

Integration of Artificial Intelligence into the TPACK Model: Transforming Teaching in the Digital Age

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Abstract: This study examines the integration of artificial intelligence (AI) into the TPACK (Technological Pedagogical Content Knowledge) model through the validation and reliability analysis of an instrument called TPACK-AI. A quantitative design was used with a sample of 407 university teachers from Mexico, Colombia, and Chile. The results indicate the instrument's high internal consistency (McDonald's $\omega = 0.938$, Cronbach's $\alpha = 0.937$) and reveal perceptual differences of TPACK dimensions among the institutions. Pedagogical knowledge (PK) was the highest-rated dimension. Factor analysis identified two main components: one associated with pedagogical and technological competencies and another related to content integration with technology. AI was highlighted as an enhancer of TPACK by optimizing personalized learning, educational data analysis, and automation of pedagogical processes. The correlations suggest an interdependence among pedagogical, technological, and content knowledge. It is concluded that the TPACK-AI proposal represents an evolution of the traditional framework, integrating AI as a catalyst for innovative teaching based on emerging technologies in higher education.

Keywords: Competencies, Teaching, Artificial Intelligence, TPACK, Higher Education.

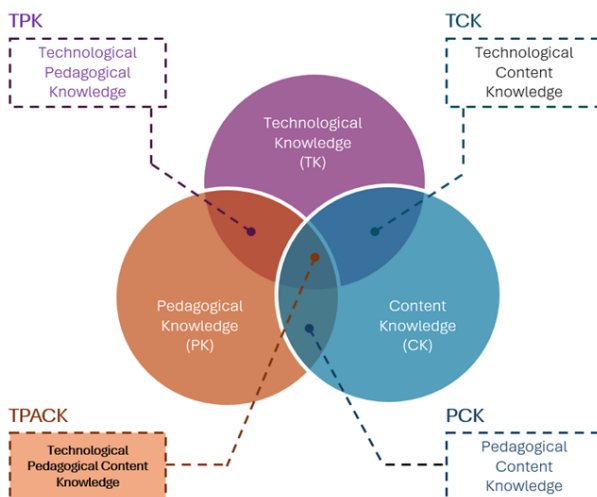
1. Introduction

The TPACK (Technological Pedagogical Content Knowledge) model defines the knowledge teachers need to effectively integrate technology into teaching (Alemán-Saravia & Deroncela-Acosta, 2021; Niess, 2011). Developed by Mishra and Koehler, this model incorporates the concept of Pedagogical Content Knowledge (PCK) and includes the technological component in the training processes (Mishra & Koehler, 2006). The model highlights the importance of understanding the interactions of technological tools, content, and pedagogical strategies (Class, 2024), recognizing

that the isolated use of technology does not ensure better learning outcomes (Aquino et al., 2022; Fahadi & Khan, 2022).

The TPACK's structure comprises three basic types of knowledge: Content (CK), Pedagogical (PK), and Technological (TK), and includes intermediate combinations: Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK). The intersection of these elements forms the core of the TPACK model, facilitating the design of effective learning experiences using technology (Pazilah, Hashim & Yunus, 2024; Zhang, 2021), as illustrated in Figure 1.

Figure 1: TPACK Model.



Source: Mishra and Koehler (2006).

TCK allows for examining how technology influences content understanding and teaching. For example, Kong and Lai (2022) demonstrated that block-based programming environments improve computational thinking and strengthen abstraction and problem-solving by visualizing logical processes. Similarly, virtual reality facilitates understanding complex concepts by offering immersive experiences that are difficult to replicate in a traditional classroom (Larsen, 2023). On the other hand, TPK permits exploring how technology transforms teaching strategies (Belda-Medina & Calvo-Ferrer, 2022), including collaborative online learning through digital platforms and virtual environments, which encourage asynchronous and synchronous interactions, promoting the construction of knowledge (Gómez-Trigueros, 2025; Kamid et al., 2021).

PCK allows for adapting teaching strategies to make content accessible and meaningful (Kaplon-Schilis & Lyublinskaya, 2020). It emphasizes understanding how to effectively teach a topic, beyond the subject's domain (Nithitakkharanon & Nuangchalerm, 2022). For example, a high-level PCK instruction might employ storytelling and character analysis to develop reading comprehension skills (Nurwahidah, Sulfasyah & Rukli, 2023). The effective integration of PCK, TCK, and TPK structures the TPACK model, which allows teachers to use technology thoughtfully to improve content and pedagogical strategies (Yang & Dong, 2024). This fundamental model is presented as a framework for assessing teachers' technological competencies in different approaches: training,

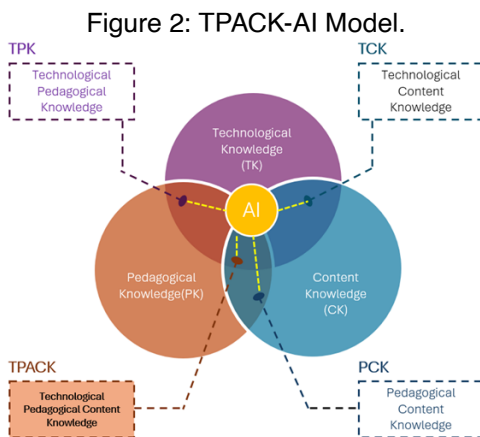
teaching mathematics, and the design of teaching materials (Miguel-Revilla, Martínez-Ferreira & Sánchez-Agustí, 2020; Othman & Maat, 2020; Syamdianita & Cahyono, 2021).

