

 Research Article

TPCK of Mathematics Trainee Teachers: A Comparison using Mahalanobis Distance

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Abstract

This body of knowledge, known as ‘Technological Pedagogical Content Knowledge (TPCK)’, is essential to teaching both today and in the future. Teachers possess a high degree of knowledge that is based on ‘Pedagogical Knowledge (PK)’, ‘Technological Knowledge (TK)’, ‘Content Knowledge (CK)’, ‘Technological Pedagogical Knowledge (TPK)’, ‘Technological Content Knowledge (TCK)’, and ‘Pedagogical Content Knowledge (PCK)’. This research work was done by collecting data from B.Ed. trainee teachers with mathematics as a method subject in West Bengal, India. The objective of the study is to compare the TPCK knowledge base of mathematics trainee teachers with respect to gender and residence. The descriptive Survey Method is followed. Trainee teachers with mathematics as a method subject from West Bengal, India, are taken as a sample. The TPACK-Math Scale by Önal (2016) is used for this study. Collected data is prepared by using MS Excel, analysed by SPSS 26, JASP 0.18.1, and MATLAB 2021b. Descriptive statistics (Mean, SD, and Covariance) and inferential statistics (Mahalanobis Distance) are used for this study. Calculated value of Mahalanobis Distance between male and female is 0.3417 (<1) and between rural and urban is 0.6625 (<1). There is no significant difference between male vs female and rural vs urban mathematics trainee teachers with respect to ‘TK’, ‘PK’, ‘CK’, ‘TPK’, ‘TCK’, ‘PCK’, ‘CNTK’, and ‘TPCK’. It is concluded that the dynamical nature of the knowledge base considered for the present study is independent of gender and residence of trainee teachers. Possible causes for such a non-significant finding in the educational research context are discussed. A comprehensive interpretation of the inherent limitations is acknowledged, and to overcome these limitations and deepen the understanding of TPCK development in mathematics education, further research is suggested.

Keywords: TPCK, Trainee-Teachers, Reliability, Relationship

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1. INTRODUCTION

The National Education Policy (NCF 2020) envisions the establishment of an autonomous body called the ‘National Educational Technology Forum (NETF)’ to provide a platform for the free exchange of ideas on the use of technology to improve learning, assessment, planning, administration, and so on, both in schools and in higher education. One of the NCF 2023’s guiding concepts is technological integration. The NCF emphasizes the necessity of using technology in education in order to improve India’s educational standards. According to the NCF, technology will assist teachers in making lessons more engaging and participatory.

The aim of NETF is to make India a global leader in distributing, experimenting with, and developing educational technology and research. The mission is to provide a platform for the free exchange of ideas for the development, evolution, and effective use of technology, as well as to improve learning, assessment,

planning, and administration through facilitation, capacity building, promoting innovation and research, and setting standards and benchmarking in order to emerge as a global leader.

From above mentioned facts it is clear that in teaching-learning, Technological Pedagogical Content Knowledge (TPCK) together with Pedagogical Knowledge (PK), Technological Knowledge (TK), Content Knowledge (CK), Technological Pedagogical Knowledge (TPK), Technological Content Knowledge (TCK), Pedagogical Content Knowledge (PCK) and Context Knowledge (CNTK) are the important knowledge bases for teachers in the present situation.

Critical importance for educational reform in West Bengal, India, where technology integration was faced with significant systemic challenges, was held by the Technological Pedagogical Content Knowledge (TPACK) framework. A major institutional obstacle was revealed by surveys of secondary school teachers in the region to be the “lack of effective training” alongside a critical deficit in the “knowledge and competence of teachers in ICT integration into pedagogy”. This evidence suggested that technology use often remained at a superficial “skill level” rather than a deep curricular integration. The TPACK framework was considered essential because it moved beyond mere TK to define the specific integrated knowledge required (TPK and TCK), which was deemed necessary for teachers, for example, to promote effective science and mathematics teaching through the Bengali language (Setua, 2023). Furthermore, considering the stark digital divide, fragile connectivity, intermittent power supply, and infrastructural voids prevalent in vast rural areas, the TPACK model’s emphasis on Contextual Knowledge (CTK) became a crucial domain, guiding educators to adapt their teaching strategies and content representation effectively despite these ecological constraints. By using TPACK as a prescriptive blueprint, teacher professional development programs could be systematically designed to address these specific competency gaps, and ultimately, the successful translation of technology integration into enhanced student learning achievement and the development of 21st-century skills was ensured (Brianza et al., 2022).

1.1. Literature Review

Shulman (1987) defined a framework for teacher knowledge by incorporating “content knowledge, general pedagogical knowledge, e.g., classroom control, using group work, pedagogical content knowledge, curriculum knowledge, knowledge of learners and their characteristics, knowledge of educational contexts, e.g., schools and the wider community, and knowledge of educational ends, purposes, and values.” Technological Pedagogical Content Knowledge (TPCK) is the integration of technology, pedagogy, and content knowledge (Mishra & Koehler, 2006). According to Koehler and Mishra (2009), TPCK is an expansive strategy that combines effective approaches through the use of instructional methods in content teaching, as well as the foundations of effective teaching with technology and technology-assisted idea presentation.

