.

Table 2: Demographic characteristics.

Parameter	Type	EFA (*n* = 195) Frequency	Percentage (%)	CFA (*n* = 208) Frequency	Percentage (%)
Gender	Female	101	51.79	116	55.77
	Male	94	48.21	92	44.23
Education	Undergraduates	94	48.21	105	50.48
	Postgraduates	101	51.79	103	49.52
Teaching practicum experience	Yes	155	79.49	137	65.87
	No	40	20.51	71	34.13

3.3 Data Analysis

Data were analyzed using SPSS. 27 and AMOS. 29. EFA was conducted with 195 responses to investigate the questionnaire's underlying structure. Sampling adequacy was examined using the Kaiser–Meyer–Olkin measure and Bartlett's test of sphericity. Principal axis factoring with Promax rotation was used to allow correlations among the knowledge dimensions. Factor retention was informed by parallel analysis, the scree plot, and theoretical interpretability, while item selection considered factor loadings and cross-loadings.

CFA was subsequently conducted with 208 responses to evaluate the resulting measurement model. Model fit was assessed using CFI, TLI and RMSEA, interpreted collectively rather than through a single index (Kline, 2023). Convergent validity was evaluated using standardized factor loadings and AVE, while reliability was assessed using Cronbach's α and composite reliability. Discriminant validity was examined using the Fornell–Larcker criterion and HTMT. CFA latent factor correlations were used to address the relationships among the knowledge dimensions. Internal consistency was assessed using Cronbach's α and composite reliability. Correlations among the latent factors were examined to address the relationships between knowledge dimensions.

4. Results

4.1 Exploratory factor analysis (EFA)

EFA was conducted with 195 pre-service science teachers to examine the underlying structure of the 28-item questionnaire. The KMO measure and Bartlett's test of sphericity were used to assess whether the correlation matrix was suitable for factor analysis. The KMO value was 0.956, and Bartlett's test was statistically significant, $\chi^2(378) = 6384.55$, $p < .001$, indicating that the data were suitable for EFA. Principal axis factoring was selected to examine the common variance underlying the items. Oblimin rotation was applied because the proposed knowledge dimensions were expected to be related. An eight-factor solution was examined in accordance with the theoretical framework. The scree plot was inspected to examine the distribution of the initial eigenvalues (Figure 2). The plot showed a pronounced decline after the first factor, followed by a more gradual decrease. It therefore did not provide an unambiguous basis for retaining eight factors. The eight-factor solution was consequently evaluated through its interpretability and correspondence with the proposed knowledge dimensions. The extracted factors jointly accounted for 61.11% of the total variance.