The TPACK model has been adapted to modern educational contexts (Gómez-Trigueros & Yáñez de Aldecoa, 2021; Greenwood, 2023), addressing data literacy, data science, and the implementation of emerging technologies such as mobile devices, educational platforms, immersive environments, and Artificial Intelligence (AI) (Cui & Zhang, 2022; Feldman-Maggor, Blonder & Alexandron, 2025; Hazzan & Mike, 2023). AI can transform the model by expanding its elementary dimensions (content, pedagogy, technology), personalizing learning, and developing digital competencies in teacher training (Gonzales & Gonzales, 2021).

This article explores the integration of AI into the TPACK model. It introduces the TPACK-AI instrument, which was designed to measure teacher competency in incorporating and applying AI in educational practices. The guiding research question was: How can integrating AI into the TPACK model be effectively measured to assess emerging digital competencies in teaching?

2. Methodology

AI can be integrated into the TPACK model by designing a questionnaire that more accurately assesses the interaction of technology, pedagogy, and content in teaching (Al-Abdullatif, 2024). AI redefines the model's dimensions to address the challenges and opportunities advanced technology offers (Hava & Babayiğit, 2025; Zulianti et al., 2025). Each TPACK dimension can be redefined to show how AI enriches teaching, learning, and assessment (Tram, 2024). For example, TCK can incorporate AI applications that present content dynamically, while PCK can employ student performance data analysis to adjust pedagogical strategies to support learning. Finally, TPK can integrate AI assistants and adaptive learning tools to optimize teaching (Ning et al., 2024). Thus, the TPACK model is reconfigured with AI to catalyze synergy among its components, allowing teachers to combine technology, pedagogy, and content (Karataş & Ataç, 2025; Mishra & Koehler, 2006), leveraging data analytics, personalization, and dynamic interactions (Runge, Hebibi & Lazarides, 2025). Figure 2 illustrates the integration of AI into the TPACK model.



Source: Own elaboration.

2.1. Instrument Development

The TPACK-AI model entails the integration of key AI indicators, such as interpreting learning analytics, designing personalized teaching, and using AI to solve problems in the classroom (Celik, 2023; Celik & Dogan, 2025). To guarantee the instrument’s validity, ten expert researchers in educational innovation elaborated the instrument. They came from Latin American and European universities: Tecnológico de Monterrey (Mexico), Universidad de la Guajira (Colombia), Universidad Bolivariana del Ecuador (Ecuador), Universidad San Carlos (Guatemala), Universidad de Helsinki (Finland), Universidad de Córdoba (Spain), and Universidad de la Coruña (Spain). This group of experts comprised four men and six women, all with a doctorate and extensive scientific production in educational innovation.

Involving researchers from different academic institutions with extensive experience provided a comprehensive and multifaceted perspective on the instrument’s effectiveness and applicability. They contributed to the design, development, and validation of the TPACK AI questionnaire. After producing a first draft of the dimensions associated with the TPACK with AI, they made the necessary adjustments, which led to the creation of the final version of the self-assessment instrument. The validation method involved computing Aiken’s V coefficient, obtaining a score of 0.8692, which is considered very high (Merino-Soto, 2023).

For item purification, we adopted an a priori defined multicriteria approach. Following expert content validation (Aiken’s $V \geq .80$), the EFA retained items with primary loadings $\geq .40$, communalities $\geq .30$, and corrected item–total correlations $\geq .30$. Items with cross-loadings $\geq .30$ were discarded, and a minimum gap of .20 between the primary loading and any secondary loading was required. Items failing to meet two or more of these criteria were considered candidates for removal. Final decisions balanced psychometric evidence with conceptual coverage in order to preserve the theoretical breadth of each dimension of the TPACK-AI model. Table 1 details the evolution of the traditional TPACK dimensions and their transformation by incorporating AI.

Table 1: TPACK and TPACK-AI.

Dimension	Traditional TPACK	TPACK with AI
Technological Knowledge (TK)	Understanding basic technological tools (digital whiteboards, educational software, etc.).	Proficiency in advanced AI tools, such as generative AI learning analytics, intelligent tutoring systems, and chatbots.
Content Knowledge (CK)	Mastery of discipline-specific concepts, theories, and principles.	Use AI to access up-to-date content, generate personalized materials, and create interactive simulations.
Pedagogical Knowledge (PK)	Teaching strategies based on traditional pedagogical theories (constructivism, collaborative learning, etc.).	Incorporating AI-generated data to tailor pedagogical strategies to individual student needs.
Technological Content Knowledge (TCK)	Use of technological tools to teach specific content (science simulators).	Integrating AI tools such as natural language systems, augmented reality, and simulators to explore complex concepts.
Pedagogical Content Knowledge (PCK)	Design of specific pedagogical strategies for the content to be taught.	Using AI to analyze evidence-based, real-time performance data and adjust pedagogical strategies.
Technological Pedagogical Knowledge (TPK)	Use of technologies to improve interaction and pedagogical dynamics in the classroom.	Deploying AI to personalize learning, encourage engagement, and automate the evaluation of progress.
Technological Pedagogical Knowledge of Content (TPACK)	Balanced integration of content, pedagogy, and technology in teaching.	Advanced synergy of content, pedagogy, and AI-powered technology to personalize and optimize learning.

