Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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How to cite: Wen J, Yang C, Bungbua P. Improving TPACK Competence Among Apparel Engineering Educators: A Diagnostic and Strategic Study. Textile & Leather Review. 2025; 8:699-723. https://doi.org/10.31881/TLR.2025.039

How to link: https://doi.org/10.31881/TLR.2025.039

Published: 4 September 2025

Improving TPACK Competence Among Apparel Engineering Educators: A Diagnostic and Strategic Study

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Article

https://doi.org/10.31881/TLR.2025.039

Received 8 July 2025; Accepted 20 August 2025; Published 4 September 2025

ABSTRACT

This study explores the current status of Technological Pedagogical Content Knowledge (TPACK) among apparel engineering teachers in applied undergraduate institutions in Jiangxi, China. A mixed-methods design was employed, integrating questionnaire data (n = 447) and semi-structured interviews (n = 10) to validate a localised TPACK scale and identify key influencing factors. Results show that digital infrastructure and institutional policy support positively impact TPACK competence, especially in technological knowledge and instructional design. Teachers' technology adoption willingness, professional development motivation, and favourable perceptions significantly predicted their TPACK competence. Based on the findings, a five-dimensional enhancement framework is proposed to improve digital teaching capacity. The framework focuses on strengthening technical skills, optimising content design, innovating pedagogy, fostering positive attitudes, and enhancing institutional support. This research contributes to the contextual application of the TPACK framework in technical disciplines and provides practical guidance for improving digital teaching in apparel engineering education.

KEYWORDS

TPACK, apparel engineering, digital transformation, teacher competence, educational technology integration

INTRODUCTION

In the era of accelerated digital transformation, technologies such as virtual reality (VR), artificial intelligence (AI), big data, and cloud computing have been increasingly integrated into all facets of society. These technologies are exerting a profound influence on educational systems worldwide. The integration of these digital tools has dramatically reshaped traditional teaching paradigms, shifting them toward more interactive, flexible, and learner-centred models of instruction [1,2]. Consequently, the ability of teachers to integrate emerging technologies effectively into their pedagogical practices has become a critical factor in ensuring high-quality teaching and learning outcomes in the 21st century [3-6].

Against this evolving educational backdrop, the Technological Pedagogical Content Knowledge (TPACK) framework has emerged as a seminal model for understanding the knowledge base required for effective technology-integrated instruction [6]. First conceptualised by Mishra and Koehler [7], the TPACK model emphasises the intersection of three core knowledge domains: content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK). Effective teaching in digitally enriched environments necessitates not only mastery of these individual domains but also a deep understanding of their dynamic interactions [7,8]. As such, the TPACK framework has become a widely adopted reference, especially concerning digital competence [9-12].

While TPACK research has gained momentum globally, most TPACK-related studies have focused on general education or STEM fields, with relatively limited exploration in applied technical disciplines such as apparel engineering education. In this field, hands-on skills, practice-based instruction, and design thinking are central to curriculum goals. However, a few pioneering studies have begun to address this gap in apparel or design-related education. For example, Hidayat et al. examined factors affecting students' competence in fashion design education using a TPACK lens [13], while Ademtsu and Pathak discussed how curriculum structures influence fashion students' learning effectiveness [14]. Shin and Kim also explored VR-based instruction through a TPACK framework in survival-swimming design contexts [15]. In this field, hands-on skills, practice-based instruction, and design thinking are central to curriculum goals. This neglect presents a significant research gap, as the characteristics of apparel engineering—such as the emphasis on manual dexterity, material manipulation, and aesthetic creativity—pose unique challenges and opportunities for the integration of educational technologies like VR-assisted garment simulation, CAD-based textile design, and 3D printing applications [13]. Without a discipline-specific investigation, generic TPACK models may fail to address the pedagogical realities faced by apparel engineering educators. However, these efforts remain fragmented and insufficient to fully address.

The need for a discipline-specific understanding of TPACK is particularly pressing; the application of the TPACK framework entails unique considerations. For instance, the teaching of CAD-based garment design, textile material science, pattern drafting, and 3D virtual fitting requires the integration of highly technical software tools, domain-specific aesthetic judgment, and hands-on pedagogical strategies. Unlike general education subjects, apparel engineering educators must often bridge gaps between traditional craftsmanship and rapidly evolving digital platforms such as virtual simulation labs, smart manufacturing systems, and AI-assisted fashion trend forecasting. These distinctive features demand a discipline-sensitive TPACK adaptation that reflects not only the integration of technology and pedagogy, but also the creative, procedural, and practice-oriented nature of apparel instruction. Therefore, clarifying how the TPACK dimensions-technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK) manifest in apparel-specific instructional tasks is crucial to both theoretical refinement and pedagogical effectiveness.

Furthermore, recent literature in the field of technical and vocational education on technology integration in technical and vocational education and training (TVET) highlights that disciplinary culture, teacher beliefs, and institutional support systems all play crucial roles in shaping the implementation of digital teaching innovations [16-18]. For instance, Ertmer and colleagues demonstrated that even in resource-rich environments, the successful adoption of educational technology is often hindered by teachers' internal beliefs and attitudes rather than external constraints alone [19,20]. Similarly, Chai et al. emphasised that teachers' TPACK development is not merely the result of training but is closely linked to their motivation, confidence, and school culture [9,21]. These findings suggest that a comprehensive understanding of TPACK must be integrated.

