Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

# Development and Validation of a Student-Centered Tpack-Based Instrument for Evaluating Technology-Supported Environmental Learning in Higher Education

**Zulfiya Unerbayeva**
Abai Kazakh National Pedagogical University
**Turar Akylbekova**
t.akylbekova@abaiuniversity.edu.kz

Abai Kazakh National Pedagogical University
**Onlassyn Kulumbetova**
Abai Kazakh National Pedagogical University
**Salih Çepni**
Bursa Uludağ Ünìversìtesì
**Zhazira Mukatayeva**
Abai Kazakh National Pedagogical University
**Bekbolat Ibashev**
Abai Kazakh National Pedagogical University
**Dauren Baiseitov**
Abai Kazakh National Pedagogical University

**Article**

**Keywords:** TPACK, environmental literacy, higher education, technology-supported learning, sustainability education, instrument validation, Education for Sustainable Development (ESD)

**Posted Date:** August 18th, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-10267829/v1

**License:** This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

**Additional Declarations:** No competing interests reported.

# Abstract

The Technological Pedagogical Content Knowledge (TPACK) framework has been widely applied to examine teachers' competencies for technology integration; however, validated instruments designed to assess students' perceptions of technology-supported learning remain limited. Addressing this gap, the present study developed and psychometrically validated a student-centered TPACK-based assessment instrument for evaluating university students' perceptions of technology-supported environmental learning in higher education. The study extends the application of the TPACK framework beyond teacher education by adapting it to a student-centered context and proposes a conceptual framework linking TPACK with technology-supported environmental learning within Education for Sustainable Development (ESD).

Data were collected from 115 undergraduate students at Abai Kazakh National Pedagogical University (Kazakhstan). The final instrument comprised 41 items representing the seven dimensions of the TPACK framework. Psychometric evaluation included reliability analysis, exploratory factor analysis, descriptive statistics, and correlation analysis. The instrument demonstrated excellent internal consistency (Cronbach's α = 0.914–0.972), high Composite Reliability (0.952–0.968), and satisfactory convergent validity (AVE = 0.769–0.868). Construct validity was supported by exploratory factor analysis (KMO = 0.929; Bartlett's Test of Sphericity: $\chi^2 = 6863$, df = 820, $p < .001$). Significant positive correlations among all TPACK dimensions further confirmed the theoretical coherence of the proposed framework.

The study contributes to the educational technology literature by providing a validated student-centered TPACK-based instrument for evaluating technology-supported environmental learning. The proposed instrument offers researchers and higher education institutions an evidence-based tool for curriculum evaluation, digital learning research, and the implementation of Education for Sustainable Development in technology-enhanced learning environments.


# 1. Introduction

Technological Pedagogical Content Knowledge (TPACK) is widely recognized as a theoretical framework explaining the interaction between technology, pedagogy, and subject content in effective learning environments (Koehler & Mishra, 2009; Mishra & Koehler, 2006). Building on Shulman's concept of Pedagogical Content Knowledge (PCK), TPACK emphasizes that meaningful learning emerges not from isolated competencies, but through the integrated application of technological, pedagogical, and content-related knowledge (Chai et al., 2013; Shulman, 1986; Voogt et al., 2013). In contemporary higher education, the framework has become increasingly important in the context of Education for Sustainable Development (ESD), where digital technologies support interactive, student-centered, and sustainability-oriented learning processes (OECD, 2017; Wals, 2015).

To better illustrate the theoretical structure of the TPACK framework and the interaction between technology, pedagogy, and content knowledge, Fig. 1 presents the integrated conceptual model underlying technology-supported learning.

This framework explains the relationships among three major domains: Technology Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK), together with their integrated intersections (Chai et al., 2013; Koehler & Mishra, 2009). Rather than viewing technology as a separate instructional component, the framework conceptualizes digital tools as embedded within pedagogical strategies and subject content (Voogt et al., 2013). In environmental education, this integration supports students' engagement with sustainability-related issues through simulations, collaborative learning, visualizations, and interactive digital resources (Monroe et al., 2019; Zsóka et al., 2013).

Although several frameworks have been proposed to describe digital competence in education, such as DigCompEdu and the SAMR model, these frameworks primarily focus on teachers' digital skills or levels of technology integration. In contrast, this framework explicitly conceptualizes the interaction among technological, pedagogical, and content knowledge, making it particularly appropriate for examining learning environments in which technology supports subject-specific understanding. Because environmental literacy requires not only the acquisition of environmental knowledge but also the integration of appropriate pedagogical approaches and digital learning resources, TPACK provides a more comprehensive theoretical foundation for the development of the present assessment instrument.

Environmental literacy is commonly defined as a multidimensional construct that includes environmental knowledge, attitudes, critical thinking, and environmentally responsible behavior (McBride et al., 2013; Roth, 1992). Recent sustainability-oriented research further conceptualizes environmental literacy as a transformative learning process involving systems thinking, participatory engagement, and action-oriented competencies (Ardoin et al., 2020; Hollweg et al., 2011). Technology-supported learning environments are therefore considered an important pedagogical context for supporting environmental learning and the implementation of Education for Sustainable Development (ESD) in higher education (Aitbayeva et al., 2021; Turarbekova et al., 2022).

The conceptual basis of the present study assumes that technology-supported environmental learning environments create pedagogical conditions that support meaningful student learning within the context of Education for Sustainable Development. Accordingly, the proposed instrument evaluates students' perceptions of these learning environments rather than environmental literacy outcomes themselves. Technology-supported pedagogical strategies enable learners to explore environmental content through inquiry, collaboration, problem solving, and critical reflection, thereby enhancing the quality of environmental learning experiences. Within this framework, TK contributes to students' ability to access and analyze environmental information, PK supports collaborative and problem-based learning activities, while CK provides conceptual understanding of sustainability issues such as climate change, pollution, and ecological responsibility (Boeve-de Pauw & Van Petegem, 2013). Previous TPACK research has primarily focused on teachers' competencies and technology integration. Comprehensive reviews have consistently reported that the majority of TPACK studies have examined preservice and in-service teacher education, while comparatively little attention has been devoted to students' learning experiences and learning outcomes (Chai et al., 2013; Wang et al., 2018). Existing instruments rarely examine how the interaction of technology, pedagogy, and content shapes students' technology-

supported environmental learning experiences from a student-centered perspective (Schmid et al., 2021; Schmidt et al., 2009; Valtonen et al., 2017; Ardoin et al., 2020).

The present study addresses this gap by applying TPACK as a student-centered analytical framework. Instead of evaluating teachers' instructional competencies, the study investigates students' perceptions of technology-supported environmental learning experiences and validates a student-centered assessment instrument for this purpose. This approach extends the application of TPACK beyond instructional design toward the analysis of sustainability-oriented learning processes.

To explain the relationships between technology-supported environmental learning and the TPACK framework, the study proposes the conceptual framework presented in Fig. 2.

Figure 2. Proposed conceptual framework illustrating the relationships between the TPACK framework and technology-supported environmental learning in higher education.

The framework assumes that effective integration of technology, pedagogy, and environmental content creates technology-supported environmental learning environments that facilitate meaningful student learning within the context of Education for Sustainable Development. The conceptual framework proposes that technology, pedagogy, and environmental content interact to shape students' perceptions of technology-supported environmental learning experiences in higher education (Ardoin et al., 2020; Hollweg et al., 2011).

The relationship between TPACK domains and the components of environmental literacy is summarized in Table 1.