2.2. Instrument

The TPACK-AI questionnaire, with 42 items on a 4-point Likert scale (1=Strongly Disagree; 4=Strongly Agree), assesses the integration of AI in teaching practice in the seven dimensions of the TPACK model. The items analyze the mastery of AI algorithms, AI-based pedagogical strategies, the use of intelligent tools (adaptive platforms, virtual assistants), the ability of teachers to select and apply AI based on educational content and context, and the willingness to integrate AI into active methodologies (problem-based learning and personalized teaching). The instrument's validation was affirmed by Aiken's V coefficient of 0.963. Table 2 presents the items reformulated for the integration of AI.

Table 2: TPACK-AI Questionnaire.

TPACK Dimension	AI-related item
Content Knowledge (CK)	1.1. I know how to solve technical problems using artificial intelligence tools.
	1.2. I assimilate technological knowledge easily, including the use of generative artificial intelligence.
	1.3. I keep current with new technologies and trends in artificial intelligence.
	1.4. I often experiment and test with AI technologies to explore their potential.
	1.5. I know many different technologies, including artificial intelligence platforms.
	1.6. I have the technical knowledge to use artificial intelligence effectively.
	1.7. I have had sufficient opportunities to work with artificial intelligence technologies in various educational contexts.
Pedagogical Knowledge (PK)	2.1. I have sufficient knowledge about the subject(s) I teach, and how artificial intelligence can enrich them.
	2.2. I employ several methods and strategies to develop my knowledge to use artificial intelligence in my teaching.
Technological Knowledge (TK)	3.1. I know how to assess student performance using AI-powered tools.
	3.2. I know how to adapt my teaching in real time based on the personalized recommendations generated by artificial intelligence.
	3.3. I can adapt my teaching style to benefit students with different learning styles, using content created with artificial intelligence.
	3.4. I know how to evaluate student learning by integrating products or creating activities supported by artificial intelligence.
	3.5. I use a wide variety of teaching approaches, incorporating artificial intelligence as a pedagogical resource.
	3.6. I know the most common successes and mistakes of students interacting with artificial intelligence tools.
	3.7. I know how to organize, manage, and maintain classroom dynamics using artificial intelligence in activities.
Pedagogical Content Knowledge (PCK)	4.1. I can select different teaching approaches incorporating artificial intelligence to promote students' thinking and learning about subject(s).
Technological Content Knowledge (TCK)	5.1. I know artificial intelligence technologies that I can use to understand and develop subject content.
Technological Pedagogical Knowledge (TPK)	6.1. I know how to select artificial intelligence technologies that improve teaching approaches for specific lessons.
	6.2. I can select artificial intelligence technologies that enhance student learning in a lesson.
	6.3. My training as a teacher has made me reflect more carefully on how artificial intelligence influences teaching approaches in the classroom.
	6.4. I use critical thinking to consider how to use artificial intelligence in the classroom.
	6.5. I can adapt the use of artificial intelligence technologies to different teaching activities and student needs.
Technological Pedagogical Knowledge of Content (TPACK)	7.1. I can construct lessons that properly integrate the subject(s), AI technologies, and teaching approaches.
	7.2. I know how to select artificial intelligence technologies to improve the content I teach in the classroom, how it is taught, and what the students learn.
	7.3. I know how to use strategies in my classroom teaching subjects that combine content, artificial intelligence technologies, and teaching approaches that I have learned.
	7.4. I can guide and help others coordinate the use of content, AI technologies, and teaching approaches in my school and/or administrative region.
	7.5. I can select AI technologies that enrich lesson content and potentiate their educational impact.

2.3. Study Participants and Procedure

The sample included 407 professors from three Latin American universities in Mexico, Colombia, and Chile. Participants were selected through non-probabilistic convenience sampling, ensuring diversity of discipline and educational levels. Of the total, 55% were women and 45% were men, with an average age of 42 years (SD =

8.7) and 15 years of teaching experience (SD = 6.2). All participants possessed basic knowledge regarding using digital tools in teaching, but only 60% had received specific training in AI applied to education. Before the application, a pilot study was conducted with 50 teachers to evaluate the items' clarity, adjust the wording, if necessary, and improve its accuracy; To ensure the procedure's validity, controls were implemented in data collection, such as eliminating incomplete or inconsistent responses and verifying the uniqueness of each participation. The TPACK-AI questionnaire was applied virtually online, allowing participation without geographical hindrances. Data collection began in November 2024 and lasted three weeks.