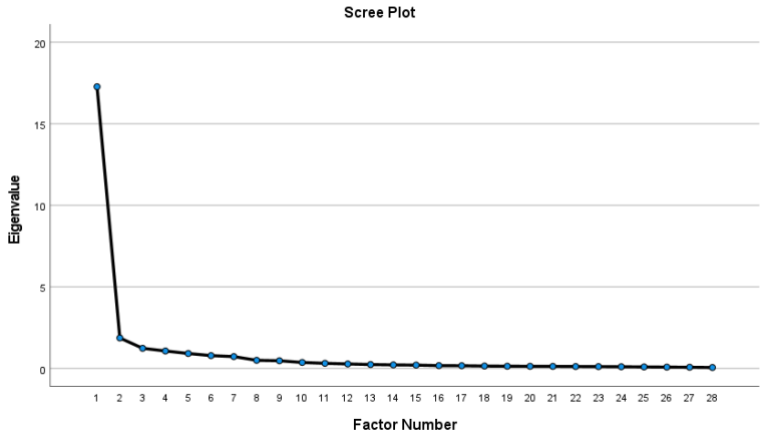


Figure 2: Scree plot of the initial eigenvalues

The pattern matrix presented in Table 3 showed that the items clustered according to the eight proposed dimensions. The absolute primary factor loadings ranged from .498 to .879, while all secondary loadings had absolute values below .30. Specifically, the primary loadings ranged from .821 to .879 for CK, .664 to .722 for PK, .738 to .769 for TK, .498 to .576 for PCK, .522 to .647 for TCK, .547 to .829 for TPK, .502 to .823 for TPACK, and .560 to .843 for PST. Rotation converged in 11 iterations. Each factor contained three or four items, and all 28 items were retained for subsequent CFA. These findings provided preliminary support for the proposed dimensional structure, although confirmation using the independent CFA sample was still required. In response to the first research question, the theoretically specified eight-factor EFA solution comprised CK, TK, PK, PCK, TCK, TPK, TPACK, and PST, represented by 28 retained items. The first seven dimensions contextualized TPACK within integrated STEM teaching, while PST addressed knowledge associated with pre-service teacher preparation.

Table 3: Factor loadings from the pattern matrix

Item	1	2	3	4	Item	5	6	7	8
CK1	.832				TPK1	.829			
CK2	.852				TPK2	.547			
CK3	.879				TPK3	.821			
CK4	.821				TK1		.738		
PST1		.560			TK2		.762		
PST2		.680			TK3		.769		
PST3		.814			TK4		.761		
PST4		.843			PK1			−.664	
TPACK1			−.636		PK2			−.719	
TPACK2			−.694		PK3			−.722	
TPACK3			−.502		PCK1				PCK1
TPACK4			−.823		PCK2				PCK2
TCK1				.647	PCK3				PCK3
TCK2				.522					
TCK3				.606					

Note. Extraction method: principal axis factoring. Rotation method: Oblimin with Kaiser normalization. Coefficients with absolute values below .30 are omitted. Factor signs are retained. Factors: 1 = CK; 2 = PST; 3 = TPACK; 4 = TCK; 5 = TPK; 6 = TK; 7 = PK; 8 = PCK.

4.2 Confirmatory factor analysis (CFA)

Confirmatory factor analysis (CFA) was conducted with 208 valid responses to evaluate the proposed eight-factor knowledge model for pre-service science teachers' integrated STEM teaching. The correlated first-order model demonstrated an acceptable overall fit: $\chi^2(322) = 660.816$, $p < .001$, $\chi^2/df = 2.052$, CFI = .951, TLI = .942, IFI = .951, NFI = .909, and RMSEA = .071, with a 90% confidence interval of [.064, .079]. Although GFI (.813) and AGFI (.764) were comparatively low, the principal incremental and approximate fit indices provided support for the proposed measurement structure. The model fit indices are reported in Table 4, and the standardized CFA model is presented in Figure 3.

Table 4: Model fit indices for the eight-factor CFA model.

Fit indices	Values	Criteria	Summary
CMIN/DF	2.052	< 3.00	Acceptable
RMSEA	.071	< .08	Acceptable
CFI	.951	≥ .90	Acceptable
TLI	.942	≥ .90	Acceptable
NFI	.909	≥ .90	Acceptable
IFI	.951	≥ .90	Acceptable

Note. $\chi^2(322) = 660.816$, $p < .001$. The 90% confidence interval for RMSEA was [.064, .079]. Criteria indicate conventional acceptable fit rather than stringent good fit.