In China, national education reform policies have explicitly promoted, especially in applied undergraduate colleges and universities, the digital transformation of teaching and learning has been explicitly encouraged through national-level policies aimed at enhancing the quality and equity of education [22]. These institutions, which focus on cultivating practice-oriented professionals, are under increasing pressure to modernise curricula and teaching strategies through technological integration. However, studies show that faculty in such institutions often encounter barriers related to technical proficiency, pedagogical innovation, and institutional support systems, which may hinder effective TPACK-based instruction [14,23].

Focusing on apparel engineering educators in Jiangxi Province, China, this study addresses three critical gaps in the current literature: (1) the lack of empirical data on the current state of TPACK competence in this specialised field; (2) the absence of a contextualised model that considers both environmental factors (e.g., digital infrastructure, policy support) and individual psychological dimensions (e.g., professional motivation, technology acceptance); and (3) the need for a discipline-specific enhancement path tailored to the unique pedagogical characteristics of apparel education.

To address these issues, the present study proposes a multidimensional framework for diagnosing and enhancing TPACK competence among apparel engineering teachers. Drawing on validated measurement tools [4,24], this study assess not only the traditional TPACK domains but also incorporate external variables such as digital transformation readiness—comprising infrastructure, resource availability, policy context, and digital management [25]—as well as internal variables such as teachers' willingness to adopt technology, their motivation for professional development, and subjective attitude toward technology integration [19,26,27]. This comprehensive approach aligned with recent findings suggesting that successful TPACK development hinges on a combination of institutional enablers and individual dispositions [10].

Importantly, the study's theoretical contribution lies in adapting the TPACK framework to a TVET-specific context, thereby enriching its applicability across diverse educational settings. An integrated analysis of environmental and psychological factors enhances the validity and interpretability of the findings. By analysing the structural relationships among digital environment variables, teacher cognition, and TPACK outcomes, the study offers actionable insights for curriculum designers, teacher trainers, and policymakers in promoting effective digital pedagogy in apparel engineering education.
Therefore, this study seeks to answer four key research questions:

1. What is the current level of TPACK competence among apparel engineering teachers in applied undergraduate institutions in Jiangxi Province?
2. How does the degree of digital transformation in these institutions influence teachers' TPACK development?
3. To what extent do individual psychological and behavioural factors (i.e., willingness to adopt technology, professional development motivation, subjective attitude) predict TPACK competence?
4. Based on these findings, how can an evidence-based, practical enhancement path be constructed to support TPACK development in apparel engineering education?

Addressing these questions is not only theoretically significant in refining the scope of TPACK research but also practically relevant for supporting teacher professional development in disciplines that are both technically specialised and pedagogically complex. In doing so, this study contributes to the broader goal of advancing digital equity and instructional innovation in higher education across disciplines. Research questions and objectives.

Based on the above research questions, the following hypotheses are proposed:

- H1: Digital transformation (in terms of infrastructure, resources, policy, and management) is positively associated with apparel engineering educators' TPACK competence.
- H2: Teachers' willingness to use technology positively predicts their TPACK competence.
- H3: Teachers' motivation for professional development positively predicts their TPACK competence.
- H4: Teachers' subjective attitude toward technology integration positively predicts their TPACK competence.

RESEARCH DESIGN

Research Methodology

To systematically investigate the current status of TPACK competence and its influencing factors. This study adopted a mixed-methods research design that combines quantitative surveys with qualitative interviews.

The first phase involved administering a structured questionnaire to obtain large-scale quantitative data. This survey aimed to identify the relationship between teachers' overall TPACK competence level and key variables. It covered dimensions of TPACK competence (technological knowledge, pedagogical knowledge, content knowledge, and their integration), the status of digital transformation support, as well as teachers' willingness to apply technology, their motivation for professional development, and their subjective attitudes.

To complement and deepen the quantitative findings, the second phase employed semi-structured interviews on teaching behaviours, their challenges in using technology, and their perceived experience of TPACK competence within the context of digital transformation. The interview guide was designed around three key instructional components: design, methods, and evaluation. Teaching methodology and teaching evaluation. The interview process considered representativeness and diversity, aiming to delve deeper into the rationale behind the questionnaire results.

To analyse the quantitative data collected from the questionnaires, SPSS 26.0 and AMOS 24.0 were utilised for statistical processing. Descriptive statistics were used to summarise participants' TPACK levels and demographic characteristics. Pearson correlation analysis was conducted to examine the relationships among TPACK dimensions, digital transformation variables, and individual psychological factors. Multiple linear regression analyses were employed to identify key predictors of TPACK competence. Additionally, confirmatory factor analysis (CFA) and structural equation modelling (SEM) were applied to validate the reliability and construct validity of the measurement models. All statistical tests adhered to a significance level of $p < 0.05$.

Data collection

Data were collected in two stages, corresponding to the mixed-methods research design. In the first stage, the research team developed and distributed a comprehensive questionnaire covering TPACK competence, institutional digital support, and attitudinal factors. The questionnaire was adapted from established scales, then localised and adjusted to align with the teaching characteristics of the apparel engineering profession. Its reliability and validity were subsequently verified through expert review and pre-testing.

The study population comprised teachers of apparel engineering in several applied undergraduate colleges and universities in Jiangxi Province, China. Sampling was designed to reflect variation in academic rank, teaching experience, and educational background. A total of 447 valid questionnaires were collected, providing a reliable database for subsequent analyses.

In the second stage, in-depth interviews were conducted with a subset of survey respondents. Based on purposive sampling, 10 teachers with varied teaching experience and technical proficiency were selected for face-to-face or online interviews.