2.4. Ethics

Data collection was carried out with the participants' informed consent and was approved by the Ethics Committee of Universidad Bolivariana del Ecuador (UBE) (approval code: UBE-2025-001). The process was supervised by the Women in Smart Education: Complexity & AI Literacy Hub (WISE-AI) research group. All data were protected in accordance with applicable regulations on the protection of personal data. The study was supported by the Vicerrectoría de Investigación y Vinculación Social.

2.5. Data Analysis

Statistical analysis using MINITAB 21.1.0 and JASP 0.19.0 evaluated the instrument's reliability. An internal consistency analysis was performed with McDonald's ω and Cronbach's α coefficients; frequency scale reliability statistics assessed the average correlation between items and determined instrument homogeneity, and an individual reliability analysis by dimension examined the impact on internal consistency of eliminating each dimension. In addition, a principal component analysis identified the underlying factors in the questionnaire structure, an exploratory factor analysis determined the clusterings of the dimensions and validated the structure of the TPACK-AI model, and finally, a confirmatory factor analysis assessed the fit of the model and confirmed the validity of the dimensions evaluated.

3. Results

The preliminary analysis shows consistency in the means among the three universities. Table 3 indicates that the PK attained the highest mean in all institutions, highlighting the University of Bío-Bío (UBB) with an average of 3.57. In contrast, the CK presented slightly lower values of 3.20 in UBB and 3.11 in the Bolivarian University of Ecuador (UBE), revealing differences in perceptions of the disciplinary content. The standard error of the mean was low in all dimensions, ranging from 0.031 to 0.088, indicating accuracy in the calculations of the means, and the standard deviation (0.520-0.748) exposed moderate variability, suggesting that perceptions among participants were relatively consistent, although with slight variations among the universities. The Universidad San Carlos (USC) had higher means and less dispersion than the other institutions, pointing to more homogeneity in the perceptions of the competencies achieved with the TPACK-AI model. On the other hand, the UBE varied in most dimensions with a standard deviation of 0.748 for PCK and 0.705 for TCK, which can mean pronounced differences in the perception of integrated knowledge.

Table 3: Descriptive Analysis.

Dimension	University	Mean	Standard error of the mean	Standard Deviation
CK	Universidad del Bio-Bio	3.204	0.079	0.627
	Universidad San Carlos	3.162	0.032	0.581
	Universidad Bolivariana del Ecuador	3.113	0.060	0.602
PK	Universidad del Bio-Bio	3.571	0.071	0.567
	Universidad San Carlos	3.520	0.035	0.631
	Universidad Bolivariana del Ecuador	3.455	0.072	0.725
TK	Universidad del Bio-Bio	3.288	0.078	0.620
	Universidad San Carlos	3.556	0.031	0.563
	Universidad Bolivariana del Ecuador	3.464	0.064	0.646
PCK	Universidad del Bio-Bio	3.206	0.088	0.699
	Universidad San Carlos	3.474	0.036	0.655
	Universidad Bolivariana del Ecuador	3.386	0.074	0.748
TCK	Universidad del Bio-Bio	3.286	0.083	0.658
	Universidad San Carlos	3.295	0.040	0.719
	Universidad Bolivariana del Ecuador	3.228	0.070	0.705
TPK	Universidad del Bio-Bio	3.321	0.066	0.520
	Universidad San Carlos	3.462	0.032	0.584
	Universidad Bolivariana del Ecuador	3.426	0.063	0.629
TPACK	Universidad del Bio-Bio	3.206	0.083	0.655
	Universidad San Carlos	3.404	0.035	0.624
	Universidad Bolivariana del Ecuador	3.358	0.068	0.685

3.1. Reliability Analysis

The instrument’s internal consistency was evaluated by calculating McDonald’s ω and Cronbach’s α and the average correlation between the items. The McDonald’s coefficient ω was 0.938, with a confidence interval between 0.929 and 0.946, indicating an excellent instrument reliability, given its value close to 1. The confidence interval limits show low variability and high measurement accuracy. Similarly, Cronbach’s coefficient α was 0.937, with a confidence interval between 0.927 and 0.945. The similarity between McDonald’s ω and Cronbach’s values α confirms the homogeneity of the items evaluated. The average correlation between the items was 0.685, with a confidence range between 0.632 and 0.728. This high average correlation value suggests strong positive correlations between the items, indicating that they consistently measure the same construct. Overall, the results reveal excellent internal consistency, with high and stable values in all three reliability indicators.

Table 4 presents the reliability analysis of each dimension. McDonald’s ω and Cronbach’s α coefficients were high, ranging from 0.918 to 0.936, showing that eliminating any dimension would not significantly compromise the internal consistency of the questionnaire. The dimension with the highest reliability was CK (0.936), while TPK showed the lowest (0.918), although both are excellent values. The corrected item-total correlation showed high values in TPK (0.902) and TPACK (0.864), which indicates that these dimensions are highly aligned with the others in the scale and contribute significantly to measuring the overall construct. The means ranged from 3.157 (CK) to 3.513 (PK), and the standard deviations ranged from 0.587 (TPK) to 0.708 (TCK). The data indicate moderate response variability, with mean values consistently above 3 on a 4-point scale, suggesting generally positive perceptions across all dimensions assessed.