Table 1
Relationship between TPACK Domains and Technology-Supported Environmental Learning

| TPACK Domain | Role in Learning Process | Role in Technology-Supported Environmental Learning | Example |
|---|---|---|---|
| TK | Use of digital tools | Accessing environmental information | Searching environmental data |
| CK | Understanding environmental concepts | Understanding environmental content | Climate change, sustainability |
| PK | Learning strategies | Supporting active learning | Discussions, problem-based learning |
| PCK | Teaching environmental topics | Facilitating concept understanding | Case studies |
| TCK | Technology for presenting content | Digital representation of environmental concepts | Simulations |
| TPK | Technology in learning activities | Technology-enhanced collaboration | Digital projects |
| TPACK | Integrated learning environment | Integration of technology, pedagogy and environmental content | Technology-supported environmental learning |

Technological Content Knowledge (TCK) supports the visualization and presentation of environmental concepts through simulations and digital resources. Technological Pedagogical Knowledge (TPK) enhances collaborative and inquiry-based learning activities (Monroe et al., 2019; Zsóka et al., 2013), while the integrated TPACK domain represents the overall effectiveness of digitally supported environmental learning (Koehler & Mishra, 2009; Voogt et al., 2013).

In Kazakhstan, recent studies have increasingly focused on environmental education, sustainable development, and the digital transformation of higher education. Previous research has highlighted the growing integration of sustainability-related topics into university curricula and the expanding use of digital technologies to support student learning (Aitbayeva et al., 2021; Turarbekova et al., 2022). In addition, OECD reports have emphasized the importance of strengthening both digital competencies and sustainability-oriented education within Kazakhstan's higher education system (OECD, 2017).

Despite these developments, existing studies have primarily examined institutional reforms, digitalization processes, and general environmental education practices. Limited attention has been given to understanding students' perceptions of technology-supported environmental learning and to developing validated student-centered assessment instruments for this context. Furthermore, no validated student-centered instrument based on the framework has been developed to assess the relationship between technology-enhanced learning and environmental literacy among university students in Kazakhstan.

Therefore, the present study addresses this gap by developing and validating a student-centered TPACK-based assessment instrument for evaluating university students' perceptions of technology-supported environmental learning in technology-supported higher education contexts. By focusing on students' learning experiences rather than teachers' competencies, the study extends the application of the framework and provides empirical evidence from the context of Kazakhstan.

Research Questions

1. RQ1. Is the proposed TPACK-based instrument reliable for assessing technology-supported environmental learning experiences among university students?
2. RQ2. Does the instrument demonstrate acceptable construct validity?
3. RQ3. What is the factor structure of the proposed TPACK-based instrument?

Hypotheses

H1: TPACK-related domains are positively correlated within students' perceptions of technology-supported environmental learning.

To the best of our knowledge, no validated student-centered TPACK-based instrument has been developed specifically for assessing technology-supported environmental learning among university students in Kazakhstan.

## 2. Methodology

## 2.1 Instrument Development

This study was guided by the Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006; Koehler & Mishra, 2009) to develop and validate a student-centered assessment instrument for evaluating university students' perceptions of technology-supported environmental learning. Unlike previous TPACK-based instruments, which were primarily designed to assess teachers' technological and pedagogical competencies, the present instrument was specifically developed to capture students' perceptions of learning experiences in technology-supported environmental education.

The instrument development followed established procedures for educational scale construction (DeVellis, 2016; Worthington & Whittaker, 2006). First, an extensive review of the literature on TPACK, technology-enhanced learning, environmental education, and Education for Sustainable Development (ESD) was conducted to define the theoretical domains and generate an initial pool of questionnaire items. Existing TPACK instruments were examined to identify appropriate item structures and measurement approaches; however, all questionnaire items were adapted and reformulated to reflect students' learning experiences rather than teachers' instructional competencies.

The questionnaire was organized according to the seven domains of the TPACK framework: Technological Knowledge (TK), Content Knowledge (CK), Pedagogical Knowledge (PK), Pedagogical

Content Knowledge (PCK), Technological Content Knowledge (TCK), Technological Pedagogical Knowledge (TPK), and Technological Pedagogical Content Knowledge (TPACK). Rather than assessing environmental literacy directly, the instrument evaluated students' perceptions of how technology-supported learning environments facilitate understanding of environmental topics, engagement with sustainability-related content, and integration of technology into the learning process.

To establish content validity, the preliminary questionnaire was reviewed by specialists in educational technology, pedagogy, and environmental education following established validation procedures (Haynes et al., 1995). Based on their recommendations, several items were revised, reworded, or removed to improve conceptual clarity and correspondence with the theoretical constructs. The revised version was subsequently pilot-tested before psychometric validation.

The final instrument consisted of 41 items distributed across seven TPACK dimensions: Technological Knowledge (TK, 7 items), Content Knowledge (CK, 6 items), Pedagogical Knowledge (PK, 6 items), Pedagogical Content Knowledge (PCK, 6 items), Technological Content Knowledge (TCK, 4 items), Technological Pedagogical Knowledge (TPK, 6 items), and Technological Pedagogical Content Knowledge (TPACK, 6 items). Responses were recorded using a five-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree).

As presented in Table 2, the instrument provides a comprehensive assessment of students' perceptions of technology-supported environmental learning through the integrated dimensions of the TPACK framework.

Table 2
Structure of the Proposed TPACK-Based Assessment Instrument

| **Dimension** | **Number of Items** |
|---|---|
| Technology Knowledge (TK) | 7 |
| Content Knowledge (CK) | 6 |
| Pedagogical Knowledge (PK) | 6 |
| Pedagogical Content Knowledge (PCK) | 6 |
| Technological Content Knowledge (TCK) | 4 |
| Technological Pedagogical Knowledge (TPK) | 6 |
| Technological Pedagogical Content Knowledge (TPACK) | 6 |
| **Total** | **41** |

# 2.2. Participants and Data Collection

The study involved 115 undergraduate students enrolled at Abai Kazakh National Pedagogical University (Almaty, Kazakhstan). Participants represented different academic disciplines and years of study,

providing a heterogeneous sample for validating the proposed assessment instrument.

During the semester, students participated in technology-supported learning activities incorporating environmental topics. These activities included the use of digital learning resources, online discussions, multimedia materials, collaborative assignments, digital presentations, and web-based information retrieval. The purpose of these learning activities was to provide students with experience in technology-supported environmental learning, which formed the basis for evaluating their perceptions through the proposed TPACK-based instrument.

Data collection was conducted during the final weeks of the semester after students had completed the learning activities. The questionnaire was administered online using a voluntary and anonymous survey procedure. Before participation, students were informed about the purpose of the study and provided informed consent. Completion of the questionnaire required approximately 15–20 minutes.

## 2.3. Data Analysis

Statistical analyses were performed using JASP software to evaluate the psychometric properties of the proposed assessment instrument. Internal consistency was examined using Cronbach's alpha (α) and Composite Reliability (CR). Convergent validity was assessed through the Average Variance Extracted (AVE). The factor structure of the instrument was investigated using Exploratory Factor Analysis (EFA) with Promax rotation, as correlations among the TPACK dimensions were theoretically expected.

The suitability of the data for factor analysis was evaluated using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. Descriptive statistics were calculated for all questionnaire items and dimensions. In addition, Pearson correlation analysis was performed to examine the relationships among the seven TPACK dimensions and to evaluate the internal coherence of the proposed measurement framework.