To ensure diversity and theoretical representativeness, this study adopted purposive sampling based on questionnaire responses. Specifically, ten participants were selected to reflect varied levels of TPACK competence, teaching experience, academic rank, and prior exposure to digital instructional tools. This approach ensured the inclusion of multiple perspectives relevant to the study’s quantitative dimensions.

The interview protocol was aligned with the core constructs of the questionnaire: instructional design, teaching methods, evaluation strategies, and perceived impact of digital transformation. Each interview lasted approximately 45 to 60 minutes and was conducted either face-to-face or via secure online platforms, depending on the participant’s availability. All sessions were audio-recorded and transcribed verbatim.

To analyse the qualitative data, thematic coding was performed using NVivo 12 software, guided by a deductive coding framework based on the TPACK model. This enabled us to compare and interpret patterns across data sources. The qualitative findings helped explain the nuances behind the survey trends—for example, clarifying why certain teachers scored low in technological knowledge despite institutional support. This alignment between qualitative insights and quantitative results strengthens the explanatory power and contextual depth of this study’s mixed-methods design.

Throughout the data collection process, ethical standards were strictly upheld, ensuring informed consent, anonymity and data confidentiality of the interviewees. The questionnaire data were retrieved and processed electronically, while the interview data were collated and analysed through content analysis to provide qualitative support for constructing the TPACK competence enhancement pathway.

Questionnaire design and validity, and reliability tests

To comprehensively assess the TPACK competence of apparel engineering teachers and the influencing factors, the study employed three sets of instruments: the TPACK Level Scale, the Digital Transformation Research Scale, and the Willingness, Motivation, and Subjective Attitude to Apply Technology Research Scale.

Building on the theoretical foundation of Mishra and Koehler, the TPACK level scale encompasses the three dimensions of instructional design, instructional methodology and instructional evaluation, with a total of 10 indicators [7]. To verify the scale's validity, structural equation modelling (SEM) was employed to conduct a factor analysis. This analysis revealed that the average variance extracted (AVE) of each dimension was significantly higher than 0.5, and the combined reliability (CR) of each dimension also exceeded 0.7. Specifically, the AVE for the instructional design dimension was 0.773, and its CR was 0.931, indicating good convergent validity and internal consistency for the scale. In terms of discriminant validity, the correlation coefficients were less than the square root AVE values, indicating that the dimensions were well discriminated. The model fit indicators were good ($\chi^2/df=1.752$, GFI=0.977, CFI=0.992, RMSEA=0.041). Detailed results are presented in Table 1 (convergent validity), Table 2 (discriminant validity), and Table 3 (model fit indices).

Table 1. Convergent validity of TPACK teaching reform dimensions (n = 447): Results from CFA

Factor	Measurement Term	Std. Estimate	SMC	z	p	AVE Value	CR
Instructional Design	1	0.821	0.674	-	-	0.773	0.931
	2	0.835	0.697	21.898	0		
	3	0.859	0.738	22.912	0		
	4	0.992	0.984	28.293	0		
Teaching Methods	1	0.809	0.655	-	-	0.702	0.876
	2	0.862	0.742	19.18	0		
	3	0.842	0.709	18.914	0		
Teaching Evaluation	1	0.714	0.509	-	-	0.623	0.831
	2	0.811	0.658	14.779	0		
	3	0.838	0.701	14.904	0		

Note: CFA = confirmatory factor analysis; CR = composite reliability; AVE = average variance extracted.

Table 2. Discriminant validity matrix for teaching reform constructs based on TPACK (n = 447)

Constructs	Instructional Design	Teaching Methods	Evaluation of teaching and learning
Instructional Design	0.879		
Teaching Methods	0.333	0.838	
Evaluation of teaching and learning	0.406	0.169	0.789

Note: Square root of AVE values are shown in bold on the diagonal

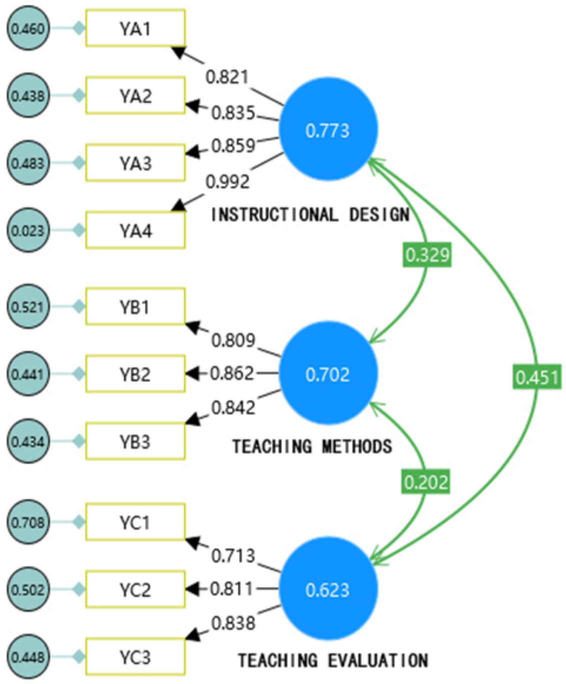

Figure 1. Structural Equation Model of Teaching Practices in the TPACK Framework

Table 3. Model fit indices for the TPACK-based teaching reform measurement model (n = 447)