Different investigations covering many facets of TPACK have already been conducted (Groth et al., 2009; Guerrero, 2010; Niess et al., 2010; Özgün-Koca et al., 2009, 2010; Gupta & Jan, 2013; Kumar, 2013; Mahato and Sen, 2023a, 2023b). Sen (2016, 2022) and Sen and Samanta (2015a, 2015b, 2015c, & 2015d) both stress the significance of pedagogical content knowledge (PCK) as a part of TPACK. Significant relationships between Technological Pedagogical and Content Knowledge (TPACK) constructs, and their integration in STEM subjects by Mathematics and Science teachers were established through Structural Equation Modeling, providing valuable insights into technology adoption for mathematics instruction (Mansour et al., 2024). A systematic literature review examining the application of Technological Pedagogical and Content Knowledge (TPACK) in mathematics education was conducted, illuminating its impact on classroom instruction, student engagement, and learning outcomes within the last decade (Hanifah et al., 2025). The Technological Pedagogical Content Knowledge (TPACK) development of both pre-service and in-service mathematics teachers was discussed following their participation in an online GeoGebra course, highlighting its significance for pedagogical innovation in instruction (Bueno et al., 2021). An analysis of mathematics teaching devices, including lesson plans and materials, was conducted to evaluate the integration of the Technological Pedagogical and Content Knowledge (TPACK) framework, revealing that teachers’ TPACK mastery significantly influenced the quality of their instructional design (Sridana et al., 2024). The inherent structure of the Technological Pedagogical and Content Knowledge (TPACK) framework was investigated from a subject-specific mathematics angle using test-based instruments, leading to the identification of distinct knowledge components that are necessary for effective

technology integration in mathematics teaching-learning scenarios (Fabian et al., 2024). The effectiveness of the online DECODE professional development program in empowering Science, Technology, Engineering, and Mathematics (STEM) teachers, particularly in refining their Technological Pedagogical Content Knowledge (TPACK) skills for the virtual environment, was systematically analyzed (Wahono et al., 2025). The quality of mathematics learning devices and their incorporation of the Technological Pedagogical Content Knowledge (TPACK) framework were descriptively analyzed among experienced teachers, leading to the finding that the majority of existing devices require significant revision to effectively integrate technology for enhanced teaching-learning outcomes (Sridana et al., 2025). The relationship between mathematics and science teachers' self-perceptions of their Technological Pedagogical Content Knowledge (TPACK) and their reported actual use of Information and Communication Technology (ICT) for various classroom activities, such as inquiry and assessment, was explored using a quantitative survey methodology (Raveh et al., 2025). The impact of active participation on the Technological Pedagogical Content Knowledge (TPACK) components of mathematics educators was quantitatively assessed through pre- and post-surveys administered to participants completing a Massive Open Online Course for Educators (MOOC-Ed) focused on teaching mathematics with technology (Smiling & Hollebrands, 2025). Mathematics teachers' specific knowledge in the use of digital technologies for instruction was analyzed through a detailed case study using the Technological Pedagogical Content Specialized Knowledge (TPCSK) instrument, revealing a strong alignment between their self-perception and demonstrated ability to integrate technology (Padilla-Escorcia et al., 2025). A systematic literature review examining how Technological Pedagogical Content Knowledge (TPACK) was utilized by mathematics teachers to structure and rationalize their instructional decisions was conducted, demonstrating that the framework provides crucial insights into effective pedagogical reasoning (Priyanda et al., 2025). The initial Technological Pedagogical Content Knowledge (TPACK) level of prospective mathematics teachers was assessed using a validated questionnaire at an early stage of their training program, revealing areas where pedagogical knowledge, particularly its intersection with technology, needs further strengthening for future instructional practice (Morales-López et al., 2021). The central Technological Pedagogical Content Knowledge (TPACK) construct was elaborated within mathematics education using the notion of situated abstraction, revealing teachers' successful strategic knowledge for managing pedagogical and content transitions when leveraging dynamic geometry software for teaching circle theorems (Bretschler, 2023). The consistency of mathematics teachers' self-reported Technological Pedagogical Content Knowledge (TPACK) was questioned after low correlations between self-reports and scores on a paper-and-pencil knowledge test, specifically addressing the topic of fractions, were observed in a study involving 173 pre-service and in-service educators (Kadluba & Obersteiner, 2025). The application of Technological Pedagogical Content Knowledge (TPACK) by pre-service teachers (PST) during their teaching practice was evaluated, revealing that they possessed strong knowledge across the seven elements of the framework, yet a very weak uphill correlation was found between their TPACK application and the availability of educational technology tools in their public school placements (Santos & Castro, 2021).

Schmid et al. (2021) executed a study that aimed to assess preservice teachers' self-reported TPACK reflections on the inclusion of digital technology in their lesson plans. Gayen and Sen (2021) conducted a study highlighting the necessity of integrating technology into the teaching-learning process to enhance educational outcomes. Chieng and Tan (2021) conducted a study to investigate Malaysian secondary science teachers' perceptions on the integration of 'information and communication technology' within the TPACK framework. Bulut and Isiksal-Bostan (2019) explored a study focusing on the examination of the TPACK self-assessment of pre-service elementary mathematics educators with an emphasis on geometry. Ozudogru and Ozudogru (2019) conducted a study where the primary aim of that research was to develop and validate a TPACK scale designed to assess the knowledge levels of mathematics teachers across the various components of the TPACK framework. Hsu and Chen (2018) performed a study to analyse the factors influencing teachers' proficiency in technology, pedagogy, and content in the digital age.