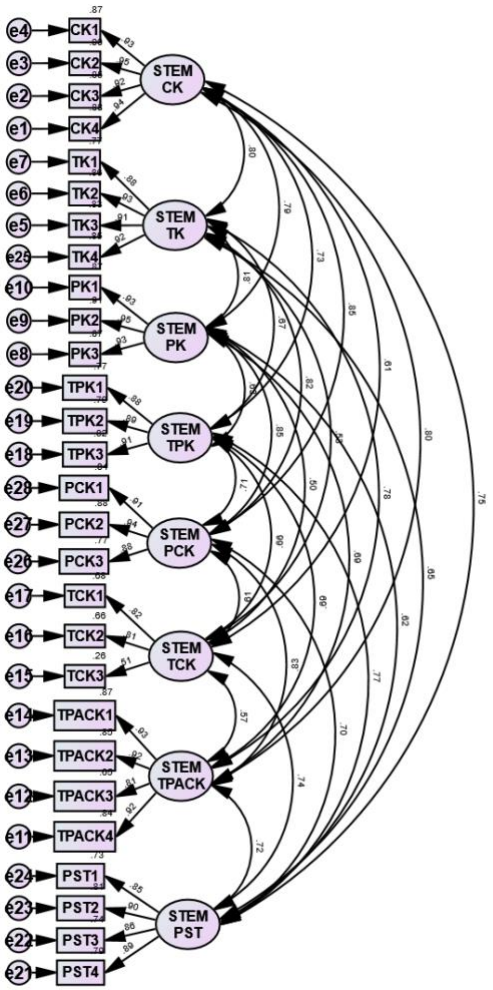


Figure 3: CFA model of the knowledge model

Convergent validity was examined using standardized factor loadings, average variance extracted (AVE), and composite reliability (CR). As shown in Table 5, standardized loadings ranged from .509 to .954. TCK3 had the lowest loading (.509), whereas all remaining items had loadings above .80. AVE values ranged from .534 to .883,

and CR values ranged from .767 to .964, exceeding the reference values of .50 and .70, respectively. These findings supported the model's convergent validity and composite reliability.

Table 5: Standardized factor loadings, AVE and CR

Path	Loading	AVE	CR	Path	Loading	AVE	CR
CK1 ← STEM-CK	.932	.872	.964	TCK1 ← STEM-TCK	.824	.534	.767
CK2 ← STEM-CK	.946			TCK2 ← STEM-TCK	.814		
CK3 ← STEM-CK	.920			TCK3 ← STEM-TCK	.509		
CK4 ← STEM-CK	.936			TPK1 ← STEM-TPK	.879	.794	.920
TK1 ← STEM-TK	.876	.828	.951	TPK2 ← STEM-TPK	.887		
TK2 ← STEM-TK	.928			TPK3 ← STEM-TPK	.907		
TK3 ← STEM-TK	.911			TPACK1←STEM-TPACK	.932	.804	.942
TK4 ← STEM-TK	.924			TPACK2←STEM-TPACK	.921		
PK1 ← STEM-PK	.933	.883	.958	TPACK3←STEM-TPACK	.809		
PK2 ← STEM-PK	.954			TPACK4←STEM-TPACK	.918		
PK3 ← STEM-PK	.932			PST1 ← STEM-PST	.853	.765	.929
PCK1←STEM-PCK	.914	.829	.936	PST2 ← STEM-PST	.899		
PCK2←STEM-PCK	.939			PST3 ← STEM-PST	.860		
PCK3←STEM-PCK	.877			PST4 ← STEM-PST	.886		

Discriminant validity was first evaluated using the Fornell–Larcker criterion. As presented in Table 6, the square root of each construct's AVE exceeded its correlations with other constructs, except for TCK in relation to PST. The TCK–PST correlation (.740) exceeded the square root of AVE for TCK (.730), indicating a small deviation from the Fornell–Larcker criterion that warrants further examination. Discriminant validity was additionally examined using the heterotrait–monotrait ratio of correlations (HTMT). As shown in Table 7, HTMT values ranged from .486 to .874. All values were below .90, meeting thresholds. Taken together, the two assessments provided qualified support for discriminant validity.

Table 6: Latent factor correlations and square roots of AVE

Dimension	CK	TK	PK	PCK	TCK	TPK	TPACK	PST
CK	—							
TK	.802	—						
PK	.789	.813	—					
PCK	.849	.816	.852	—				
TCK	.608	.531	.497	.611	—			
TPK	.730	.669	.627	.708	.663	—		
TPACK	.797	.783	.688	.831	.570	.693	—	
PST	.753	.651	.623	.704	.740	.766	.720	—

Square root of AVE	.934	.910	.940	.910	.730	.891	.896	.875

Table 7: Heterotrait–monotrait ratios of correlations (HTMT)

Dimension	**CK**	**TK**	**PK**	**PCK**	**TCK**	**TPK**	**TPACK**	**PST**
CK	—							
TK	.801	—						
PK	.799	.820	—					
PCK	.839	.817	.874	—				
TCK	.567	.512	.486	.580	—			
TPK	.728	.679	.633	.697	.606	—		
TPACK	.808	.805	.722	.856	.557	.693	—	
PST	.749	.646	.633	.696	.700	.775	.723	—

Internal consistency was assessed using Cronbach's α. As reported in Table 8, coefficients ranged from .754 to .964, exceeding the reference threshold of .70 for all eight dimensions. TCK had the lowest coefficient, consistent with its comparatively weaker inter-item associations. These results supported the internal consistency of the subscales. However, the high coefficients for some dimensions warrant further examination of potential item redundancy.