# 3. Results

## 3.1 Reliability and Convergent Validity

The reliability and convergent validity of the proposed student-centered TPACK-based assessment instrument were evaluated using Cronbach's alpha (α), Composite Reliability (CR), and Average Variance Extracted (AVE). Cronbach's alpha and CR values above 0.70 indicate satisfactory internal consistency, whereas AVE values above 0.50 provide evidence of convergent validity. The results are presented in Table 3.

Table 3
Reliability and Convergent Validity of the Proposed TPACK-Based Assessment Instrument

| Construct | Items | Cronbach's α | CR | AVE |
|---|---|---|---|---|
| TK | 1–7 | 0.949 | 0.967 | 0.805 |
| CK | 8–13 | 0.921 | 0.952 | 0.769 |
| PK | 14–19 | 0.936 | 0.960 | 0.802 |
| PCK | 20–25 | 0.935 | 0.960 | 0.802 |
| TCK | 26–29 | 0.914 | 0.964 | 0.868 |
| TPK | 30–35 | 0.972 | 0.968 | 0.835 |
| TPACK | 36–41 | 0.947 | 0.960 | 0.802 |

Table 3 summarizes the reliability and convergent validity indicators for each TPACK dimension. To provide a clearer visual representation of these results, Fig. 3 compares Cronbach's alpha coefficients together with the corresponding number of items across the seven constructs. Table 3 summarizes the reliability and convergent validity indicators for each TPACK dimension. Figure 3 presents a graphical comparison of Cronbach's alpha coefficients and the number of items across the seven dimensions.

As shown in Table 3 and Fig. 3, Cronbach's alpha coefficients ranged from 0.914 to 0.972 across the seven TPACK dimensions. The highest alpha coefficient was observed for Technological Pedagogical Knowledge (TPK; α = 0.972), whereas the lowest coefficient was recorded for Technological Content Knowledge (TCK; α = 0.914). Composite Reliability (CR) values ranged from 0.952 to 0.968, and Average Variance Extracted (AVE) values ranged from 0.769 to 0.868 for all constructs. All reliability and validity indices exceeded the recommended threshold values reported in the literature.

# 3.2 Exploratory Factor Analysis

Exploratory Factor Analysis (EFA) was conducted to examine the construct validity of the proposed student-centered TPACK-based assessment instrument. Prior to factor extraction, the suitability of the data for factor analysis was evaluated using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's Test of Sphericity. The results are presented in Table 4.

Table 4
KMO Measure and Bartlett's Test of Sphericity

| Measure | Value |
|---|---|
| Kaiser–Meyer–Olkin (KMO) | 0.929 |
| Bartlett's Test $\chi^2$ | 6863 |
| df | 820 |
| p-value | < .001 |

As presented in Table 4, the KMO value was **0.929**, while Bartlett's Test of Sphericity was statistically significant ($\chi^2 = 6863$, df = 820, $p < .001$). These results indicated that the data were suitable for exploratory factor analysis.

The EFA extracted a seven-factor solution corresponding to the seven dimensions of the TPACK framework. All questionnaire items demonstrated factor loadings above **0.50**, meeting the recommended criterion for factor retention. The extracted factors accounted for a substantial proportion of variance across the proposed dimensions.

# 3.3 Descriptive Statistics

Descriptive statistics were calculated to summarize students' perceptions across the seven dimensions of the proposed student-centered TPACK-based assessment instrument. The mean scores and standard deviations for each construct are presented in Table 5.

The results indicate that students reported relatively high levels across all dimensions, with mean scores ranging from 3.98 to 4.16 on a five-point scale. The highest mean score was observed for Content Knowledge (CK) (M = 4.16, SD = 0.74), followed closely by Technological Knowledge (TK) (M = 4.16, SD = 0.88). The lowest mean score was found for Technological Content Knowledge (TCK) (M = 3.98, SD = 0.89), although this value still reflects a generally positive perception.

Overall, the findings suggest that students perceived themselves as possessing strong technology-related, pedagogical, and environmental content knowledge competencies. The relatively small standard deviations indicate moderate variability in participants' responses, suggesting a relatively consistent pattern of perceptions across the sample.

Table 5
Descriptive Statistics of the Proposed TPACK-Based Assessment Instrument

| Construct | Mean | SD |
|---|---|---|
| TK | 4.158 | 0.876 |
| CK | 4.161 | 0.744 |
| PK | 4.094 | 0.784 |
| PCK | 4.113 | 0.758 |
| TCK | 3.976 | 0.887 |
| TPK | 4.026 | 0.869 |
| TPACK | 4.035 | 0.806 |

As shown in Table 5, the mean scores ranged from 3.976 to 4.161 on a five-point Likert scale. The highest mean score was observed for Content Knowledge (CK) (M = 4.161, SD = 0.744), followed closely by Technological Knowledge (TK) (M = 4.158, SD = 0.876). The lowest mean score was recorded for Technological Content Knowledge (TCK) (M = 3.976, SD = 0.887). Standard deviation values ranged from 0.744 to 0.887, indicating moderate variation in participants' responses across the seven TPACK dimensions.

Figure 4 presents the distribution of the mean scores across the seven TPACK dimensions. All constructs demonstrated mean values above the midpoint of the five-point scale, with relatively small differences observed among the dimensions. Content Knowledge (CK) exhibited the highest mean score (M = 4.161), followed closely by Technological Knowledge (TK) (M = 4.158). This finding suggests that students perceived themselves as relatively confident in their understanding of environmental concepts and sustainability-related issues. The result may reflect the growing emphasis on environmental topics within university curricula, as well as the increasing availability of digital resources and technology-supported learning activities that facilitate access to environmental information. In contrast, Technological Content Knowledge (TCK) showed the lowest mean score (M = 3.976), indicating that integrating technological tools with environmental content may represent a greater challenge for students. Furthermore, all dimensions demonstrated excellent internal consistency, with Cronbach’s alpha coefficients ranging from 0.914 to 0.972.

Overall, these findings support the reliability and practical applicability of the proposed instrument for assessing technology-supported environmental learning within the TPACK framework.

# 3.4 Correlation Analysis

Exploratory Factor Analysis (EFA) was conducted to examine the construct validity of the proposed instrument. Prior to factor extraction, the suitability of the data was confirmed by the Kaiser–Meyer–

Olkin (KMO) measure and Bartlett's Test of Sphericity. The KMO value of 0.929 indicated excellent sampling adequacy, while Bartlett's Test was statistically significant ($\chi^2 = 6863$, df = 820, $p < .001$), confirming that the correlation matrix was appropriate for factor analysis.

The exploratory analysis generally supported the proposed multidimensional structure of the instrument. Most items demonstrated satisfactory loadings on their intended constructs, although several items exhibited moderate cross-loadings. Given that this study represents the initial stage of instrument development and validation, these findings were considered acceptable. Future studies employing Confirmatory Factor Analysis (CFA) with larger and independent samples are recommended to further verify the proposed seven-dimensional structure.