Mahalanobis Distance (Mahalanobis, 1936) measurement solved a number of educational problems. Numerous researchers (Ahmed et al., 2020, 2021; Sen & Pal, 2020; Ahmed et al., 2022a, 2022b) used this distance to explore difficulties connected to achievement analysis. Many researchers (Mahato & Sen, 2021; Garain et al., 2021; Sen et al., 2023a, 2023b; Adhikari, 2023; Mohanta et al., 2023a, 2023b; Adhikari et al., 2023a, 2023b; Sutradhar et al., 2023) have applied this distance in many educational psychology investigations. The present research work was done by collecting data from the B.Ed. trainee teachers who have mathematics as a method subject in West Bengal, India.

1.2. Objectives

Objectives of this study are mentioned below:

- To compare the TPCK knowledge base of mathematics trainee teachers with respect to gender, and
- To compare the TPCK knowledge base of mathematics trainee teachers with respect to residence.

1.3. Hypotheses

The following null hypotheses are considered to fulfill the objective of the study:

H_{01} : There is no significant difference between male and female mathematics trainee teachers with respect to TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK.

H_{02} : There is no significant difference between rural and urban mathematics trainee teachers with respect to TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK.

2. METHODOLOGY

2.1. Method

The Descriptive Survey Method is followed for this research work. The Descriptive Survey Method is commonly utilized and one of the appropriate methods in research related to TPCK because its main objective aligns seamlessly with the foundational requirements of this framework to accurately depict the current condition and level of teachers' knowledge, along with its various components. Given that TPCK is a complex and multifaceted construct that integrates Content, Pedagogy, and Technology knowledge, descriptive surveys serve as the most effective and efficient approach to obtaining a quantitative overview of its status among a large group of educators.

2.2. Sample and Sampling

503 samples are selected by the Stratified Random Sampling method from the B.Ed. trainee teachers from West Bengal who have mathematics as a method subject. The age of the trainee teachers varied from 23 to 32 years. Only pre-service trainee teachers are considered for this research because only a small number of in-service trainee teachers are doing B.Ed. Two strata, gender and residence of the trainee teachers, are considered by the researchers. Sample distribution is represented by the following figure:

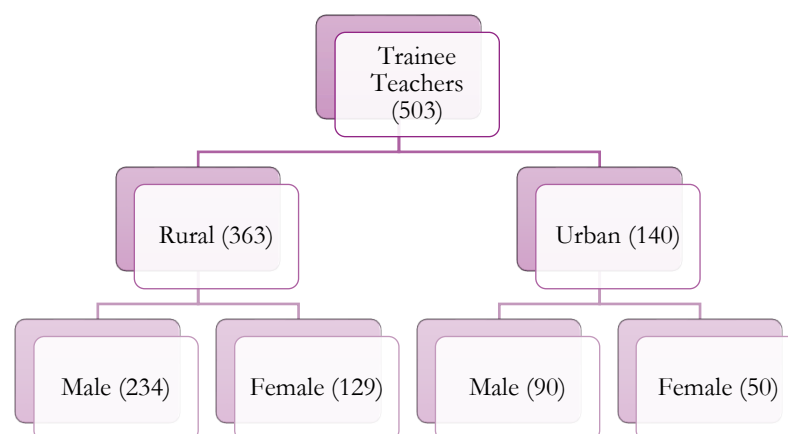


Figure 1. Sample Profile of the Study

2.3. Tool Used

TPACK-Math Scale by Önal (2016) is used for this study. The instrument, created by Önal (2016), assesses the TPACK competencies of pre-service mathematics teachers. Comprising 59 items on a five-

point Likert scale (with a scoring pattern, 5= I am completely competent, 1= I am completely incompetent), the items are categorized into nine distinct factors. These factors consist of TK, CK, PK, PCK, TCK, TPK, TPCK, and CTK.

Collected data is prepared by using MS Excel (for data tabulation and cleaning), analyzed by SPSS 26 (for calculating Mean, SD, Correlation, and Covariance), JASP 0.18.1(for calculating McDonald’s ω , Cronbach’s α , and Guttman’s λ_2), and MATLAB 2021b (for calculating Mahalanobis Distance).

Statistical Technique Used: Appropriate descriptive statistics (Mean, SD, and Covariance) and inferential statistics (MD) are used for this study.

To calculate MD, the following equations are used:

$$MD = \sqrt{(\mu_1 - \mu_2)^T \xi^{-1} (\mu_1 - \mu_2)}$$

$$\xi = \frac{\xi_1 n_1 + \xi_2 n_2}{N}$$

Where μ_1, μ_2 are the mean vectors, ξ_1, ξ_2 are the Covariance Matrices of the respective groups of samples with sizes n_1 and n_2 , respectively, ξ is the pooled covariance matrix, and $N = n_1+n_2$.

3. RESULTS AND DISCUSSION

The McDonald’s ω , Cronbach’s α , and Guttman’s λ_2 values for the measure of reliability are represented in Table 1. An exceptionally high level of reliability was demonstrated by the high observed coefficients, particularly Cronbach’s α and McDonald’s ω , both registering 0.958. The standard benchmark of 0.70 was significantly surpassed. The fact that the items used to measure the eight distinct, yet highly interconnected, latent knowledge bases were functioning coherently and stably was confirmed by this convergence of strong values. This structural integrity was considered essential for confidently interpreting the relationships between the constructs and validating the instrument’s suitability for assessing the complex nature of integrated TPCK competence among this cohort of mathematics trainee teachers. A high level of reliability was shown by the values. Thus, it might be used for the present study.