Table 4: Reliability Statistics for Individual Dimensions.

Dimension	If a dimension is deleted		Correlation between the element and the rest	Mean	Standard deviation
	McDonald's ω	Cronbach's α			
CK	0.936	0.936	0.692	3.157	0.591
PK	0.933	0.931	0.750	3.513	0.644
TK	0.923	0.922	0.855	3.502	0.594
PCK	0.930	0.929	0.772	3.421	0.685
TCK	0.934	0.932	0.750	3.280	0.708
TPK	0.918	0.918	0.902	3.436	0.587
TPACK	0.922	0.920	0.864	3.369	0.643

3.2. Principal Component Analysis

The Bartlett Sphericity Test ($X^2 = 3155.856$, $gl = 21$, $p < .001$) confirmed the statistical significance of the correlations between the dimensions evaluated. The significant result ($p < .001$) suggests a solid correlation structure, justifying the performance of a factor analysis in the study. This is consistent with the theoretical assumptions of the model, indicating that the dimensions share relationships and can be analyzed together to understand their influence on teaching competencies. Also, the Chi-square Test ($X^2 = 443.202$, $gl = 3$, $p < .001$) revealed a statistically significant difference between the observed covariance matrix and the expected matrix under an independence model.

Table 5 shows the load coefficients of each dimension in the two main components (RC1 and RC2), along with their uniqueness values. The Promax rotation was applied, an oblique method that allows correlation between factors. The RC1 component showed a strong association with the dimensions PCK (0.961), TK (0.956), and PK (0.860). These high values indicate that the first component mainly shows pedagogical and technological competencies of the TPACK-AI model, with a high variance explained by these dimensions. The coefficients' consistency supports the TPACK model's theoretical structure, demonstrating teachers' knowledge about technological integration in education. The RC2 component was associated with the content dimensions, highlighting CK (1.056), TCK (0.781), and TPACK (0.614), which reveals that this component captures the content dimension and its integration with technology, aligning with the use of technological tools to enhance teaching. The TPK dimension presented a balanced distribution between both factors (RC1 = 0.479; RC2 = 0.531), reflecting its influence both in the pedagogical-technological field and in the connection between content and technology. Low uniqueness values indicate that the items are well represented by the two extracted components.

Table 5: Component loads.

Dimension	RC1	RC2	Uniqueness
PCK	0.961		0.176
TK	0.956		0.092
PK	0.860		0.252
TPK	0.479	0.531	0.123
CK		1.056	0.153
TCK		0.781	0.249
TPACK		0.614	0.158

Note: The rotation method applied was Promax.

3.3. Exploratory Factor Analysis

Table 6 presents the load coefficients of each dimension of the TPACK-AI instrument in two main factors (Factor 1 and Factor 2), together with the uniqueness values. Factor 1 showed the highest loads in the dimensions TK (1.075), PCK (0.746), and PK (0.659). This indicates that this factor is strongly associated with technological and pedagogical competencies, explaining a considerable proportion of the variance of the dimensions. The load greater than 1.0 in TK suggests a dominant contribution in the factorial structure, which reflects an overlap or redundancy between the technological and pedagogical dimensions, being a point of attention for future instrument revisions. Factor 2 had the highest factor loads in the dimensions associated with content and its technological integration, highlighting CK (0.878), TCK (0.721), and TPACK (0.734).

These values show that this component is associated with the conceptual mastery of the contents and their presentation through technological tools. The high factor loads indicate a good correspondence between the items and the theoretical structure of the TPACK-AI model. The TPK dimension (0.664) showed a balanced factorial load between pedagogical and technological competencies, highlighting the integrating role of Pedagogical Technological Knowledge. The uniqueness values reflect the proportion of variance not explained by the extracted factors. Low values, such as in TK (0.003) and TPK (0.116), indicate that these dimensions are well explained by the factors identified.

Regarding the potential cross-loadings in TPK we conducted a focused review during the EFA and retained only items with a primary loading $\geq .40$, secondary loadings $< .30$, and a gap $\geq .20$ from the primary loading, thus meeting the predefined retention criteria. The observed secondary associations are consistent with the conceptual proximity of TPK to TCK and TPACK, without indicating overlaps that would compromise the factor's interpretation. In the CFA, the retained items showed standardized loadings $\geq .50$, and the model achieved good overall fit, supporting the factorial discrimination of TPK in the instrument.

Table 6: Factor Loads.

Dimension	Factor 1	Factor 2	Uniqueness
TK	1.075		0.003
PCK	0.746		0.304
PK	0.659		0.370
CK		0.878	0.365
TPACK		0.734	0.164
TCK		0.721	0.354
TPK		0.664	0.116

Note: The rotation method applied was Promax.

3.3.1. Confirmatory factor analysis

Previo a la AFC establecimos umbrales de evaluación: cargas estandarizadas $\geq .50$ (preferentemente $\geq .60$); ajuste global con CFI/TLI $\geq .90$ (idealmente $\geq .95$), RMSEA $\leq .08$ con IC90% que incluya $\leq .08$ y SRMR $\leq .08$. Asimismo, verificamos validez convergente y confiabilidad compuesta mediante AVE $\geq .50$ y CR $\geq .70$. Estos criterios guiaron la interpretación del modelo y la retención final de los indicadores en cada factor del TPACK-AI.