Table 6
Pearson Correlations Among the TPACK Dimensions

| Variable | TK | CK | PK | PCK | TCK | TPK | TPACK |
|---|---|---|---|---|---|---|---|
| TK | 1.000 | 0.757 | 0.725 | 0.684 | 0.752 | 0.586 | 0.664 |
| CK | 0.757 | 1.000 | 0.843 | 0.843 | 0.769 | 0.730 | 0.714 |
| PK | 0.725 | 0.843 | 1.000 | 0.847 | 0.785 | 0.755 | 0.823 |
| PCK | 0.684 | 0.843 | 0.847 | 1.000 | 0.854 | 0.794 | 0.759 |
| TCK | 0.752 | 0.769 | 0.785 | 0.854 | 1.000 | 0.831 | 0.821 |
| TPK | 0.586 | 0.730 | 0.755 | 0.794 | 0.831 | 1.000 | 0.908 |
| TPACK | 0.664 | 0.714 | 0.823 | 0.759 | 0.821 | 0.908 | 1.000 |

As shown in Table 6, all correlation coefficients were positive and statistically significant. Correlation coefficients ranged from 0.586 to 0.908, indicating moderate to strong relationships among the seven TPACK dimensions. The strongest correlation was observed between Technological Pedagogical Knowledge (TPK) and Technological Pedagogical Content Knowledge (TPACK) ($r = 0.908$), whereas the weakest correlation was identified between Technological Knowledge (TK) and Technological Pedagogical Knowledge (TPK) ($r = 0.586$). To facilitate interpretation of the correlation matrix, the relationships among the seven dimensions are illustrated in Fig. 5.

Figure 5 visually represents the correlation network among the seven TPACK dimensions. Positive associations were observed across all constructs, with variations in the strength of the relationships corresponding to the coefficients reported in Table 6.

## 3.5. Summary of Key Findings

The results of the psychometric evaluation demonstrate that the proposed student-centered TPACK-based assessment instrument exhibits satisfactory measurement properties. High levels of internal consistency and convergent validity were observed across all seven TPACK dimensions. Exploratory Factor Analysis supported the proposed seven-factor structure, while descriptive statistics indicated

generally positive student perceptions of technology-supported environmental learning. In addition, Pearson correlation analysis revealed positive relationships among all TPACK dimensions, confirming the internal coherence of the proposed assessment framework. These findings provide the empirical basis for the interpretation and discussion presented in the following section.

# 4. Discussion

The present study developed and psychometrically validated a student-centered TPACK-based assessment instrument for evaluating university students' perceptions of technology-supported environmental learning in higher education. The findings demonstrate that the proposed instrument possesses satisfactory psychometric properties and provide empirical support for extending the application of the TPACK framework beyond its traditional focus on teachers' professional competencies. Rather than assessing teachers' knowledge for technology integration, the instrument captures how students perceive technology-supported learning experiences within environmental education, thereby addressing an important gap identified in previous TPACK research.

The reliability analysis demonstrated excellent internal consistency across all seven dimensions of the instrument. Cronbach's alpha coefficients, Composite Reliability (CR), and Average Variance Extracted (AVE) all exceeded the recommended thresholds, indicating that the constructs were measured consistently and possessed satisfactory convergent validity. These findings are consistent with previous validation studies of TPACK instruments (Schmidt et al., 2009; Chai et al., 2013; Schmid et al., 2021), suggesting that the conceptual domains of technological, pedagogical, and content knowledge remain stable when adapted from teacher-focused instruments to a student-centered context. Consequently, the proposed instrument can be considered a reliable tool for investigating students' perceptions of technology-supported environmental learning.

Construct validity was further supported by the exploratory factor analysis. The Kaiser–Meyer–Olkin statistic and Bartlett's Test confirmed the suitability of the data for factor analysis, while the extracted factor solution generally corresponded to the theoretically proposed multidimensional structure. Although several items demonstrated moderate cross-loadings, this finding is not uncommon during the initial stage of multidimensional instrument development, particularly for theoretically related constructs such as TPACK. Because technological, pedagogical, and content knowledge are conceptually interconnected, some degree of overlap among dimensions is expected. Nevertheless, the overall factor structure remained interpretable and theoretically meaningful. Future research should further examine the measurement model using Confirmatory Factor Analysis (CFA), Structural Equation Modeling (SEM), and formal discriminant validity assessment with larger and independent samples.

The descriptive statistics revealed generally high scores across all TPACK dimensions, indicating that students perceived technology-supported environmental learning positively. Content Knowledge and Technological Knowledge achieved the highest mean scores, whereas Technological Content Knowledge demonstrated comparatively lower values. This pattern may reflect the increasing availability of digital

learning resources and environmental content in higher education, while simultaneously indicating that integrating technological tools with discipline-specific environmental concepts remains a relatively complex learning process. These findings suggest that future curriculum development should place greater emphasis on helping students meaningfully connect digital technologies with environmental problem-solving rather than focusing solely on technology use.

The correlation analysis further confirmed the integrated nature of the TPACK framework. Significant positive relationships were observed among all seven dimensions, supporting the theoretical assumption proposed by Mishra and Koehler (2006) that technological, pedagogical, and content knowledge function as mutually reinforcing rather than independent constructs. Similar relationships have previously been reported in teacher-focused TPACK studies (Schmidt et al., 2009; Chai et al., 2013). The present findings extend this evidence by demonstrating that comparable structural relationships can also be identified from students' perspectives within technology-supported environmental learning environments. Although the correlation between Technological Pedagogical Knowledge (TPK) and Technological Pedagogical Content Knowledge (TPACK) was relatively high ($r = 0.908$), this relationship is theoretically expected because TPACK represents the integrated application of technological, pedagogical, and content knowledge. The coefficient remained below commonly accepted thresholds indicating severe multicollinearity; however, future studies employing CFA and discriminant validity analyses should further investigate the distinctiveness of these closely related constructs.

The principal theoretical contribution of this study lies in extending the application of the TPACK framework beyond teacher education. Previous research has predominantly conceptualized TPACK as a model for evaluating teachers' professional competencies and technology integration practices. In contrast, the present study demonstrates that TPACK can also serve as a conceptual framework for examining students' experiences in technology-supported environmental learning. Rather than measuring environmental literacy directly, the proposed instrument evaluates the technological, pedagogical, and content-related characteristics of learning environments that support environmental learning and Education for Sustainable Development (ESD). This student-centered perspective broadens the theoretical applicability of TPACK and contributes to the expanding literature on digital learning, environmental education, and sustainability-oriented higher education.

The practical implications of the study are equally important. The validated instrument provides universities with an evidence-based tool for evaluating students' perceptions of technology-supported environmental learning and identifying strengths and weaknesses across different TPACK dimensions. Such information may support curriculum redesign, faculty professional development, digital transformation initiatives, and institutional strategies aimed at implementing Education for Sustainable Development. The instrument is particularly relevant for Kazakhstan, where higher education institutions are increasingly integrating digital technologies and sustainability principles into teaching and learning practices.

Several limitations should be acknowledged. First, the study was conducted at a single higher education institution using a relatively modest sample of undergraduate students, which may limit the generalizability of the findings. Second, the instrument was validated using self-reported questionnaire data, making the results potentially susceptible to common method bias and social desirability effects. Third, construct validation relied on Exploratory Factor Analysis, which represents an initial stage of psychometric evaluation. Future research should therefore employ Confirmatory Factor Analysis, Structural Equation Modeling, measurement invariance testing, and cross-cultural validation using larger and more diverse samples to provide stronger evidence regarding the structural stability, discriminant validity, and generalizability of the proposed instrument across different higher education contexts.

Overall, the findings demonstrate that the proposed student-centered TPACK-based assessment instrument constitutes a reliable and theoretically grounded tool for evaluating university students' perceptions of technology-supported environmental learning. By extending the application of TPACK from teacher competencies to students' learning experiences, the study contributes both a validated measurement instrument and a broader conceptual perspective that may support future research, institutional evaluation, and the advancement of Education for Sustainable Development in higher education.