Table 1. TPACK-Math Scale Reliability Statistics

Estimate	McDonalds ω	Cronbachs α	Guttman's λ_2
Point estimate	0.958	0.958	0.959
95% CI lower bound	0.953	0.952	0.948
95% CI upper bound	0.964	0.963	0.968

Table 2. Descriptive Statistics of Male Mathematics Trainee Teachers

Variables	Descriptive Statistics		
	Mean	Std. Deviation	N
TK	23.72	7.001	324
PK	38.73	7.343	324
CK	32.93	6.863	324
TPK	20.34	4.623	324
TCK	16.95	4.505	324
PCK	24.76	5.359	324
TPCK	30.01	7.764	324
CNTK	17.31	3.712	324

Descriptive statistics of male mathematics trainee teachers (N=324) are represented in Table 2. The mean scores and standard deviations for various knowledge components, likely based on the TPACK framework, across a sample of 324 male mathematics trainee teachers were summarized in the provided Table 2: descriptive statistics of male mathematics trainee teachers. The highest score, on average, was achieved by the trainees in PK (Mean=38.73), which was followed by CK (Mean=32.93). Conversely, the lowest average score was recorded for TCK (Mean=16.95), suggesting that this area was a relative weakness for the group. A mean of 30.01 was held by the overall integrated knowledge, TPCK, with the highest score,

SD of 7.764. A wide range of proficiency levels in this complex, integrated domain among the trainees was indicated. The most consistent scores, which were reflected by the lowest standard deviation of 3.712, were found in CNTK (Mean=17.31), which likely was representative of Context or Curriculum Knowledge.

Table 3. Correlations and Covariance of Male Mathematics Trainee Teachers

		TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	Correlation	1	.454**	.414**	.491**	.428**	.321**	.415**	.223**
	Covariance	49.019	23.345	19.900	15.884	13.486	12.042	22.562	5.792
PK	Correlation	.454**	1	.779**	.653**	.472**	.658**	.600**	.492**
	Covariance	23.345	53.921	39.271	22.180	15.631	25.900	34.200	13.419
CK	Correlation	.414**	.779**	1	.643**	.529**	.716**	.598**	.517**
	Covariance	19.900	39.271	47.106	20.414	16.353	26.339	31.855	13.167
TPK	Correlation	.491**	.653**	.643**	1	.669**	.664**	.769**	.572**
	Covariance	15.884	22.180	20.414	21.370	13.929	16.443	27.583	9.814
TCK	Correlation	.428**	.472**	.529**	.669**	1	.603**	.713**	.431**
	Covariance	13.486	15.631	16.353	13.929	20.298	14.565	24.954	7.200
PCK	Correlation	.321**	.658**	.716**	.664**	.603**	1	.689**	.612**
	Covariance	12.042	25.900	26.339	16.443	14.565	28.714	28.676	12.170
TPCK	Correlation	.415**	.600**	.598**	.769**	.713**	.689**	1	.720**
	Covariance	22.562	34.200	31.855	27.583	24.954	28.676	60.279	20.763
CNTK	Correlation	.223**	.492**	.517**	.572**	.431**	.612**	.720**	1
	Covariance	5.792	13.419	13.167	9.814	7.200	12.170	20.763	13.781

** Correlation is significant at the 0.01 level (2-tailed).

The bivariate Pearson correlation coefficients (r) and the covariance values for all combinations of knowledge components (likely TK, PK, CK, TPK, TCK, PCK, TPCK, and CNTK) among the male mathematics trainee teachers are presented in Table 3. Crucially, it was revealed by the analysis that all measured knowledge components were positively and statistically significantly correlated with one another at the $p < 0.01$ level (indicated by **), and the theoretical premise that these domains were interdependent rather than isolated was supported. The strongest observed relationship was the high positive correlation between Pedagogical Knowledge (PK) and Content Knowledge (CK) ($r = 0.779$), and the close connection between knowing what to teach and how to teach it was highlighted. The central role of the integrated Technological Pedagogical Content Knowledge (TPCK) was demonstrated by the exhibition of strong correlations with all its constituent knowledge forms, particularly Technological Pedagogical Knowledge (TPK) ($r = 0.769$) and Context Knowledge (CNTK) ($r = 0.720$). These findings affirmed that enhancing one area of a mathematics trainee’s professional knowledge was likely to be associated with improvements across other domains, and the necessity of integrated teacher preparation programs was underscored.

Table 4. Descriptive Statistics of Female Mathematics Trainee Teachers

	Mean	Std. Deviation	N
TK	22.74	5.794	179
PK	39.29	6.235	179
CK	33.58	6.519	179
TPK	19.89	4.437	179
TCK	16.84	4.536	179
PCK	24.45	5.657	179
TPCK	29.71	7.849	179
CNTK	17.22	3.376	179

The central tendency and dispersion for various professional knowledge components, consistent with the TPACK framework, for a sample size (N) of 179 female mathematics trainee teachers, were presented in Table 4: Descriptive statistics of female mathematics trainee teachers. The descriptive data indicated that the highest average proficiency was achieved by female trainees in Pedagogical Knowledge (PK) (Mean=39.29), similar to their male counterparts in prior analyses. The lowest was achieved in Technological Content Knowledge (TCK) (Mean=16.84). A mean score of 29.71 was held by Technological Pedagogical Content Knowledge (TPCK). Across all domains, the highest variability was displayed by the female trainees’ scores in TPCK (SD=7.849). Substantial individual differences in their ability to integrate

technology, pedagogy, and content were suggested, while the greatest homogeneity was shown in CNTK (SD=3.376).