Table 7 shows the relationship between the indicators of the TPACK-AI model and the identified latent factors, evaluating the consistency and strength of these associations. Factor 1, which groups the dimensions TK, CK, and PK, had statistically significant factor loads with values between 0.406 (CK) and 0.543 (TK). All relationships presented p-values less than 0.001, demonstrating a strong association between these items and the first factor. The 95% confidence intervals were relatively narrow, reflecting accuracy and stability in the estimates. TK, with values between 0.501 and 0.584, displayed a solid and well-defined effect on the factor. However, the CK item, with a factor load of 0.406, had a lower correlation with the factor, suggesting the need to revise its formulation. Factor 2, which groups PCK, TCK, TPK, and TPACK, had higher factor loads than the first component, ranging from 0.547 (PCK) to 0.587 (TPACK), with significance levels equally high ($p < .001$). The narrow and precise confidence intervals (TPACK: 0.543 to 0.631) reinforced the stability of the estimates.

Table 7: Factor Loads.

Factor	Indicator	Estimate	Std. Error	z-value	P	95% Confidence Interval	
						Lower	Upper
1	TK	0.543	0.021	25.382	< .001	0.501	0.584
	CK	0.406	0.025	16.317	< .001	0.357	0.455
	PK	0.529	0.025	21.444	< .001	0.481	0.577
2	PCK	0.547	0.026	21.018	< .001	0.496	0.598
	TCK	0.551	0.027	20.335	< .001	0.498	0.604
	TPK	0.559	0.020	28.264	< .001	0.520	0.598
	TPACK	0.587	0.022	26.199	< .001	0.543	0.631

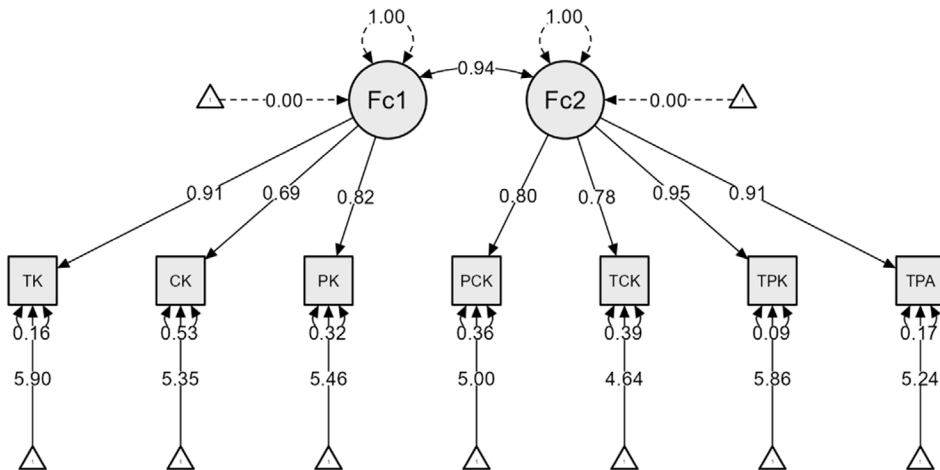
Figure 3 illustrates the relationship between two latent factors, Fc1 and Fc2, and their respective dimensions within the TPACK-AI model. The factors, represented by circles, indicate latent variables that explain the relationships between the observed indicators. In contrast, the rectangles, labeled as TK, CK, PK, PCK, TCK, TPK, and TPA, represent the dimensions. The Fc1 factor showed stronger correlations with the TK (0.91), CK (0.69), and PK dimensions (0.82). These standardized load coefficients show significant relationships, demonstrating that Fc1 captures the model's fundamental technological and pedagogical competencies. The high TK load suggests that this factor relates to technological capability, while the CK and PK loads reflect a more moderate mastery of content and pedagogical knowledge. This pattern confirms that basic technological and pedagogical competencies are the basis of the TPACK-AI model, on which more complex competencies are developed.

The Fc2 factor was mainly associated with the dimensions PCK (0.80), TCK (0.78), TPK (0.95), and TPA (0.91). The high factor loads indicate a strong association between this factor and the indicators of advanced knowledge integration, suggesting that Fc2 represents a higher level of competence integration, where technological, pedagogical, and content knowledge are synergistically combined. The highest load in TPK (0.95) highlights its link with the use of technology in pedagogical contexts. In addition, the high correlation (0.94) between the Fc1 and Fc2 factors externalizes the integrative nature of the TPACK-AI model, where core competencies are key to achieving advanced integration of knowledge.

Figure 4 presents the matrix of correlations between the dimensions of the TPACK-AI model, where numerical values are the correlation coefficients between each pair

of dimensions, and darker tones in the cells indicate strong correlations—the low to moderate correlations present significant, but not redundant, relationships between the dimensions. Note the close connection between TCK and CK (0.14), revealing the link between content knowledge and its technological application. Moderate correlations are also seen between TK and PCK (0.13) and between CK and TPACK (0.12). These pairings highlight the connection between content knowledge and the effective integration of technology into pedagogy. In contrast, the lowest correlations were observed between TPK and TPACK (0.01) and between PCK and TPACK (0.02), which could reflect a lower influence of these dimensions on the overall construct.