# 5. Conclusion

This study developed and psychometrically validated a student-centered TPACK-based assessment instrument for evaluating university students' perceptions of technology-supported environmental learning in higher education. The findings demonstrated that the proposed instrument possesses satisfactory reliability, convergent validity, and construct validity, providing empirical support for its use as a robust measurement tool in technology-supported environmental learning contexts.

The principal contribution of this study is the extension of the TPACK framework beyond its traditional application in teacher education. By adopting a student-centered perspective, the proposed instrument offers a theoretically grounded approach for evaluating how students perceive technology-supported environmental learning environments rather than teachers' instructional competencies. This contributes to the growing body of research on digital learning and Education for Sustainable Development (ESD) by providing a validated instrument for future empirical investigations.

From a practical perspective, the instrument may assist higher education institutions in evaluating technology-supported environmental learning, informing curriculum development, supporting digital transformation initiatives, and strengthening sustainability-oriented educational practices. Although the present findings are based on a single institutional sample and represent an initial stage of instrument validation, the proposed instrument provides a solid foundation for future research. Further validation using larger and more diverse samples, Confirmatory Factor Analysis (CFA), longitudinal designs, and cross-cultural studies is recommended to strengthen the generalizability and robustness of the measurement model.

The proposed instrument provides a robust foundation for future research and institutional evaluation of technology-supported environmental learning, supporting evidence-based implementation of digital transformation and Education for Sustainable Development in higher education.

## Limitations and Future Research

Several limitations should be acknowledged when interpreting the findings of this study. First, the instrument was validated using data collected from a single higher education institution and a relatively modest sample of undergraduate students, which may limit the generalizability of the results. Although the sample size was adequate for Exploratory Factor Analysis (EFA) and the initial validation of the instrument, larger and more diverse samples are required to further evaluate the stability of the proposed measurement model. Second, because this study represents the initial stage of instrument development, construct validity was examined using EFA only. Several items demonstrated moderate cross-loadings, suggesting that additional validation is warranted. Future studies should therefore employ Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM) using independent samples to verify the proposed seven-factor structure and establish stronger evidence of discriminant validity. Finally, cross-cultural validation across different higher education systems would further strengthen the generalizability and practical applicability of the proposed student-centered TPACK-based assessment instrument.

## Declarations

# Author Contribution

Conceptualization, B.I., T.A. and D.B.; methodology, B.I., T.A. and S.Ç.; validation, B.I., D.B. and Z.M.; formal analysis, B.I. and D.B.; investigation, B.I., Z.U. and O.K.; resources, T.A. and D.B.; data curation, B.I.; writing—original draft preparation, B.I.; writing—review and editing, T.A., D.B., Z.M., S.Ç., Z.U. and O.K.; visualization, B.I.; supervision, T.A., D.B. and S.Ç.; project ad-ministration, T.A.; funding acquisition, none. All authors have read and agreed to the published version of the manuscript.

# Data Availability

The datasets generated and analyzed during the current study are not publicly available because they contain participants' responses but are available from the corresponding author on reasonable request.

## References

1. Aitbayeva A et al (2021) Environmental education and sustainable development in Kazakhstan higher education institutions. Int J Sustain High Educ 22(5):1021–1038

2. Ajzen I (1991) The theory of planned behavior. Organ Behav Hum Decis Process 50(2):179–211. https://doi.org/10.1016/0749-5978(91)90020-T
3. Angeli C, Valanides N (2009) Epistemological and methodological issues for the conceptualization, development, and assessment of ICT–TPCK. Comput Educ 52(1):154–168. https://doi.org/10.1016/j.compedu.2008.07.006
4. Archambault LM, Crippen KJ (2009) Examining TPACK among K–12 online distance educators in the United States. Contemp Issues Technol Teacher Educ 9(1):71–88
5. Ardoin NM, Bowers AW, Gaillard E (2020) Environmental education outcomes for conservation: A systematic review. Biol Conserv 241:108224. https://doi.org/10.1016/j.biocon.2019.108224
6. Boeve-de Pauw J, Van Petegem P (2013) A cross-cultural study of environmental values and their effect on environmental behavior. Environ Behav 45(5):551–583
7. Brown TA (2015) Confirmatory factor analysis for applied research, 2nd edn. Guilford Press
8. Wang W, Schmidt-Crawford D, Jin Y (2018) Preservice Teachers' TPACK Development: A Review of Literature. J Digit Learn Teacher Educ 34(4):234–258. https://doi.org/10.1080/21532974.2018.1498039
9. Chai CS, Koh JHL, Tsai CC (2013) A review of technological pedagogical content knowledge. Educational Technol Soc 16(2):31–51
10. Cox S, Graham CR (2009) Diagramming TPACK in practice: Using an elaborated model of the TPACK framework to analyze and depict teacher knowledge. TechTrends 53(5):60–69
11. DeVellis RF (2016) Scale development: Theory and applications, 4th edn. Sage
12. Fabrigar LR, Wegener DT, MacCallum RC, Strahan EJ (1999) Evaluating the use of exploratory factor analysis in psychological research. Psychol Methods 4(3):272–299. https://doi.org/10.1037/1082-989X.4.3.272
13. Hair JF, Black WC, Babin BJ, Anderson RE (2019) *Multivariate data analysis* (8th ed.). Cengage
14. Harris J, Mishra P, Koehler M (2010) Teachers' technological pedagogical content knowledge and learning activity types. J Res Technol Educ 41(4):393–416
15. Haynes SN, Richard DC, Kubany ES (1995) Content validity in psychological assessment: A functional approach to concepts and methods. Psychol Assess 7(3):238–247. https://doi.org/10.1037/1040-3590.7.3.238
16. Hollweg KS, Taylor JR, Bybee RW et al (2011) *Developing a framework for assessing environmental literacy*
17. Kline RB (2016) Principles and practice of structural equation modeling, 4th edn. Guilford Press
18. Koehler MJ, Mishra P (2009) What is technological pedagogical content knowledge? Contemp Issues Technol Teacher Educ 9(1):60–70
19. Likert R (1932) A technique for the measurement of attitudes. Archives Psychol 140:1–55
20. McBride BB, Brewer CA, Berkowitz AR, Borrie WT (2013) Environmental literacy, ecological literacy, ecoliteracy: What do we mean and how did we get here? Ecosphere 4(5):1–20.