Commonly used indicators	Criteria for judgement	Observed Value
χ^2	-	56.055
df	-	32
p	>0.05	0.005
χ^2/df	<3	1.752
GFI	>0.9	0.977
RMSEA	<0.10	0.041
RMR	<0.05	0.043
CFI	>0.9	0.992
NFI	>0.9	0.981
NNFI	>0.9	0.988
TLI	>0.9	0.988
AGFI	>0.9	0.96
IFI	>0.9	0.992
PGFI	>0.5	0.568
PNFI	>0.5	0.698
PCFI	>0.5	0.705
SRMR	<0.1	0.028

Note: Acceptable model fit thresholds: RMSEA < 0.08, CFI > 0.90, TLI > 0.90

In addition to the TPACK level scale, the Digital Transformation Research Scale was also validated. It consisted of four dimensions: technical infrastructure, digital resource development, policy support and digital management. The questionnaire items were designed regarding the current digitalisation practices of domestic universities. Validity testing showed that the average variance extracted (AVE) values ranged from 0.592 to 0.670, while the composite reliability (CR) values ranged from 0.811 to 0.890, both exceeding acceptable thresholds for construct reliability. Discriminant validity was also confirmed, and the overall model fit indices were within acceptable ranges (χ^2/df=3.598, GFI=0.922, CFI=0.939, RMSEA=0.076). The discriminant validity results of the Digital Transformation Research Scale are presented in Table 5, and the model fit indices are shown in Table 6.

Table 4. Convergent validity of the "digital transformation" research scale

Factor	Measurement Term	Std. Estimate	SMC	z	p	AVE Value	CR
Technology Infrastructure	1	0.802	0.644	-	-	0.639	0.875
	2	0.886	0.785	20.487	0		
	3	0.85	0.723	19.739	0		
	4	0.637	0.406	13.88	0		
Digital Resource Development	1	0.847	0.717	-	-	0.596	0.855
	2	0.722	0.521	16.189	0		
	3	0.743	0.551	16.768	0		
	4	0.772	0.597	17.58	0		
Policy Support	1	0.877	0.769	-	-	0.67	0.89
	2	0.832	0.692	21.779	0		
	3	0.729	0.531	17.838	0		
	4	0.829	0.688	21.685	0		
Digital Management	1	0.791	0.626	-	-	0.592	0.811
	2	0.857	0.735	14.71	0		
	3	0.643	0.414	12.896	0		

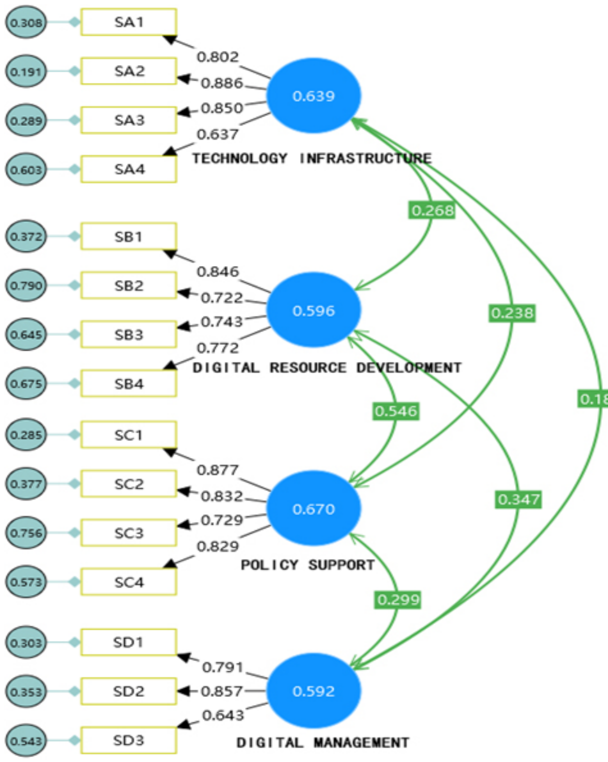

Figure 2. Structural Equation Model of Digital Transformation Factors

Table 5. Discriminant validity matrix for teaching reform constructs based on TPACK (n = 447)

Constructs	Technology Infrastructure	Digital Resource Development	Policy Support	Digital Management
Technology infrastructure	0.800			
Digital resource development	0.257	0.772		
Policy support	0.218	0.474	0.819	
Digital management	0.144	0.294	0.259	0.769

Note: Square root of AVE values are shown in bold on the diagonal

Table 6. Model fit indices for the TPACK-based teaching reform measurement model (n = 447)

Commonly used indicators	Criteria for judgement	Observed Value
χ^2	-	302.221
df	-	84
p	>0.05	0
χ^2/df	<3	3.598
GFI	>0.9	0.922
RMSEA	<0.10	0.076
RMR	<0.05	0.061
CFI	>0.9	0.939
NFI	>0.9	0.918

Commonly used indicators	Criteria for judgement	Observed Value
NNFI	>0.9	0.924
TLI	>0.9	0.924
AGFI	>0.9	0.889
IFI	>0.9	0.939
PGFI	>0.5	0.646
PNFI	>0.5	0.734
PCFI	>0.5	0.751
SRMR	<0.1	0.047

Following the validation of the Digital Transformation Research Scale, the Willingness to Use Technology, Motivation, and Subjective Attitude Research Scale was examined, was examined to assess teachers' psychological dispositions. It measures their willingness to use technology, their drive for professional growth, and their subjective attitude toward technology-integrated teaching and learning, respectively. The average variance extracted (AVE) values for these three dimensions were 0.600, 0.642, and 0.735, respectively, while the composite reliability (CR) values all exceeded 0.8, indicating high internal consistency and construct reliability. The model fit indices also met acceptable thresholds ($\chi^2/df = 3.014$, GFI = 0.958, CFI = 0.975, RMSEA = 0.067). The convergent validity results for the Willingness, Motivation, and Subjective Attitude Scale are presented in Table 7. Table 8 displays the discriminant validity results, and Table 9 presents the model fit indices.