Figure 3: TPACK-AI Model Plot.



Source: Own elaboration.

Figure 4: TPACK-AI Model Matrix Plot.

	TK	CK	PK	PCK	TCK	TPK	TPACK
TK	0						
CK	.08	0					
PK	.05	.01	0				
PCK	.13	.04	.04	0			
TCK	.04	.14	.03	.03	0		
TPK	.01	.08	.05	.02	.01	0	
TPACK	.03	.12	.07	.02	0	.01	0

Source: own elaboration.

4. Discussion

The TPACK-AI model expands the traditional framework by integrating Artificial Intelligence (AI), optimizing the interaction between pedagogical, technological, and

content knowledge. The results indicate that Pedagogical Knowledge (PK) persists as the strongest dimension, and the effectiveness of AI depends on its integration into well-founded teaching strategies (Kaplon-Schilis & Lyublinskaya, 2020). However, the lower perception of Content Knowledge (CK) in various academic contexts points to the need to strengthen disciplinary training in the integration of AI. Niess (2011) argues that effective technological integration requires a deep understanding of the content. Therefore, teacher education programs must balance pedagogical and disciplinary development, ensuring that AI complements, not replaces, content knowledge (Luik et al., 2024). The variability found at the Bolivarian University of Ecuador suggests that contexts with less technological infrastructure can generate heterogeneous perceptions of digital skills, which may demonstrate that the implementation of AI also produces inequalities in technological adoption (Crompton & Burke, 2023).

The findings reaffirm the applicability of the TPACK-AI model as a framework for assessing teacher readiness in digital environments. The high internal consistency of the instrument (McDonald's $\omega = 0.938$ and Cronbach's $\alpha = 0.937$) confirms its reliability. According to Mishra and Koehler (2006), effective teaching with technology depends on the balanced interaction of knowledge, which supports the integration of AI into the TPACK model. The high correlations between the items demonstrate that the model's dimensions are well defined, supporting the role of AI as a key component to strengthen technological competence and technological-pedagogical knowledge (Chauke et al., 2024). The measurement of emerging digital competencies through the TPACK-AI model helps identify areas for improvement in teacher training, promoting professional development that aligns with the demands of the digital age.

Principal component analysis and exploratory factor analysis corroborate the theoretical structure of the TPACK-AI model, demonstrating its effectiveness in assessing emerging digital competencies in teaching. The strength of the correlations in the Bartlett Sphericity Test and the fit of the factor model support the existence of two main factors: the RC1/Factor 1 Component, which groups pedagogical and technological competencies, and the RC2/Factor 2 Component, which incorporates the content dimensions and their technological integration. This reveals that AI effectively organizes and measures teacher knowledge. In this sense, Cui and Zhang (2022) highlight that data literacy is key to teaching with AI, emphasizing its impact on teaching methodology rather than content.

Employing AI as a catalyst to measure these competencies allows for a more accurate assessment in digital educational environments. The distribution of factor loads reflects that Technological Pedagogical Knowledge (TPK) is a bridge between pedagogical competencies and the integration of emerging technologies, confirming the importance of this interrelationship for teacher professional development, as Mishra and Koehler (2006) proposed. The high factor load of Technological Knowledge (TK) in Factor 1 and RC1 Component ratifies its importance in configuring digital competencies in teaching. In this regard, Gómez-Trigueros (2025) points out that digital self-efficacy influences technological integration, which explains the greater factor load of TK. The low uniqueness in key dimensions such as TK and TPK supports the validity of the TPACK-AI model, confirming its effectiveness in measuring emerging digital competencies and better understanding technological integration in teaching practices.

The confirmatory factor analysis shows that integrating AI in the TPACK (TPACK-AI) model accurately measures emerging digital competencies in teaching. Two latent

factors were identified: Factor 1, which groups TK, CK, and PK, presents significant factor loads (0.406 - 0.543, $p < .001$), highlighting its importance in the initial integration of AI. Yang and Dong (2024) suggest that implementing ICT in early childhood education depends on the classroom context, reiterating the need for contextual integration of AI. Factor 2, which includes PCK, TCK, TPK, and TPACK, shows higher factor loads (0.547 - 0.587, $p < .001$), indicating that the advanced combination of these insights is key to effective AI integration. The high correlation between the factors (0.94) reveals that core competencies are essential for a more advanced implementation of AI. Feldman-Maggor et al. (2025) state that AI improves teachers' capacities to assess and provide feedback on learning, reinforcing the potential of TPACK-AI.

The low correlation between dimensions such as TPK and TPACK (0.01) suggests that the direct relationship between pedagogical technology and comprehensive technological-pedagogical knowledge requires a more refined framework. Pazilah et al. (2024) highlight that teacher self-efficacy is key to technological integration, which reveals that training should strengthen confidence in using AI. This highlights the need for professional development programs focused on AI and TPACK. AI-specific assessment instruments are essential to measure its impact, and the robustness of the TPACK-AI questionnaire is confirmed by not affecting its internal consistency. Aquino et al. (2022) allude to the fact that professional development frameworks must be adapted to new technologies, reinforcing the relevance of TPACK-AI. In general, it is confirmed that AI enhances the synergy between pedagogical, technological, and disciplinary knowledge, redefining its application in education.