https://doi.org/10.1890/ES13-00075.1

21. Mishra P, Koehler MJ (2006) Technological pedagogical content knowledge: A framework for teacher knowledge. Teachers Coll Record 108(6):1017–1054. https://doi.org/10.1111/j.1467-9620.2006.00684.x
22. Monroe MC, Plate RR, Oxarart A et al (2019) Identifying effective climate change education strategies: A systematic review of the research. Environ Educ Res 25(6):791–812. https://doi.org/10.1080/13504622.2017.1360842
23. OECD (2017) Higher Education in Kazakhstan 2017. OECD Publishing. https://doi.org/10.1787/9789264268531-en
24. Podsakoff PM, MacKenzie SB, Lee JY, Podsakoff NP (2003) Common method biases in behavioral research: A critical review of the literature and recommended remedies. J Appl Psychol 88(5):879–903. https://doi.org/10.1037/0021-9010.88.5.879
25. Roth CE (1992) *Environmental literacy: Its roots, evolution and directions in the 1990s*
26. Schmid M, Brianza EM, Petko D (2020) Developing a short assessment instrument for Technological Pedagogical Content Knowledge (TPACK.xs) and comparing the factor structure of an integrative and a transformative model. Computers and Education, 157 online. https://doi.org/10.1016/j.compedu.2020.103967
27. Schmidt DA, Baran E, Thompson AD, Mishra P, Koehler MJ, Shin TS (2009) Technological pedagogical content knowledge (TPACK): The development and validation of an assessment instrument for preservice teachers. J Res Technol Educ 42(2):123–149. https://doi.org/10.1080/15391523.2009.10782544
28. Shulman LS (1986) Those who understand: Knowledge growth in teaching. Educational Researcher 15(2):4–14. https://doi.org/10.3102/0013189X015002004
29. Steg L, Vlek C (2009) Encouraging pro-environmental behavior: An integrative review and research agenda. J Environ Psychol 29(3):309–317
30. Stern PC (2000) Toward a coherent theory of environmentally significant behavior. J Soc Issues 56(3):407–424
31. Taber KS (2018) The use of Cronbach's alpha when developing and reporting research instruments in science education. Res Sci Educ 48(6):1273–1296. https://doi.org/10.1007/s11165-016-9602-2
32. Turarbekova A et al (2022) Digital transformation in higher education in Kazakhstan: Opportunities and challenges. Educ Inform Technol 27:8431–8450
33. Valtonen T, Sointu E, Kukkonen J et al (2017) TPACK and twenty-first century skills. Australasian J Educational Technol 33(3):15–31
34. Voogt J, Fisser P, Pareja Roblin N, Tondeur J, Van Braak J (2013) Technological pedagogical content knowledge: A review of the literature. J Comput Assist Learn 29(2):109–121. https://doi.org/10.1111/j.1365-2729.2012.00487.x

35. Wals AE (2015) Beyond unreasonable doubt: Education and learning for socio-ecological sustainability
36. Worthington RL, Whittaker TA (2006) Scale development research: A content analysis and recommendations for best practices. Couns Psychol 34(6):806–838
37. Zsóka Á, Szerényi ZM, Széchy A, Kocsis T (2013) Greening due to environmental education? Environmental knowledge, attitudes, consumer behavior and everyday pro-environmental activities of Hungarian high school and university students. J Clean Prod 48:126–138

# Figures

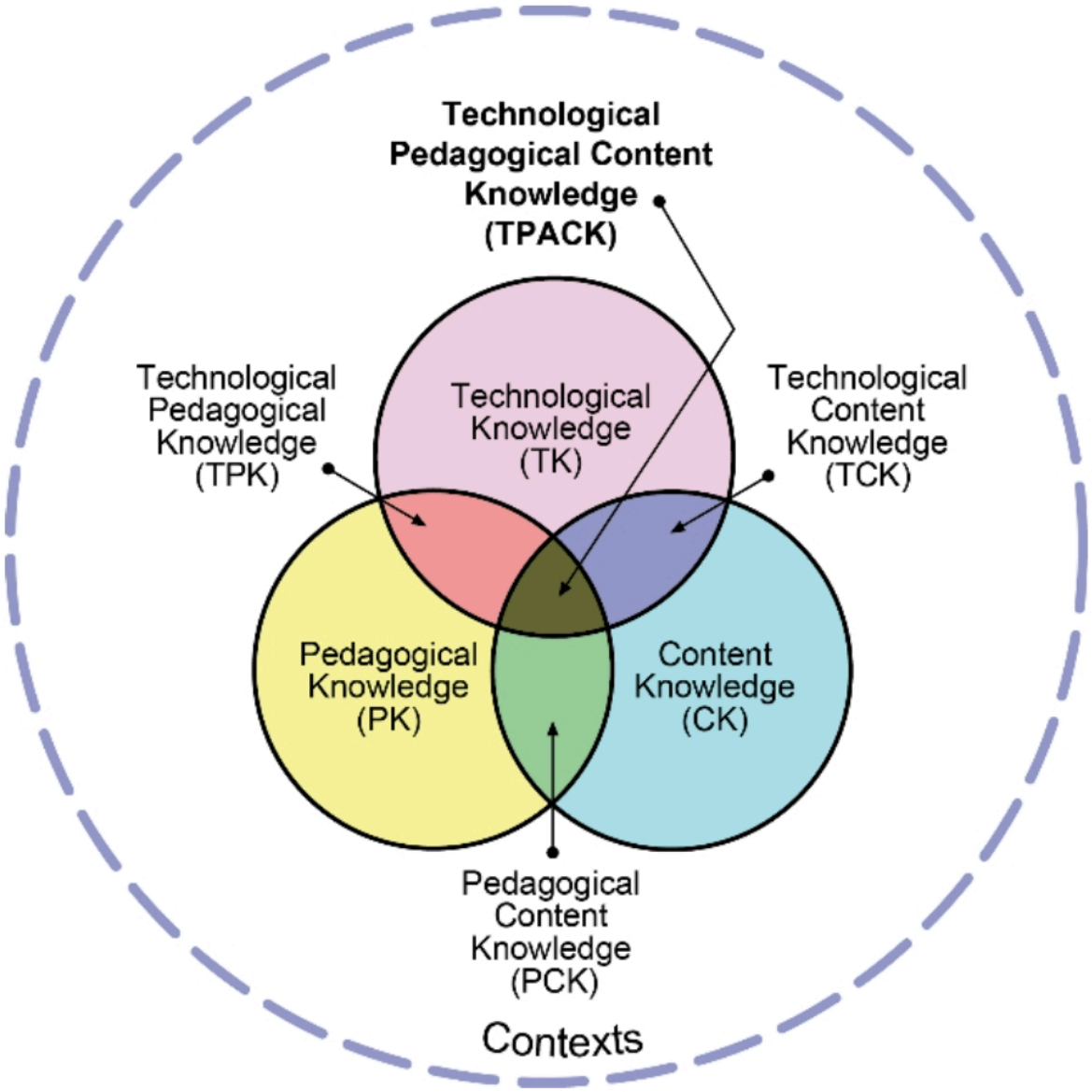



**Figure 1**

TPACK — the foundation of effective digital teaching (https://tpack.org/tpack-image/)