Table 8: Internal consistency reliability of the eight dimensions

Dimension	No. of items	Minimum inter-item correlation	Maximum inter-item correlation	Cronbach's α
STEM-CK	4	.856	.890	.964
STEM-TK	4	.801	.854	.950
STEM-PK	3	.867	.892	.957
STEM-PCK	3	.799	.851	.935
STEM-TCK	3	.398	.653	.754
STEM-TPK	3	.761	.842	.920
STEM-TPACK	4	.719	.860	.941
PST	4	.715	.811	.928

To address the second research question, correlations among the latent knowledge dimensions were examined using the CFA model. As shown in Table 6, all correlations were positive, ranging from .497 to .852. The strongest association was between PK and PCK (.852), followed by CK and PCK (.849) and PCK and TPACK (.831). The weakest association was between PK and TCK (.497). These findings indicated that the knowledge dimensions were interconnected, but did not establish causal or reciprocal influences.

At the item level, within-dimension correlations ranged from .398 to .892, whereas between-dimension correlations ranged from .138 to .776 (Table 9). TCK showed comparatively weaker within-dimension correlations (.398–.653) than the other dimensions. These descriptive associations supplemented the reliability and validity assessments but were not treated as independent evidence of discriminant validity.

Table 9: Ranges of within- and between-dimension inter-item correlations.

Dimension	CK	TK	PK	PCK	TCK	TPK	TPACK	PST
CK	.856–.890							
TK	.618–.721	.801–.854						

PK	.611–.728	.611–.743	.867–.892					
PCK	.625–.772	.609–.731	.638–.770	.799–.851				
TCK	.204–.524	.183–.421	.172–.437	.217–.497	.398–.653			
TPK	.520–.702	.418–.637	.493–.600	.445–.673	.138–.598	.761–.842		
TPACK	.602–.719	.591–.683	.559–.690	.615–.776	.199–.480	.468–.683	.719–.860	
PST	.555–.654	.445–.565	.454–.572	.479–.634	.200–.588	.506–.695	.457–.618	.715–.811

5. Discussion

This study developed and examined a TPACK-based knowledge model for pre-service science teachers' integrated STEM teaching. The findings provided preliminary support for eight related dimensions: CK, PK, TK, PCK, TCK, TPK, TPACK, and PST. The CFA model demonstrated acceptable overall fit, and all dimensions met the reference criteria for AVE and composite reliability. These results extend the application of TPACK to a specific disciplinary and developmental context. Whereas Mishra and Koehler (2006) emphasized the interaction of content, pedagogy, and technology, the present model contextualizes these relationships within integrated STEM teaching and pre-service teacher preparation. Previous research has also used TPACK to examine teachers' perceived knowledge for integrative STEM education (Chai et al., 2019).

Regarding the first research question, the proposed model suggests that pre-service STEM teaching knowledge involves both knowledge for instructional design and knowledge for learning to teach. Contextualizing the TPACK domains within interdisciplinary STEM tasks clarifies the former, whereas PST makes the connection between coursework, observation, feedback, and teaching preparation explicit. This distinction is consistent with Korthagen's (2010) perspective on connecting theoretical knowledge with practical teaching experiences. However, PST remains a proposed extension whose conceptual boundaries and empirical distinctiveness require continued examination. The present study contributes a complementary approach by retaining the seven TPACK dimensions and incorporating preparation-related knowledge.