Table 7. Convergent of the research scale "Willingness, motivation and subjective attitude to use technology"

Factor	Measurement Term	Std. Estimate	SMC	z	p	AVE Value	CR
Willingness to	1	0.752	0.565	-	-	0.6	0.818
apply	2	0.827	0.684	15.38	0		
technology	3	0.743	0.551	14.408	0		
Professional	1	0.781	0.609	-	-	0.642	0.843
Development	2	0.779	0.606	15.985	0		
Dynamics	3	0.843	0.711	16.731	0		
	1	0.879	0.772	-	-	0.735	0.917
Subjective	2	0.856	0.733	24.035	0		
Attitude	3	0.853	0.728	23.882	0		
	4	0.841	0.707	23.276	0		

Table 8. Distinguishing the validity of the research scale "Willingness, motivation and subjective attitude to use technology"

Constructs	Technology Infrastructure	Digital Resource Development	Policy Support	Digital Management
Willingness to apply technology	0.775			0.775
Professional Development Dynamics	0.366	0.801		0.366
Subjective Attitude	0.539	0.438	0.857	0.539

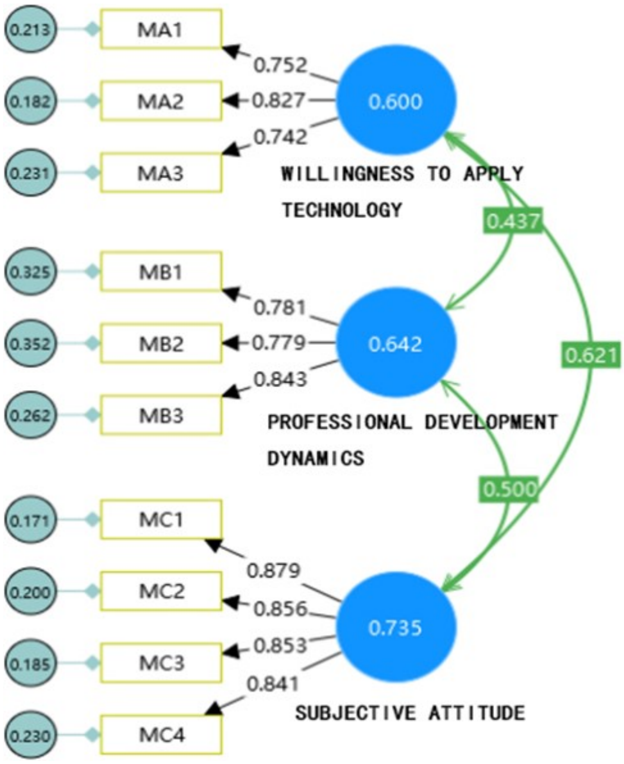

Figure 3. Structural Equation Model of Teachers' Psychological Factors Influencing TPACK Competence

Table 9. Goodness of fit of the research scale "Willingness, motivation and subjective attitude towards technology adoption"

Commonly used indicators	Criteria for judgement	Observed Value
χ^2	-	96.439
df	-	32
p	>0.05	0
χ^2/df	<3	3.014
GFI	>0.9	0.958
RMSEA	<0.10	0.067
RMR	<0.05	0.026
CFI	>0.9	0.975
NFI	>0.9	0.964

Commonly used indicators	Criteria for judgement	Observed Value
NNFI	>0.9	0.965
TLI	>0.9	0.965
AGFI	>0.9	0.928
IFI	>0.9	0.975
PGFI	>0.5	0.558
PNFI	>0.5	0.685
PCFI	>0.5	0.693
SRMR	<0.1	0.037

Therefore, all three types of questionnaires used in this study have good reliability and validity, and can provide robust data support for subsequent data analysis and the construction of TPACK competence enhancement pathways.

RESULTS AND DISCUSSION

The four hypotheses (H1–H4) proposed in the Introduction were tested using Pearson correlation and multiple regression analyses. Each hypothesis is addressed separately below, with corresponding statistical evidence and a clear statement of whether the hypothesis is supported.

Analysis of the current status of TPACK capabilities

Based on the validated measurement scales, this study conducted of the current state of TPACK competence among apparel engineering teachers in applied undergraduate colleges and universities in Jiangxi Province, China, this study conducted a descriptive statistical analysis based on the questionnaire data. The analysis focused on three core dimensions: instructional design, instructional methodology, and instructional evaluation.

The results showed that most teachers demonstrated moderate to high levels of competence across each of the TPACK dimensions. This suggests that teachers generally have a certain degree of IT integration competence, driven by digital transformation. Among the three, instructional design had the highest scores, indicating that teachers are relatively adept at organising course content and developing instructional resources using digital tools. However, scores for instructional methodology and instructional evaluation dimensions were slightly lower, suggesting that while teachers can integrate IT into the curriculum, there is still room for improvement in applying classroom teaching strategies and leveraging data for teaching evaluation and feedback.

Specifically, the instructional design dimension showed AVE=0.773, CR=0.931 for the instructional design dimension, AVE=0.702, CR=0.876 for the instructional methods dimension, and AVE=0.623, CR=0.831 for the instructional evaluation dimension. These statistics suggest an imbalance in TPACK components, highlighting the need for targeted improvements, particularly in teaching strategies and assessment [28].