Table 5. Correlations and Covariance of Female Mathematics Trainee Teachers

		TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	Correlation	1	.653**	.578**	.647**	.589**	.392**	.612**	.335**
	Covariance	33.574	23.586	21.830	16.630	15.481	12.857	27.813	6.552
PK	Correlation	.653**	1	.781**	.660**	.544**	.665**	.582**	.610**
	Covariance	23.586	38.870	31.729	18.250	15.379	23.459	28.489	12.850
CK	Correlation	.578**	.781**	1	.568**	.460**	.675**	.593**	.487**
	Covariance	21.830	31.729	42.492	16.433	13.589	24.907	30.316	10.718
TPK	Correlation	.647**	.660**	.568**	1	.720**	.602**	.690**	.554**
	Covariance	16.630	18.250	16.433	19.691	14.483	15.104	24.025	8.294
TCK	Correlation	.589**	.544**	.460**	.720**	1	.456**	.653**	.397**
	Covariance	15.481	15.379	13.589	14.483	20.575	11.713	23.250	6.087
PCK	Correlation	.392**	.665**	.675**	.602**	.456**	1	.622**	.708**
	Covariance	12.857	23.459	24.907	15.104	11.713	32.001	27.636	13.518
TPCK	Correlation	.612**	.582**	.593**	.690**	.653**	.622**	1	.424**
	Covariance	27.813	28.489	30.316	24.025	23.250	27.636	61.601	11.245
CNTK	Correlation	.335**	.610**	.487**	.554**	.397**	.708**	.424**	1
	Covariance	6.552	12.850	10.718	8.294	6.087	13.518	11.245	11.399

** . Correlation is significant at the 0.01 level (2-tailed).

The interrelationships among the various professional knowledge components for the 179 female trainees were presented in Table 5: Correlations and Covariance of female mathematics trainee teachers, utilizing Pearson correlation coefficients (r) and covariance. Similar to the male cohort, the results showed that all knowledge components (TK, PK, CK, TPK, TCK, PCK, TPCK, and CNTK) were positively and significantly correlated with each other at the $p < 0.01$ level, and the notion of an interconnected knowledge structure was reinforced. The strongest correlation was found to exist between Pedagogical Knowledge (PK) and Content Knowledge (CK) ($r = 0.781$). This closely mirrored the male group’s highest correlation, and the essential synergy of these two domains was further validated. Notably, the correlations involving Technological Knowledge (TK) (r ranging from 0.335 to 0.653) were generally higher for the female trainees compared to the male trainees (referencing Table 3). A potentially stronger linear relationship between technology-specific knowledge and other TPACK domains within the female cohort was suggested.

Descriptive statistics were computed for all eight knowledge bases across the analyzed subgroups (N=503 total), revealing the relative strengths and weaknesses perceived by the trainees. All variables (TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK) exhibited moderate mean values across all groups. In the gender comparison, male (N=324) and female (N=179) trainee teachers showed strikingly similar profiles. Both groups reported the highest mean scores in the foundational domains of Pedagogical Knowledge (PK; Male: Mean=38.73; Female: Mean=39.29) and Content Knowledge (CK; Male: Mean=32.93; Female: Mean=33.58). Crucially, the overall integrated TPCK score was nearly identical (Male: Mean=30.01; Female: Mean=29.71).

Table 6. Descriptive Statistics of Rural Mathematics Trainee Teachers

	Mean	Std. Deviation	N
TK	23.32	6.880	363
PK	39.06	6.413	363
CK	33.47	6.279	363
TPK	20.61	4.365	363
TCK	16.91	4.528	363
PCK	25.10	4.983	363
TPCK	29.98	7.903	363
CNTK	17.45	3.622	363

The descriptive statistics for the professional knowledge components, consistent with the TPACK framework, for a large sample (N) of 363 rural mathematics trainee teachers, were presented in Table 6: Descriptive statistics of rural mathematics trainee teachers. The results indicated that the highest mean

score of the rural trainees was found in PK (Mean=39.06). This was followed closely by CK (Mean=33.47). The lowest average proficiency was observed in TCK (Mean=16.91). A mean of 29.98 was held by the integrated knowledge, TPCK. The highest level of score variability was displayed by the trainees in TPCK (SD=7.903), suggesting that considerable heterogeneity in the integration of knowledge among rural trainees was present. Conversely, the greatest homogeneity (lowest variability) was shown in CNTK (SD=3.622). A critical baseline for understanding the knowledge structure of teachers specifically prepared for rural contexts was provided by these statistics, enabling further comparisons with urban cohorts to identify differential training needs.