The inclusion of interdisciplinary content knowledge addresses a central requirement of integrated STEM teaching: understanding both disciplinary concepts and meaningful connections across disciplines. Within this model, CK encompasses scientific understanding and connections with other STEM disciplines; integration is therefore not treated solely as a teaching strategy. This conceptualization is consistent with Kelley and Knowles (2016), who situated STEM integration within authentic contexts connecting scientific inquiry, engineering design, technological literacy, and mathematical thinking. More recently, Portillo-Blanco et al. (2024) documented both shared principles and continuing diversity in definitions of integrated STEM education. These perspectives suggest that interdisciplinary knowledge should be explicitly defined when adapting teacher knowledge frameworks to STEM. Nevertheless, the present CK scale should not be interpreted as a comprehensive assessment of knowledge across all four STEM disciplines. Its coverage requires further examination through expert review and performance-based tasks.

To address the second research question, the positive correlations indicate that respondents perceived the knowledge dimensions as interconnected aspects of STEM teaching preparation. The close relationships of PCK with CK, PK, and TPACK are consistent with its conceptual role in connecting disciplinary understanding with instructional decisions. PST's associations with the TPACK-related dimensions further suggest that learning from coursework, observation, and feedback is connected with perceived readiness for STEM instructional design. Nevertheless, these relationships neither demonstrate mutual influence nor establish that growth in one dimension produces growth in another. The strong associations involving PCK also require attention to whether the corresponding dimensions are sufficiently differentiated. For teacher education, the findings suggest that subject

courses and teaching methods courses could be connected through shared lesson-design tasks. Pre-service teachers could identify the scientific concepts underlying an engineering problem, anticipate students' misconceptions, and plan appropriate scaffolding and assessment. This emphasis is supported by Berisha and Vula (2024), whose collaborative STEM course helped pre-service teachers develop integrated lesson plans but also revealed continuing difficulties with formative assessment.

The technology-related dimensions highlight the different forms of knowledge involved in using digital tools for integrated STEM teaching. TK provides a foundation for selecting and operating relevant technologies. TCK connects these technologies with disciplinary content by emphasizing how digital representations make scientific phenomena and relationships accessible to learners. TPK concerns how technology supports inquiry, data analysis, and collaboration, while TPACK coordinates these uses with interdisciplinary content and pedagogical goals in integrated lesson design. This differentiation complements Chai et al.'s (2019) examination of technology-related knowledge in science, mathematics, engineering, and integrative STEM teaching. It also highlights the value of preparing pre-service teachers to evaluate the scientific accuracy of digital representations and justify their instructional choices. Teacher education activities can support this preparation by asking students to compare simulations, interpret sensor-generated data, and incorporate appropriate tools into STEM lessons addressing authentic problems.

The addition of PST represents the model's focus on learning to teach during initial teacher preparation. Its items address applying coursework, learning from classroom observations, and revising lesson plans through feedback. PST therefore makes preparation-related processes visible alongside the knowledge required for instructional design. This focus corresponds with Zhang and Zhu's (2023) identification of interdisciplinary preparation, assessment, and technology integration as important directions in STEM pre-service teacher education. Nevertheless, PST's conceptual status warrants further clarification: some items may capture reflective learning capabilities rather than knowledge itself.

Practically, the model offers a provisional framework for organizing pre-service STEM preparation around connected knowledge domains. Teacher educators could use the dimensions to structure activities that combine interdisciplinary problem analysis, technology selection, lesson planning, microteaching, and feedback-based revision. These are proposed applications rather than effects demonstrated by this study. Because the questionnaire relies on self-reports, its scores primarily reflect perceived knowledge and capabilities; they should be supplemented with lesson-plan evaluations, classroom observations, and knowledge tasks. Moreover, the correlated first-order CFA does not establish a higher-order knowledge factor or justify interpreting a total score as a single construct. Longitudinal and multi-institutional studies are needed to examine how the dimensions develop during teacher preparation and how they relate to the quality of integrated STEM teaching.

6. Implications

This study offers a framework for understanding pre-service science teachers' perceived knowledge for integrated STEM teaching. Theoretically, it contextualizes the seven TPACK domains within interdisciplinary STEM instruction and incorporates preparation-related knowledge. This extension draws attention to how pre-service teachers connect coursework, classroom observations, and reflective revision with instructional planning. The model therefore provides a basis for examining both the knowledge involved in STEM lesson design and the preparation processes through which prospective teachers learn to apply it.