Moreover, analysis of the mean scores and distribution patterns revealed noticeable individual differences in teachers' TPACK competence. These differences are influenced by variables such as technical proficiency, subject background, and teaching experience, providing a foundation for developing differentiated training strategies.

Therefore, while teachers exhibit an overall moderate to strong TPACK foundation, its structural level remains imperfect. Enhancing competence in teaching methodology and teaching evaluation continues to be a key target area. In subsequent sections, this study will explore the key influencing factors to provide an empirical basis for designing the competence enhancement path.

Analysis of the Impact of Digital Transformation on TPACK Competence

H1 predicts that digital transformation (in terms of infrastructure, resources, policy, and management) is positively associated with apparel engineering educators' TPACK competence. Building on the descriptive results in the previous section, this part further investigates how digital transformation affects TPACK competence among apparel engineering teachers, using Pearson's correlation and multiple linear regression analysis.

Firstly, the correlation analysis results demonstrate that each TPACK dimension has a significant positive correlation with the four dimensions of digital transformation: technology infrastructure, digital resource construction, policy support, and digital management ($p < .01$). For example, the correlation between "technological infrastructure" and "instructional design" was 0.48. Similarly, the correlation coefficient between "digital resource development" and "instructional method" also reaches 0.48, and the correlation coefficient between "digital resources construction" and "teaching methods" is 0.44. These correlations suggest that a robust digital environment can effectively support teachers in integrating technology into instructional design and teaching methods. The correlation analysis between "pedagogical model reform" and "digital transformation" is presented in Table 10. Therefore, H1 is supported. Digital transformation factors, particularly technological infrastructure ($\beta = 0.296$, $p < 0.001$) and policy support ($\beta = 0.243$, $p < 0.01$), show significant positive effects on TPACK competence.

Table 10. Correlations (Pearson’s r, n = 447) between digital transformation and TPACK dimensions

Variables	Reform of the teaching model	Instructional Design	Teaching Methods	Evaluation of teaching and learning
Digital Transformation	0.523***	0.440***	0.394***	0.305***
Technology Infrastructure	0.384***	0.299***	0.290***	0.259***
Digital Resource Development	0.368***	0.313***	0.281***	0.206***
Policy Support	0.370***	0.344***	0.265***	0.185***
Digital Management	0.299***	0.226***	0.242***	0.193***

Note: Pearson’s r, two-tailed test; *p < .05, **p < .01, ***p < .001.

Further regression analyses validated the predictive effect of digital transformation on TPACK competence. A multiple linear regression model was constructed with the composite TPACK score as the dependent variable and the four dimensions of digital transformation—technological infrastructure, digital resource development, policy support, and digital management—as independent variables. The model was statistically significant, $F(4, 442) = 35.67$, $p < .001$, with a coefficient of determination $R^2 = 0.487$, indicating that approximately 48.7% of the variance in TPACK competence could be explained by these four predictors.

Specifically, "technological infrastructure" ($\beta = 0.296$, $p < 0.001$) and "policy support" ($\beta = 0.243$, $p < 0.01$) emerged as the two most significant predictive factors. This indicates that a robust technological environment and strong institutional support play a crucial role in promoting teachers' TPACK competence. In contrast, the regression coefficients for "digital resources construction" and "digital management" were also positive, and while they did not reach statistical significance, they still indicated a positive trend.

The study's findings demonstrate that digital transformation not only equips teachers with the necessary technical conditions and institutional safeguards but also significantly fosters the development of TPACK competence by enriching teaching resources and digitalising the teaching environment. Therefore, based on these findings, enhancing TPACK competence requires not only improving infrastructure and institutional support but also developing digital teaching resources and fostering a supportive professional environment, strengthening the provision of digital teaching resources, improving the policy support system, and cultivating an environment conducive to teachers' continuous professional growth.

Influence of Teachers’ Willingness, Motivation, and Attitude on TPACK Competence

H2 posits that teachers’ willingness to use technology positively predicts their TPACK competence. In addition to external environmental factors like digital transformation conditions, teachers' individual psychological and behavioural variables exert a key influence on the formation and enhancement of their TPACK competencies. This study further analyses the relationship between three types of variables, namely, willingness to use technology, professional development motivation and subjective attitude, and TPACK competence.

Correlation analyses revealed that all three variables were significantly positively correlated with the total TPACK score ($p < .01$). Specifically, the correlation coefficient between "willingness to apply technology" and TPACK competence was 0.524; for "motivation to develop professionally", it was 0.478; and for "subjective attitude" it was 0.563. These findings indicate that positive attitudes and intrinsic motivation at the individual level play a significant role in the development of TPACK competence. H2 posits that teachers' willingness to use technology positively predicts their TPACK competence.

H3 suggests that teachers' motivation for professional development positively predicts their TPACK competence. Further regression analyses corroborated this finding. After controlling for basic variables such as gender, years of teaching experience, and title, willingness to apply technology ($\beta = 0.312$, $p < .001$), motivation to develop professionally ($\beta = 0.271$, $p < .01$), and subjective attitude ($\beta = 0.336$, $p < .001$) demonstrated significant and positive predictive power for TPACK competence. The regression model's R^2 value was 0.537, indicating that these individual motivational variables collectively explained 53.7% of the variance in TPACK competence. Therefore, H3 is supported, confirming that stronger professional development motivation is associated with higher TPACK competence.