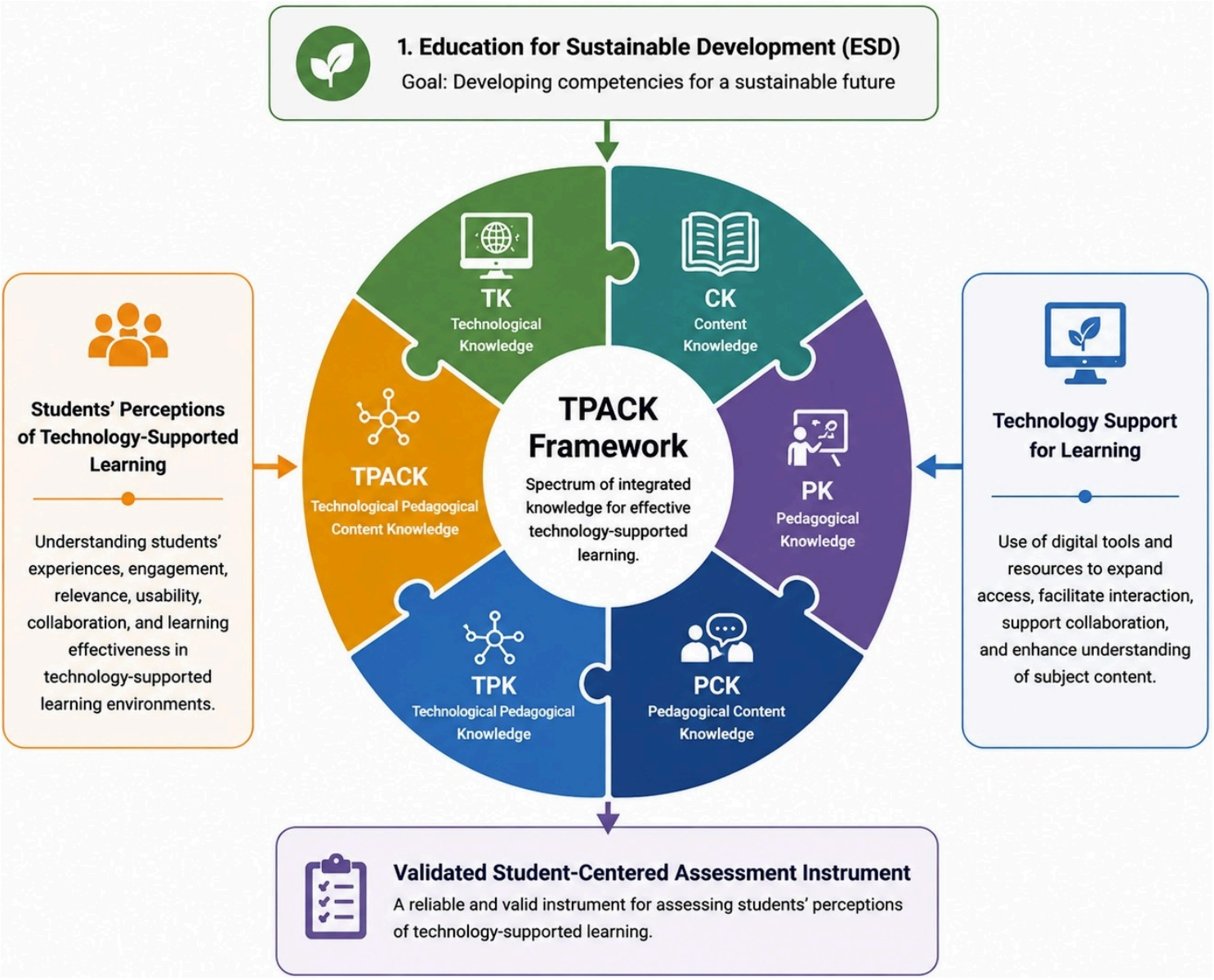
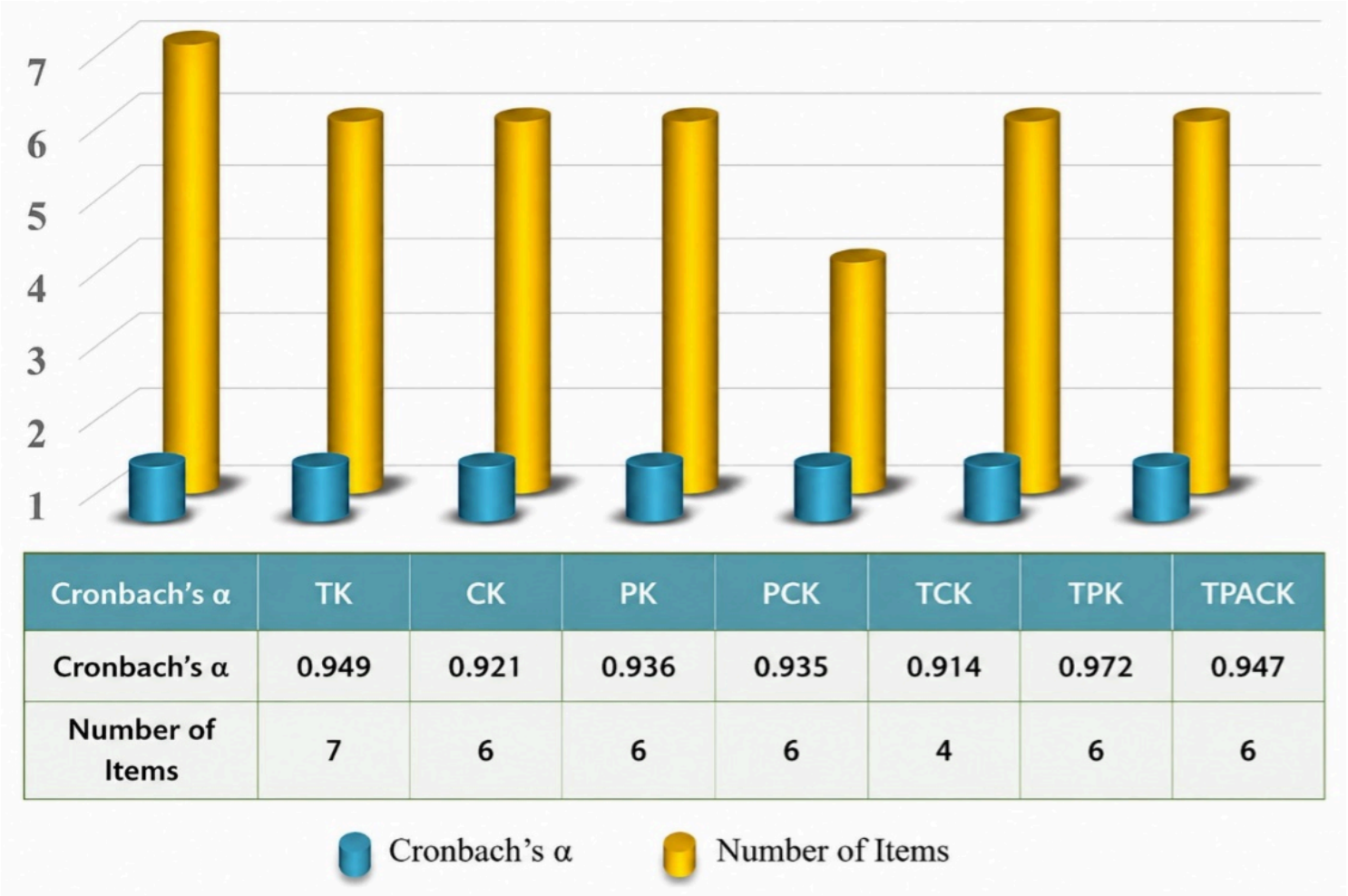



**Figure 2**

Proposed conceptual framework illustrating the relationships between the TPACK framework and technology-supported environmental learning in higher education.




| Cronbach's α | TK | CK | PK | PCK | TCK | TPK | TPACK |
|---|---|---|---|---|---|---|---|
| Cronbach's α | 0.949 | 0.921 | 0.936 | 0.935 | 0.914 | 0.972 | 0.947 |
| Number of Items | 7 | 6 | 6 | 6 | 4 | 6 | 6 |