The above findings indicate that incorporating artificial intelligence into the TPACK framework is a theoretical innovation and a practical necessity in the face of the accelerated transformation of educational environments. This study has shown how AI acts as a catalyst to optimize the personalization of learning, automate pedagogical processes, and strengthen data-driven teacher decision-making. These functions allow us to rethink the role of teachers with a more strategic and adaptive perspective and open new possibilities for higher education in digital training contexts. As Ning et al. (2024) put it, the TPACK-AI framework responds to the complexity of the relationships between disciplinary, pedagogical, and technological knowledge with a holistic view to assess teaching competency in the era of artificial intelligence.

In addition, the results confirm the reliability of the TPACK-AI instrument, which was designed to capture the new dynamics of technological integration in teaching practices. A high internal consistency and a clear factor structure are observed that distinguish fundamental components (such as pedagogical and technological knowledge) from combinations (such as technological-pedagogical knowledge of the content). This finding aligns with what has been reported by research that highlights the need to consider elements such as AI-TCK and AI-TPK as key mediators in AI-oriented teacher professional development (AI-Abdullatif, 2024; Hava & Babayiğit, 2025; Karataş & Ataç, 2025; Mishra & Koehler, 2006; Runge et al., 2025; Tram, 2024; Zulianti et al., 2025).

This study contributes to the conceptual and methodological advancement of the field by offering a systematic, contextualized, and empirically validated instrument, with potential for application in various regions and institutions. Consolidating TPACK-AI as an analytical and practical framework favors institutional decision-making for teacher training, curriculum design, and educational policies focused on emerging technologies. In the future, it is recommended to deepen longitudinal research that

analyzes the impact of using the TPACK-AI model to improve teaching performance and student learning, as well as its adaptation to other educational levels and disciplines.

Accordingly, it can be stated that proposals linking AI with TPACK have been complementary. Celik (2023) incorporates the ethical evaluation of AI analyzing dimensions such as transparency, inclusivity, equity, and accountability and shows that these judgments are positively related to TPK, TCK, and TPACK, reinforcing that TK alone is not sufficient for robust educational integration. In turn, Hava and Babayiğit (2025) provide evidence that teachers' digital competence significantly predicts AI-TPACK competencies. Against these approaches, the emerging TPACK-AI model contributes three concrete advances. First, it injects AI into the seven classic dimensions (CK, PK, TK, PCK, TCK, TPK, and TPACK) with operational indicators of use such as learning analytics, personalization, tutors/assistants, and automation, so the framework presented here is not an add-on to TPACK but an actionable matrix for redesigning teaching with AI.

5. Conclusion

Integrating artificial intelligence into the TPACK (TPACK-AI) model reinforces the relationship between pedagogical, technological, and disciplinary knowledge, providing a solid framework for assessing digital competencies in teaching. In this study, pedagogical knowledge was the strongest dimension, highlighting the importance of well-grounded teaching strategies for integrating AI. However, the lower perception of content knowledge suggests strengthening disciplinary training for effective implementation. In addition, differences in the perception of digital skills according to the institutional context show inequalities in technological adoption, placing AI as a possible indicator of these gaps. The results reaffirm the TPACK-AI model's usefulness in measuring and developing digital competencies in teaching.

This study validates an innovative model to assess emerging digital competencies in teaching, significantly contributing to education and technology. Integrating artificial intelligence into the TPACK model strengthens the assessment of teacher readiness in digital environments. It provides a solid guide for the design of more relevant and effective training programs. Its main contribution lies in expanding the traditional TPACK approach by incorporating AI, a central component in education in the 21st century. This incorporation favors the development of new teaching methodologies and promotes literacy in artificial intelligence, preparing teachers for the challenges of increasingly digitized educational contexts.

Among the study's main limitations is the use of non-probabilistic convenience sampling, which limits the generalizability of the results to teaching populations outside of Latin America. Likewise, although the TPACK-AI instrument showed high levels of reliability, its application focused only on higher education without considering significant differences in educational levels or specific disciplines. Another limitation is the dependence of the questionnaire on self-assessments, which can be affected by social desirability biases or subjective perceptions of the dominance of artificial intelligence in pedagogical practices.

Based on these limitations, it is suggested that future research adopt longitudinal designs that allow observing the development and transformation of TPACK-AI competencies over time, particularly in continuing teacher education contexts. It

would also be valuable to expand the sample to other educational levels, such as primary or high school education, and explore significant differences among disciplines to determine how integrating artificial intelligence varies according to the field of knowledge. It is also recommended to complement self-reporting instruments with mixed methodologies, such as classroom observations, interviews, or case studies, which offer a more profound and contextualized understanding of AI in teaching practices. Finally, it is proposed to investigate the impact of specific training programs in TPACK-AI, evaluating their effectiveness in pedagogical transformation and improvement of student learning.

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