Practically, the questionnaire could help teacher educators identify perceived strengths and preparation needs across the eight dimensions and plan targeted learning activities. The positive relationships among the dimensions suggest the value of creating opportunities to connect disciplinary knowledge, pedagogy, technology, and reflective learning. Science content, STEM teaching methods, and educational technology courses could incorporate shared tasks in which pre-service teachers analyze an authentic problem, identify relevant disciplinary connections, select suitable digital tools, and develop an integrated lesson. Microteaching, mentor feedback, and peer discussion could then support revision of these plans. The dimension-level scores should be interpreted as indicators of perceived knowledge and supplemented with lesson-plan evaluations and teaching observations.

Teacher preparation should also emphasize students' perspectives. pre-service teachers need opportunities to anticipate difficulties learners may encounter when connecting concepts across STEM disciplines and to plan appropriate scaffolding. Analyzing classroom examples and students' work could help them select accessible representations, formulate guiding questions, and monitor students' reasoning during inquiry and engineering design. Together, these activities offer a practical way to use the proposed framework to organize coherent, learner-responsive STEM teacher preparation.

7. Conclusion

Preparing science teachers for integrated STEM teaching requires attention to disciplinary connections, pedagogical decisions, technology use, and professional learning during initial teacher education. This study developed a TPACK-based knowledge model and a questionnaire encompassing eight related dimensions for pre-service science teachers. Expert consultation, exploratory factor analysis, and confirmatory factor analysis provided preliminary evidence supporting the proposed structure, convergent validity, and composite reliability. The model contributes by making interdisciplinary content knowledge explicit within a STEM teaching context and incorporating knowledge associated with pre-service preparation. The findings also indicate that the dimensions are interconnected, although the boundary between TCK and PST requires further clarification. The questionnaire offers a provisional tool for examining perceived preparation needs and informing teacher education activities. Further validation using diverse samples and performance-based evidence is needed before drawing stronger conclusions about its capacity to assess actual teaching knowledge or predict instructional quality.

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Appendix A.

Scale of Questionnaire for pre-service Science Teachers

Dimension	Items
CK	1.I understand the science concepts needed to teach an integrated STEM topic.
	2.I can explain how scientists and engineers approach the same problem in different ways.
	3.I understand how mathematical concepts relate to scientific phenomena in a STEM topic.
	4.I can explain the scientific principles behind an engineering solution.
PK	1.I know how to guide students through a STEM inquiry activity.
	2.I know how to assess students' learning during a STEM activity.
	3.I know how to guide students to design, test, and improve a solution.
TK	1.I know how to use common digital tools for science teaching.
	2.I know how to use a STEM-specific tool, such as a sensor or simulation program.
	3.I know how to solve basic technical problems when using digital tools.
	4.I know how to learn to use an unfamiliar digital tool.
PCK	1.I can select science content suitable for teaching through a STEM theme.
	2.I can anticipate difficulties students may have when learning a science concept within a STEM theme.
	3.I know how to provide support when students struggle to understand a science concept within a STEM activity.
TCK	1.I know which technological resources are suitable for teaching specific STEM content.
	2.I know how to use digital tools to visualize scientific phenomena that students cannot observe directly.
	3.I can judge whether a digital representation accurately shows the science concept being taught.
TPK	1.I know how to use digital tools to help students collect data during an inquiry activity.
	2.I know how to use digital tools to help students analyze the data they collect.
	3.I know how to use technology to support students' collaboration in a STEM activity.
TPACK	1.I can select technology and teaching methods that fit the STEM content I plan to teach.
	2.I can design a STEM lesson that connects science with another STEM discipline to address a real-world problem.
	3.I can design a technology-supported assessment to check students' understanding of an integrated STEM topic.
	4.I can adjust my choice of technology and teaching methods when students struggle with specific STEM content.
PST	1.I can apply what I learned in teacher education courses when planning a STEM lesson.
	2.I know how to use classroom observations to identify areas for improvement in my STEM teaching.
	3.I can revise a STEM lesson plan based on feedback from a mentor or peers.
	4.I know how to investigate a problem in my STEM teaching by collecting evidence from students' work.