Table 7. Correlations and Covariance of Rural Mathematics Trainee Teachers

		TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	Correlation	1	.439**	.405**	.526**	.453**	.323**	.444**	.192**
	Covariance	47.329	19.372	17.478	15.807	14.113	11.089	24.136	4.786
PK	Correlation	.439**	1	.745**	.676**	.503**	.685**	.611**	.539**
	Covariance	19.372	41.120	30.015	18.934	14.597	21.902	30.954	12.524
CK	Correlation	.405**	.745**	1	.597**	.484**	.717**	.615**	.504**
	Covariance	17.478	30.015	39.432	16.375	13.767	22.428	30.512	11.458
TPK	Correlation	.526**	.676**	.597**	1	.713**	.635**	.778**	.561**
	Covariance	15.807	18.934	16.375	19.050	14.096	13.821	26.830	8.875
TCK	Correlation	.453**	.503**	.484**	.713**	1	.513**	.678**	.409**
	Covariance	14.113	14.597	13.767	14.096	20.505	11.573	24.258	6.705
PCK	Correlation	.323**	.685**	.717**	.635**	.513**	1	.623**	.674**
	Covariance	11.089	21.902	22.428	13.821	11.573	24.832	24.519	12.172
TPCK	Correlation	.444**	.611**	.615**	.778**	.678**	.623**	1	.571**
	Covariance	24.136	30.954	30.512	26.830	24.258	24.519	62.450	16.351
CNTK	Correlation	.192**	.539**	.504**	.561**	.409**	.674**	.571**	1
	Covariance	4.786	12.524	11.458	8.875	6.705	12.172	16.351	13.121

** . Correlation is significant at the 0.01 level (2-tailed).

The inter-correlations (r) and covariance among the eight professional knowledge components for the 363 rural mathematics trainee teachers were presented in Table 7: Correlations and Covariance of rural mathematics trainee teachers. The findings indicated that all pair-wise correlations were positive and statistically significant at the p<0.01 level, and a high degree of interdependence across the TPACK domains for this cohort was confirmed. The strongest correlation was observed between PK and CK (r=0.745), and the vital connection between these foundational elements in the rural teacher preparation context was underscored. The central, integrated role of the comprehensive TPCK was demonstrated by the exhibition of the highest correlation with TPK (r=0.778), and strong associations with its other constituent elements. Notably, the lowest correlation was found between TK and CNTK (r=0.192). This suggested that for rural trainees, the relationship between knowing specific technologies and the broader context of teaching was the weakest among all measured links. These results were considered crucial for designing integrated curricula specifically tailored for rural educators.

Table 8. Descriptive Statistics of Urban Mathematics Trainee Teachers

	Mean	Std. Deviation	N
TK	23.51	5.866	140
PK	38.57	8.251	140
CK	32.37	7.789	140
TPK	19.06	4.867	140
TCK	16.93	4.486	140
PCK	23.48	6.419	140
TPCK	29.69	7.505	140
CNTK	16.83	3.489	140

The central tendency and dispersion for the eight professional knowledge components, within the framework of TPACK, for a sample (N) of 140 urban mathematics trainee teachers, were presented in Table 8: Descriptive statistics of urban mathematics trainee teachers. The descriptive data showed that the highest mean score was achieved by urban trainees in PK (Mean=38.57), like the other cohorts. This was

followed by CK (Mean=32.37). The lowest average score was recorded for CNTK (Mean=16.83). The integrated knowledge, TPCK, was found to have a mean of 29.69. Notably, the highest standard deviation in PK (SD=8.251) was exhibited by the urban trainees, and high variability was shown in CK (SD=7.789). This suggested greater individual differences in these foundational knowledge areas compared to the rural cohort (referencing Table 6). Conversely, the least variability was shown by the urban trainees' scores for CNTK (SD=3.489). These descriptive findings were considered foundational for conducting independent samples t-tests to formally examine significant differences in knowledge levels between the urban and rural trainee groups.

Table 9. Correlations and Covariance of Urban Mathematics Trainee Teachers

		TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	Correlation	1	.694**	.619**	.617**	.551**	.426**	.578**	.466**
	Covariance	34.410	33.610	28.304	17.621	14.497	16.054	25.468	9.542
PK	Correlation	.694**	1	.835**	.619**	.485**	.613**	.567**	.513**
	Covariance	33.610	68.074	53.635	24.841	17.955	32.458	35.098	14.761
CK	Correlation	.619**	.835**	1	.643**	.558**	.665**	.564**	.513**
	Covariance	28.304	53.635	60.667	24.364	19.502	33.231	32.993	13.942
TPK	Correlation	.617**	.619**	.643**	1	.654**	.635**	.678**	.568**
	Covariance	17.621	24.841	24.364	23.686	14.271	19.847	24.775	9.644
TCK	Correlation	.551**	.485**	.558**	.654**	1	.652**	.731**	.452**
	Covariance	14.497	17.955	19.502	14.271	20.124	18.761	24.618	7.081
PCK	Correlation	.426**	.613**	.665**	.635**	.652**	1	.787**	.588**
	Covariance	16.054	32.458	33.231	19.847	18.761	41.201	37.911	13.176
TPCK	Correlation	.578**	.567**	.564**	.678**	.731**	.787**	1	.762**
	Covariance	25.468	35.098	32.993	24.775	24.618	37.911	56.329	19.954
CNTK	Correlation	.466**	.513**	.513**	.568**	.452**	.588**	.762**	1
	Covariance	9.542	14.761	13.942	9.644	7.081	13.176	19.954	12.172

** . Correlation is significant at the 0.01 level (2-tailed).

The bivariate correlation coefficients and covariance values among key knowledge domains, based on the responses of urban mathematics trainee teachers, are presented in Table 9. All observed correlations were statistically significant at the 0.01 level (2-tailed). Strong, positive interrelationships across all constructs of the TPACK framework were indicated by the results. Notably, the strongest correlation was exhibited by PCK with TPCK ($r=.787$), suggesting that a sophisticated understanding of teaching methods tailored to specific mathematical content was highly predictive of integrated technology use. Furthermore, a robust correlation between CK and PK ($r=.835$) was observed, reinforcing the foundational requirement for content and pedagogy in effective teaching practice. The findings collectively demonstrated that knowledge components were interdependent, particularly highlighting the centrality of TPCK, which was shown to have strong relationships with both its component parts and the crucial construct of CNTK ($r=.762$).

