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TECHNOLOGY-ENHANCED INSTRUCTION AND MATHEMATICS ACHIEVEMENT: THE PREDICTIVE ROLE OF TPACK DOMAINS

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ABSTRACT

This study investigated students' perceptions of technology-supported instruction and its relationship to mathematics achievement in terms of the Technological Pedagogical Content Knowledge (TPACK) model. A purposive sample of 113 first-year university students who were enrolled in general mathematics course were selected for the study. Data were gathered using a researcher-designed survey instrument with a four-point Likert scale to measure perceptions of three knowledge types: Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK). Students' mathematics achievement was gathered from their official academic records with informed consent to ensure an objective performance indicator. Descriptive analysis showed that students perceived TPK ($M = 2.67$, $SD = 0.85$) and PCK ($M = 2.52$, $SD = 0.86$) as good, while TCK ($M = 2.46$, $SD = 0.86$) was perceived as poor. Spearman correlation analysis showed significant positive correlations between mathematics achievement and PCK ($\rho = .38$, $p < .001$), TCK ($\rho = .24$, $p = .011$), and TPK ($\rho = .41$, $p < .001$). Multiple regression analysis showed that the three knowledge types together explained 34% of the variance in mathematics achievement ($R^2 = .34$, $p < .001$), with TPK being the strongest predictor ($\beta = .37$). The results indicate that the role of integrated technological and pedagogical competence is more important in mathematics achievement than TCK alone.

Keywords: Technology-enhanced instruction, academic performance, TPACK framework, Pedagogical Content Knowledge (PCK), Technological Pedagogical Knowledge (TPK), mathematics education

INTRODUCTION

The infusion of technology in mathematics education has brought about a paradigm shift in teaching practices, providing opportunities for engaging and interactive learning. Various studies have shown that technology-enhanced instruction (TEI), including the use of digital tools, online platforms, and adaptive software, can greatly enhance students' academic achievement in mathematics and other related subjects. For instance, experimental and quasi-experimental studies have found that students who received technology-based instruction outperformed those who received instruction through traditional teaching practices, in various educational settings and among different groups of students (Orquita & Gumanoy, 2025; Rizada & Rey, 2023; Calzada & Antonio, 2024). These positive outcomes can be attributed to the benefits of personalized learning, immediate feedback, and increased opportunities for active engagement (Sailer et al., 2024; Eltahir & Babiker, 2024).

Notwithstanding, the effectiveness of TEI is not consistent and is highly dependent on teaching practices and the quality of technology integration. Systematic reviews and meta-analyses have underscored that technology is most effective when used for advanced, interactive, and constructive learning activities, and not merely as a substitute for traditional teaching practices (Sailer et al., 2024; Woldemariam et al., 2023). The importance of the teacher cannot be overemphasized, as their capacity to integrate digital and non-digital learning activities, and to provide cognitive support, is critical in optimizing student outcomes (Milkova et al., 2025; Hong et al., 2024; Valverde-Berrocoso et al., 2022). Educator professional development is, therefore, a critical consideration to ensure effective implementation and to address issues such as lack of adoption and varying digital competencies of teachers and students (Milkova et al., 2025; Hong et al., 2024; Aslam et al., 2024).

However, despite its potential, TEI also has its drawbacks. The digital divide, which is marked by disparities in access to technology and internet connectivity, may widen the gap in education, especially for students who come from lower socioeconomic backgrounds (Hong et al., 2024; Arones et al., 2022; Rizada & Rey, 2023). Moreover, some studies have found that the mere use of technology does not necessarily lead to better academic outcomes; rather, its effects are contingent on variables such as engagement, autonomous learning, and the relevance of technology to learning objectives (Lu et al., 2024; De Guzman Egbalic, 2025). Overemphasizing the use of technology without proper integration may even lead to a degradation of critical thinking and problem-solving abilities (Valverde-Berrocoso et al., 2022).

Given these complexities, ongoing research is needed to assess the direct impact of TEI on measurable academic outcomes, especially among students transitioning to higher education. By focusing on the relationship between technology-based instruction and student achievement, this study aims to inform curriculum development and instructional practices, supporting the goal of equitable and effective mathematics education for all learners (Orquita & Gumanoy, 2025; Valverde-Berrocoso et al., 2022; Rizada & Rey, 2023).

METHODOLOGY

This study used a descriptive correlational research design to investigate the relationship between students' perceptions of technology-enhanced instruction and their mathematics academic performance. The descriptive part of the study offered a description of student profiles and their perceptions, while the correlational part of the study investigated the type and degree of the relationship between variables without attempting to establish causation. This research design was used to develop a complete understanding of how different technology-enhanced instructional methods are related to student outcomes in a naturalistic setting.

The population for this study included first-year university students aged 18 to 24 years old who were taking a general mathematics course in the first semester of the 2025-2026 academic year. A purposive sampling method was used to select 113 participants, which was determined by power analysis to ensure the statistical rigor of the study and its relevance to the specific demographic of learners being studied. The data was collected at the mid-point of the semester to ensure that students had developed a comprehensive and stable perception of the technology-enhanced instructional methods.

The primary data was gathered through a researcher-designed survey aimed at gathering demographic information and student feedback on technology-enhanced teaching. The survey employed a four-point Likert scale to avoid the neutral point and promote definitive answers to questions in the three main areas: Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK). To make the survey more accessible to the target population, it was professionally translated into Chinese.