**Figure 3**

Cronbach's Alpha Coefficients and Number of Items Across TPACK Dimensions

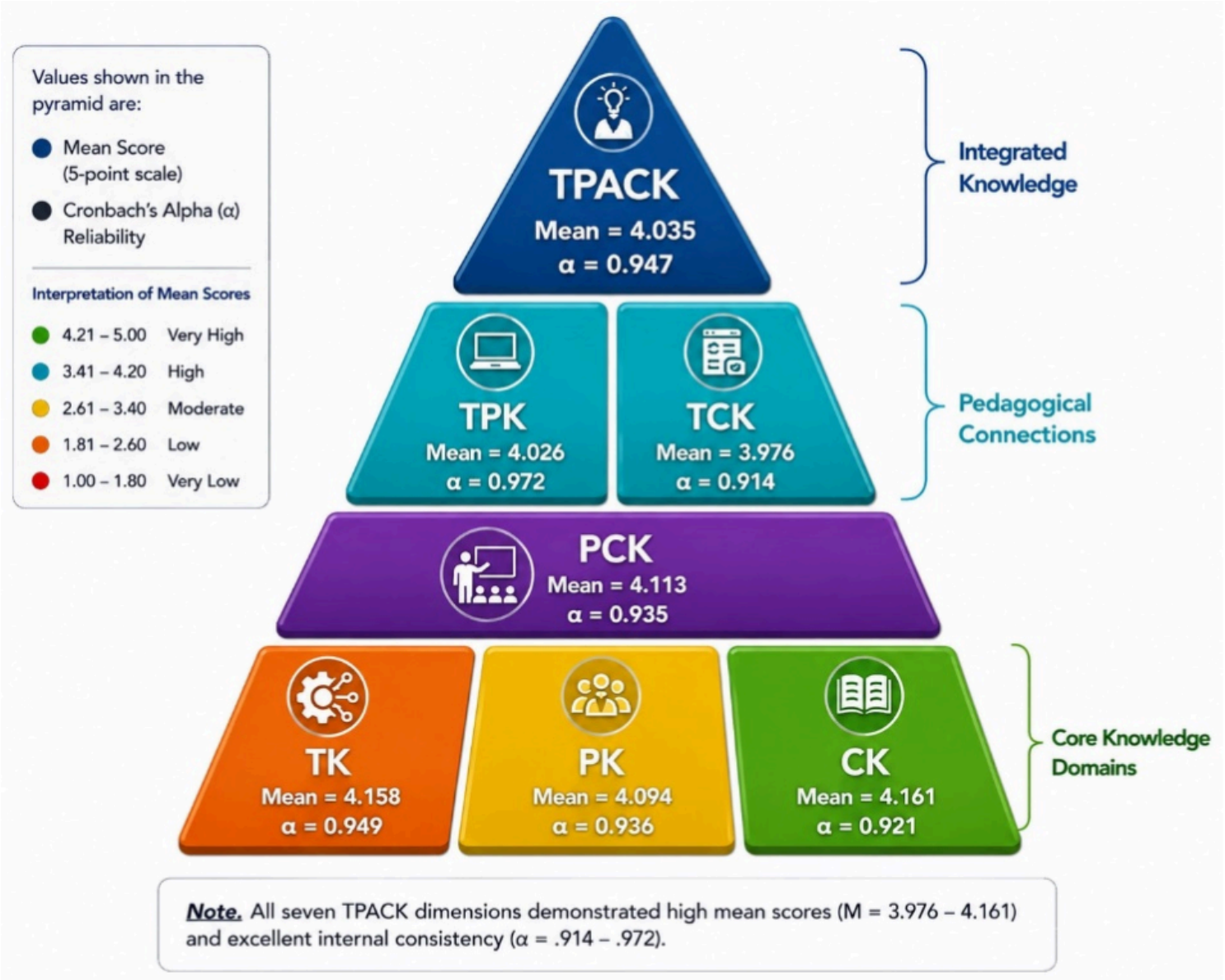



**Figure 4**

Mean Scores Across the TPACK Dimensions

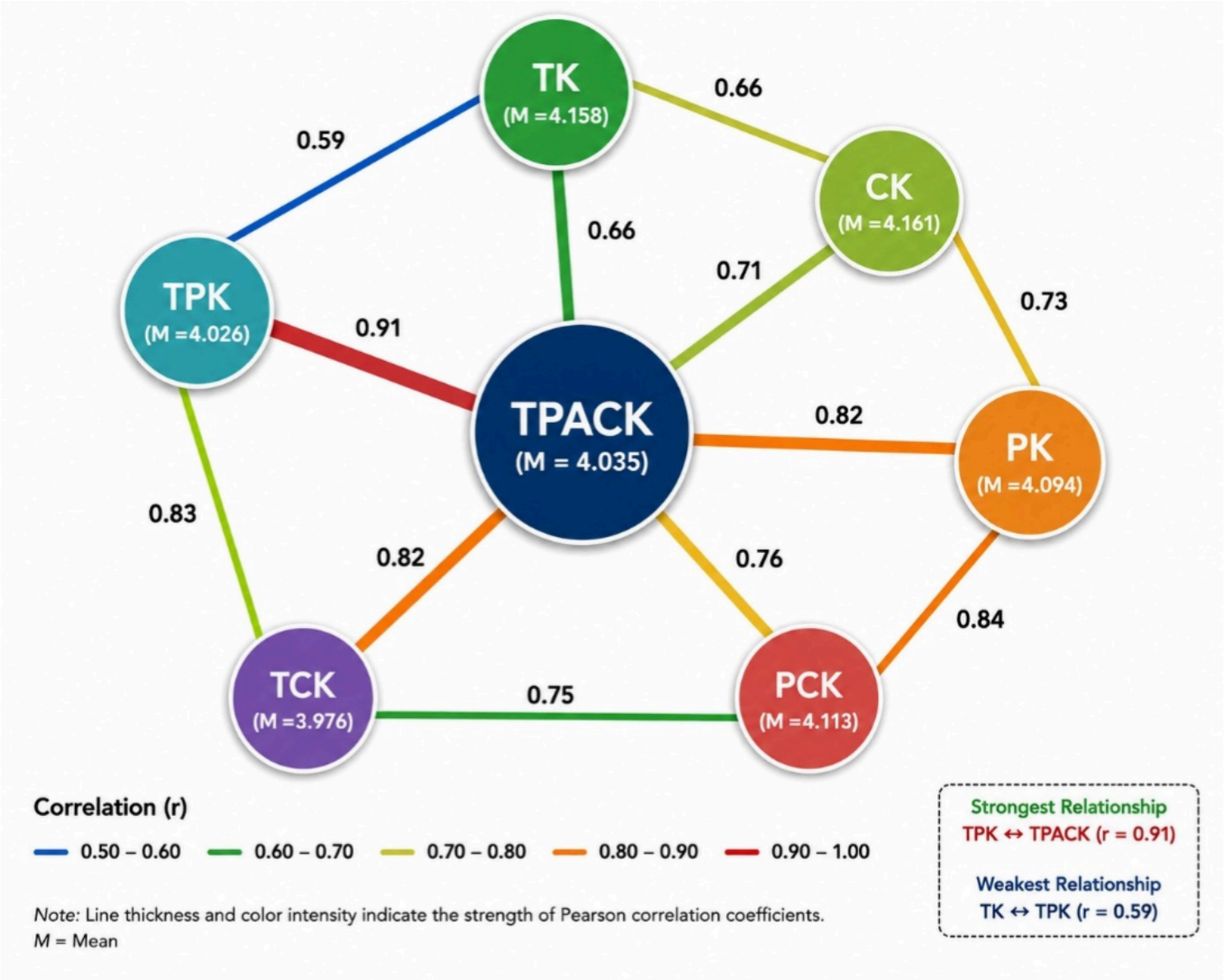



**Figure 5**

Correlation Network of the TPACK Dimensions

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- QuestionnaireAnonymous.docx
- DataandMaterialsDocumentation1.docx
- TPACKAnonymizedDataandDocumentationEnglish.xlsx