H4 proposes that teachers' subjective attitude toward technology integration positively predicts their TPACK competence. Furthermore, subjective attitude, identified as the most influential factor, reflects that teachers' cognitive and affective responses to technology integration are decisive for their behavioural performance. Willingness to apply technology and motivation for professional development, on the other hand, reflect teachers' active acceptance of technology and their aspirations for self-improvement. Thus, H4 is supported, with subjective attitude emerging as the strongest predictor among the three psychological factors.

Based on the above analyses, it can be seen that in addition to the support of the external environment, individual teachers' subjective perception of technology and internal drive have a profound impact on the formation of TPACK competence. Therefore, when formulating strategies to enhance TPACK competence, it is crucial not to overlook guiding and motivating teachers' personal development. This study should stimulate teachers' intrinsic motivation and sense of professional identity by fostering a positive atmosphere, providing growth opportunities, and establishing effective incentive mechanisms. The correlation analysis between "teaching mode reform" and "willingness to apply technology", "professional development motivation" and "subjective attitude" is presented in Table 11.

Table 11. Correlations (Pearson's r, n = 447) between teachers' dispositions and TPACK competence

Variables	Reform of the teaching model	Instructional Design	Teaching Methods	Evaluation of teaching and learning
Willingness to apply technology	0.400***	0.365***	0.236***	0.263***
Professional Development Dynamics	0.452***	0.364***	0.300***	0.332***
Subjective Attitude	0.414***	0.370***	0.279***	0.245***

Note: Pearson's r, two-tailed test; *p < .05, **p < .01, ***p < .001.

Construction of an upgrading path

Based on the identified influencing factors—including both environmental and psychological variables—there is a practical need to design targeted interventions. Therefore, building upon the previous analyses of TPACK competence levels and influencing factors, this section outlines a structured enhancement pathway specifically tailored for apparel engineering teachers. This pathway covers five key aspects: technical proficiency, teaching content, teaching methods, subjective attitude, and supportive environments.

(1) Strategy for upgrading technological capabilities

Strengthening technological competence requires teachers to master essential digital tools in apparel engineering, such as CAD systems, virtual simulation platforms, and intelligent garment design software. Focused training programs should improve teachers' operational fluency and technical adaptability to integrate emerging technologies into practice-based instruction [11,15].

(2) Strategies for deepening teaching content

Teaching content should reflect cutting-edge developments in the apparel industry, including digital fashion design, sustainable textile innovation, and AI-assisted production methods. Course materials must be modernised to embed these topics, while also ensuring alignment with real-world applications and industrial standards to enhance relevance and engagement [9,29].

(3) Innovative Strategies for Teaching Methods

Instructional innovation is a key indicator of TPACK competence. Teachers should be encouraged to adopt diversified teaching methods such as the flipped classroom, project-based learning, virtual simulation experiments, etc., to enhance students' participation and practical ability. Educational organisations, such as carrying out online and offline blended teaching and using a learning management system (LMS) to achieve digital management and assessment of the whole course process [22].

(4) Positive Subjective Attitude Development Strategies

Subjective attitude has turned out to be a key predictor of TPACK competence improvement. Therefore, teachers' professional identity and technological self-confidence should be stimulated through the establishment of a teacher growth community, an experience-sharing platform, and a role model leadership mechanism. Meanwhile, teachers' cognitive and emotional commitment to the value of technology-integrated teaching should be enhanced by establishing awards for TPACK teaching innovations and by incorporating such achievements into performance evaluations and academic promotion criteria [10,30].

(5) Strategies for optimising the support environment

TPACK development depends not only on individual efforts but also on systemic support from institutions, policy frameworks, and societal forces. The school-level digital teaching infrastructure should be improved, and adequate digital resources and technical advisors should be provided. At the policy level, the development of TPACK competence should be incorporated into the teacher training system [31], and clear incentives should be introduced. At the societal level, through the mechanism of industry-education integration, teachers should be provided with opportunities to practice industrial technology, and the integrated development of "teaching-learning-research-application" should be promoted [14]. The social level should provide teachers with opportunities to practice industrial technology through the mechanism of industry-teaching integration, so as to promote the integration of "teaching-learning-research-use" [31].

Therefore, enhancing TPACK competence requires a two-pronged approach: focusing on individual teachers and leveraging external systems. This involves building a comprehensive enhancement pathway centred on technology empowerment and supported by multi-stakeholder collaboration, thereby providing robust support for promoting the transformation and quality improvement of apparel engineering education.

To visually consolidate the proposed enhancement strategy, Figure 4 presents a five-dimensional conceptual framework that highlights the key domains—Pedagogy, Attitude, Environment, Technology, and Content—driving the development of TPACK competence. This visual model serves as a practical guide for designing targeted interventions and institutional support mechanisms in digital teaching reform.

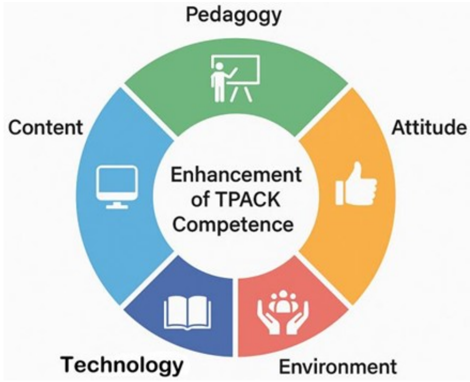

Figure 4. A Five-Dimensional Enhancement Framework for TPACK Competence

In conclusion, this study confirms that apparel engineering teachers generally demonstrate moderate to high levels of TPACK competence, demonstrating strong performance in instructional design but moderate capacity in instructional methods and evaluation. The analysis revealed that digital transformation factors, particularly technological infrastructure and policy support, play a vital role in enhancing TPACK levels. Moreover, teachers' willingness to use technology, motivation for professional development, and subjective attitudes significantly predict their TPACK competence, with attitude having the highest explanatory power.