Table 10. Pooled Covariance of Male-Female Mathematics Trainee Teachers

	TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	43.5224	23.4306	20.5866	16.1495	14.1955	12.3321	24.4306	6.0624
PK	23.4306	48.5651	36.5874	20.7816	15.5414	25.0317	32.1677	13.2169
CK	20.5866	36.5874	45.4643	18.9974	15.3692	25.8296	31.3072	12.2957
TPK	16.1495	20.7816	18.9974	20.7728	14.1261	15.9666	26.3169	9.2732
TCK	14.1955	15.5414	15.3692	14.1261	20.3966	13.5500	24.3477	6.8040
PCK	12.3321	25.0317	25.8296	15.9666	13.5500	29.8840	28.3062	12.6493
TPCK	24.4306	32.1677	31.3072	26.3169	24.3477	28.3062	60.7490	17.3758
CNTK	6.0624	13.2169	12.2957	9.2732	6.8040	12.6493	17.3758	12.9332

The pooled covariance matrix calculated for male and female mathematics trainee teachers across eight distinct knowledge domains, including components of TPACK and CNTK, was presented in Table 10. The diagonal entries, which were representative of the variances of the respective knowledge constructs, were found to be substantial. TPCK was demonstrated to have the highest variance (60.7490), followed closely by CK (45.4643). Considerable heterogeneity in the integrated knowledge and content mastery

among the combined sample was suggested. The off-diagonal values indicated that all knowledge domains shared positive covariance, and the strongest interrelationship was observed between PK and CK (36.5874). A strong co-movement and interdependence between these foundational aspects of teacher expertise were reflected. The basis for subsequent multivariate analyses, such as assessing gender differences in the means of these knowledge constructs, was provided by the overall structure of the pooled covariance matrix.

Table 11. Pooled Covariance of Rural Urban Mathematics Trainee Teachers

	TK	PK	CK	TPK	TCK	PCK	TPCK	CNTK
TK	43.7333	23.3349	20.4912	16.3119	14.2199	12.4709	24.5067	6.1097
PK	23.3349	48.6221	36.5892	20.5781	15.5316	24.8401	32.1074	13.1466
CK	20.4912	36.5892	45.3423	18.5986	15.3632	25.4348	31.2025	12.1494
TPK	16.3119	20.5781	18.5986	20.3403	14.1447	15.4982	26.2580	9.0890
TCK	14.2199	15.5316	15.3632	14.1447	20.3990	13.5736	24.3582	6.8097
PCK	12.4709	24.8401	25.4348	15.4982	13.5736	29.3880	28.2464	12.4514
TPCK	24.5067	32.1074	31.2025	26.2580	24.3582	28.2464	60.7463	17.3538
CNTK	6.1097	13.1466	12.1494	9.0890	6.8097	12.4514	17.3538	12.8569

The pooled covariance matrix for mathematics trainee teachers, segmented by rural and urban training locations, across the eight domains of professional knowledge, is reported in Table 11. The diagonal elements, which were representative of the variance of each construct, confirmed significant variability within the sample’s knowledge base. TPCK was found to have the highest variance (60.7463), and substantial individual differences in the integrated application of technology, pedagogy, and content, regardless of the trainee’s setting, were suggested. Across the off-diagonal entries, shared variance and interdependence among all knowledge domains were indicated by the positive covariance values. The strongest co-movement was observed between PK and CK (36.5892), which was consistent with prior literature on teacher expertise. The essential statistical foundation for subsequent multivariate analyses was provided by this pooled matrix structure, specifically for investigating the potential main effects on the development of these core professional knowledge components.

Table 12. MD between Male vs Female and Rural vs Urban

Dichotomous Variable	Male vs Female	Rural vs Urban
MD	0.3417	0.6625

Table 12 presents the calculated Mahalanobis Distance (MD) values used to quantify the overall separation between distinct groups of mathematics trainee teachers based on their professional knowledge profiles. MD is computed by taking the difference between the mean vectors from Tables 2 and 4 and the inverse of the variance-covariance matrix (represented by Table 10). The MD’s calculated value is 0.3417 (< 1). H_{01} was not rejected as a result. Therefore, it can be said that the dynamical character of the knowledge base (TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK) taken into consideration for the current study for male and female mathematics trainee instructors does not significantly differ.

In a comparable manner, Table 11 showed the variance-covariance matrix for trainee maths teachers in rural and urban areas. MD is computed by calculating the difference between mean vectors from Tables 6 and 8, as well as the inverse of the variance-covariance matrix (represented by Table 11). The MD’s calculated value was 0.6625 (< 1). As a result, H_{02} was not rejected. Therefore, it can be said that the dynamical character of the knowledge base (TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK), taken into consideration for the current study for rural and urban mathematics trainee instructors, does not significantly differ.

4. CONCLUSION

This study rigorously investigated the dynamic character of the TPCK knowledge base among mathematics trainee teachers with respect to gender and place of residence. The analysis confirmed the TPCK-Math scale’s high reliability and provided empirical evidence that TPCK operates as a highly integrated, dynamic system, as evidenced by universally strong, significant correlations among all eight knowledge constructs.