Theoretically, this research enriches the application of the TPACK framework within the practice-oriented context of apparel engineering, thereby addressing a notable gap in vocational and technical education. It also integrates environmental and motivational variables into the analysis, contributing to a multidimensional understanding of TPACK development.

Practically, the findings provide empirical support for policymakers and educational institutions to implement targeted strategies in teacher training, curriculum innovation, and institutional support systems. The proposed five-dimensional enhancement framework-centred on technology, content, pedagogy, mindset, and environment, can serve as a strategic roadmap for advancing digital teaching competence in apparel engineering education.

CONCLUSION

While this study offers valuable insights, several avenues remain open for future exploration. First, the sample was geographically limited to applied undergraduate institutions in Jiangxi Province, China, which inherently restricts the generalizability of the results. Jiangxi, as a less economically developed region in China, exhibits distinct contextual features such as uneven distribution of digital infrastructure, relatively conservative institutional innovation policies, and varying levels of teachers' digital literacy. These regional characteristics may have influenced the study outcomes, particularly in terms of access to digital resources and readiness for technological adoption. Therefore, future research should consider cross-regional comparisons to explore how diverse local environments shape TPACK competence development; expanding the sample across diverse regions and institution types would yield a more comprehensive understanding. Second, as the research primarily relied on quantitative methods, future work should integrate more qualitative approaches to deeply explore the underlying mechanisms of TPACK development.

Furthermore, emerging educational technologies such as artificial intelligence, big data, and intelligent systems [32] were not fully addressed. Future research could investigate the role of AI-driven tools in shaping TPACK competence [33-35], potentially establishing new frameworks like AI-TPACK to guide digital pedagogy in the era of smart education [23].

Given the increasing integration of emerging technologies such as artificial intelligence (AI), virtual reality (VR), and data-driven learning analytics in technical education, future iterations of the TPACK framework should consider how these tools can be meaningfully embedded in apparel engineering instruction. For example, AI-powered pattern recognition systems, VR-based garment simulation environments, and intelligent tutoring systems offer new modalities for content delivery, student engagement, and performance feedback—each corresponding to distinct components of TPACK. At the same time, these technologies impose new requirements on institutional infrastructure and policy innovation, underscoring the importance of sustainable digital ecosystems. Integrating such tools may not only expand the scope of technological knowledge (TK) but also reshape pedagogical strategies (PK) and content development (CK) in ways previously unattainable.

Although rooted in the context of Jiangxi's applied universities, the proposed five-dimensional enhancement framework demonstrates structural flexibility and potential for broader adaptation. The five-dimensional strategy (technology, content, pedagogy, attitude, and environment) can serve as a flexible scaffold for other applied institutions both within and outside China. For instance, in countries with advanced digital ecosystems, more emphasis may be placed on institutional policies and AI literacy, while in developing regions, foundational digital infrastructure and teacher training may require prioritisation. Cross-national adaptation could also benefit from collaboration among regional education bodies to contextualise practices and refine localised TPACK pathways. While the proposed framework holds promise for broader interdisciplinary and institutional application, its theoretical generalizability across distinct TVET domains still warrants deeper investigation. Technical and vocational disciplines vary significantly in pedagogical focus, from design-centric education in apparel engineering to highly procedural training in mechanical maintenance or civil construction. For instance, while apparel education emphasises creativity and simulation, fields such as welding, CNC machining, or structural engineering demand stringent safety protocols, mechanical precision, and compliance with national occupational standards. These variations may challenge the direct transferability of the TPACK framework, particularly in aligning technological tools with task-specific competencies.

Furthermore, the readiness of faculty and institutional cultures in these domains may differ, necessitating customised professional development approaches. Future research should therefore explore the contextual adaptation of TPACK across diverse TVET domains, identifying both commonalities and structural divergences to enhance its theoretical robustness. Future comparative research across socio-technical contexts can further validate and refine the model's transferability.

Therefore, this study puts forward a five-dimensional framework to enhance TPACK competence among apparel engineering educators, offering practical strategies across technology integration, content modernisation, pedagogical innovation, attitudinal development, and institutional support. While rooted in Jiangxi's applied universities, the framework provides a structured reference for educators and policymakers seeking to promote digital transformation in similar contexts. Future research should explore its application in other TVET disciplines and regions to further refine its effectiveness and scope. Overall, all four hypotheses (H1–H4) were supported by the empirical results, reinforcing the importance of both environmental and psychological factors in enhancing TPACK competence.

Author Contributions

Conceptualisation, methodology, supervision – Yang C, Wen J; Investigation – Wen J, Bungbua P; Resources – Wen J, Yang C; Data curation and visualisation – Wen J, Bungbua P; Writing–original draft – Wen J; Writing–review and editing – Yang C, Bungbua P; Project administration – Yang C. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This paper was financially supported by the Science and Technology Research Project of the Jiangxi Provincial Education Department (CN) (GJJ2402704).

Acknowledgements

The authors thank the support of Rattana Bundit University and Jiangxi Institute of Fashion Technology for providing research resources and institutional facilitation. No IRB approval was required for this study.

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