Let us recall the objectives and hypotheses. Using the hypotheses H_{01} and H_{02} , our goals were to compare the TPCK knowledge base of trainee teachers of mathematics with regard to gender and place of residence. Given that neither of the two hypotheses could be proven false, it can be said that trainee instructors' gender or place of residence has no bearing on the dynamic character of the knowledge base (TK, PK, CK, TPK, TCK, PCK, CNTK, and TPCK) taken into consideration for this study. The primary conclusions are drawn from the Mahalanobis Distance analysis, which tested the multivariate hypotheses. With calculated MD values of 0.3417 (gender) and 0.6625 (residence), the null hypotheses were not rejected in both cases. The conclusion was reached that neither gender nor place of residence significantly influenced the multivariate, integrated knowledge profile and the dynamic character of the TPCK competence acquired by this cohort of mathematics trainee teachers. The efficacy of standardized teacher education policies in promoting equitable outcomes in integrated technological competence was supported by this finding.

Here are several possible causes for such a non-significant finding in an educational research context:

- **Standardized training program:** The most likely cause is the uniform nature of the teacher training curriculum. If all trainee teachers, regardless of gender or home location, are exposed to the exact same course content, pedagogical methods, technology integration modules, and clinical practice requirements, the training system itself acts as a homogenizing factor, overriding pre-existing differences.
- **High-achieving cohort:** The cohort being studied may consist of highly selective or motivated individuals who, through self-regulation and dedication, converge on a similar high level of professional knowledge. In such a scenario, the influence of demographic factors like gender or residence is minimized by the strong effect of individual effort and entry competence.
- **Insensitive or aggregated measurement:** The assessment instruments used to measure the eight knowledge domains (like TK, PK, CK, TPCK, etc.) might not be sensitive enough to capture subtle, yet real, differences in how knowledge is applied or structured between the groups. Additionally, by analyzing the multivariate (combined) profile, small differences in individual sub-domains might cancel each other out, leading to a non-significant overall finding.
- **Sufficient sample size (statistical power):** While a larger sample size generally increases the ability to detect a difference (power), a lack of significance suggests that even with adequate power, the differences observed (the MD values) are small enough to be attributed to random chance rather than a systematic group effect. The Mahalanobis Distance value is reported, but the associated statistical test (like Hotelling's T^2) likely resulted in a p-value above the significance threshold (e.g., $p > .05$).
- **Focus on integrated knowledge (TPCK):** TPCK is an integrated, high-level construct. It's possible that while gender or residency might affect a single component (like Technical Knowledge, TK, or Pedagogical Knowledge, PK) in isolation, the complex process of integrating all three components (TPCK) is driven more by instructional experiences and reflective practice common to all trainees, rather than by demographic background.

5. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A comprehensive interpretation of the findings requires an acknowledgement of the inherent limitations of the research methodology.

- **Self-report bias and construct overlap:** The reliance on a self-report instrument introduces the potential for inflated self-perceptions, especially given the observed homogeneity. Pre-service teachers often find it challenging to accurately assess their TPCK competence before gaining extensive practical experience in authentic classroom settings. Furthermore, self-reported TPCK scores often overlap significantly with measures of self-efficacy, making it methodologically challenging to isolate pure knowledge assessment from confidence levels.
- **Cross-sectional design constraints:** The use of a cross-sectional design captures the TPCK status at a single endpoint of the training program. This limits the study's capacity to reveal the causal mechanisms, developmental trajectories, or differential rates of growth among the TPCK components over time. Consequently, it is impossible to definitively determine whether the observed demographic homogeneity

was a pre-existing condition upon program entry or the direct, successful outcome of the training intervention itself.

- Contextual specificity: The results are highly specific to the context, curriculum, and policies of the institution where the trainee teachers were prepared. The success in achieving demographic parity may not be generalizable to other education systems, particularly those with less standardized or less technology-intensive teacher preparation mandates. The MD findings reflect a successful institutional override of external demographic differences.

To overcome these limitations and deepen the understanding of TPCK development in mathematics education, future scholarship should pursue advanced methodological approaches.

- Implementing longitudinal development studies: Subsequent research should adopt a longitudinal design to track the development and transactional relationships among TPCK components across the full duration of the teacher preparation program. Longitudinal data would illuminate when and how specific integrated knowledge bases, particularly the weakest areas (TCK and CNTK), evolve. Such research is crucial for identifying optimal intervention timing and curricular sequencing to maximize the growth of integrated technological skills.
- Utilizing authentic and alternative assessment methods: Future studies must move beyond reliance on self-report scales by integrating mixed-methods, incorporating authentic assessment. Methods should include:
 - a. Qualitative case studies: Conducting interviews to capture the complexity of teachers' pedagogical reasoning and decision-making when designing technology-enhanced mathematics lessons, addressing cognitive obstacles that quantitative data cannot reveal.
 - b. Performance-based assessment: Evaluating TPCK enactment through the use of performance tasks, structured observations during student teaching, portfolio analysis, and the assessment of collaboratively designed instructional plans and artifacts.
- Focusing on institutional and dispositional factors: Given the statistical non-significance of gender and residence, future quantitative modeling should shift focus toward identifying the institutional and dispositional factors that demonstrably predict TPCK mastery. Research should explore variables such as trainees' motivation, technological self-efficacy, mentorship quality, type of field experience, and the specific technological tools emphasized in the curriculum, as these contextual variables are likely the true drivers of integrated TPCK proficiency.

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