Additionally, students' academic performance in mathematics was gathered from the institutional records with their consent, serving as an objective criterion for the correlation analysis.

Before the data collection process, the instrument was validated and proven reliable. The survey was reviewed by three experts in mathematics education, educational technology and measurement and evaluation. A pilot test was also conducted among a few students, and the Cronbach's alpha level of 0.80 or higher was established to ensure internal consistency. The data collection process involved collaboration with the university administration and teaching staff to identify potential participants, gain informed consent, and conduct the survey. The data was collected either electronically or on paper and later coded for analysis.

Ethical issues were of prime importance throughout the study. Prior clearance from the ethical review board of the institution was sought, and a comprehensive informed consent form was used. The participants were assured of their rights to withdraw from the study at any time and that all the data would be anonymized and kept confidential.

The quantitative data was then processed and analyzed using Jamovi software with a significance level of .05. In order to meet the research objectives, a three-step statistical method was used, starting with descriptive statistics. Means and standard deviations were calculated to describe students' perceptions of Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK), which formed the basis for interpreting their perceptions as "Good" or "Poor." Correlation analysis was then employed to investigate the strength and nature of the relationships between these educational areas and students' academic performance in mathematics. Finally, to establish the combined effect of the predictors, a multiple linear regression analysis was conducted. This analysis yielded the Coefficient of Determination (R2) to evaluate the overall explained variance in academic performance and Standardized Beta coefficients (β) to determine the individual contribution of each knowledge domain. The intercorrelations among the predictors were also assessed to confirm that the assumption of low multicollinearity was satisfied, thus justifying the use of all three variables in the predictive model.

RESULTS AND DISCUSSION

Table 1. Students' Assessment of Technology-Enhanced Instruction Across the Key Knowledge Areas

Domain	Mean	SD	Interpretation
Pedagogical Content Knowledge	2.52	0.86	Good
Technological Content Knowledge	2.46	0.86	Poor
Technological Pedagogical Knowledge	2.67	0.85	Good

The results of the study show a mixed perception of technology-enhanced teaching among the participants. The students rated Technological Pedagogical Knowledge (TPK) and Pedagogical Content Knowledge (PCK) as "Good," with a mean score of 2.67 and 2.52, respectively. This shows that the students are satisfied with the teachers’ use of technology in teaching methods, as it helps them understand complex concepts and work together. The highest mean score in these categories was recorded for the statement that technology is used to actively engage students and create a dynamic, interactive environment. However, the mean score of 2.46 in Technological Content Knowledge (TCK) was interpreted as "Poor." This is specifically related to the teacher’s use of technology tools to directly improve the understanding of mathematical concepts, with the lowest mean score in the entire study recorded for the statement about the effective use of tools for content mastery.

Numerous studies have ascertained that high levels of PCK and TPK are exactly what teachers need to effectively employ technology to facilitate inquiry, interaction, and discovery-based learning, which students view as engaging and participation-supportive (Priyanda et al., 2025; Hidayat et al., 2024; Ngwabe & Boateng, 2025). Systematic reviews of TPACK in mathematics reveal that when teachers purposefully integrate technology with specific pedagogical goals in mind, such as developing multiple representations, collaborative problem-solving, and guided explorations, students self-report increased engagement and demonstrate increased achievement, much like your positive student feedback on PCK and TPK (Kholid et al., 2023; Hidayat et al., 2024; Saliao & Cajandig, 2025). Research studies on digital pedagogy also indicate that carefully planned technology integration is a significant predictor of both engagement and mathematics achievement, as long as teachers focus on pedagogical approaches rather than strictly technical ones (Saliao & Cajandig, 2025; Taufik & A, 2025).

Conversely, the low rating of TCK is strongly represented in the literature as a typical bottleneck. Various studies have reported that mathematics teachers tend to be more confident in applying technology for generic tasks (communication, organization, classroom management) than in applying it to support the representation, transformation, or exploration of particular mathematical concepts, which indicates exactly the type of gap that your students are reporting (Amidi et al., 2024; Padilla-Escorcia et al., 2025; Chévez & Guido, 2023). Case-based and instrument design research has revealed that teachers' understanding of the "disciplinary potential" of specific technologies, such as the role of dynamic geometry software, graphing software, or applets in revealing important structures or misconceptions, tends to be underdeveloped even among teachers with very high levels of general technological competence (Padilla-Escorcia et al., 2025; Yu, 2026). This creates a technology that is engaging and interactive but not particularly related to the underlying concepts, which matches the students' observation that the technology is engaging but does not necessarily improve their understanding (Priyanda et al., 2025; Padilla-Escorcia et al., 2025; Mosia & Matabane, 2022).

Recent reviews and studies on professional development, therefore, recommend content-specific TCK and TPACK training: designing tasks that begin with fundamental mathematical concepts and then selectively choose or even co-design digital tools (such as customized applets) to make these concepts visible and discussable (Li & Li, 2024; Ngwabe & Boateng, 2025; Yu, 2026). Interventions that combined topic-specific visualization tools and blended digital/non-digital representations have been found to enhance PCK and TCK simultaneously, improving preservice and in-service teachers' ability to link technology use to conceptual understanding and problem-solving rather than to engagement outcomes alone (Ngwabe & Boateng, 2025; Ning et al., 2024; Yu, 2026; Amidi et al., 2024).

Table 2. Correlation of Technology-enhanced Instruction in Mathematics Classes to the Academic Performance

	Pedagogical Content Knowledge	**Technological Content Knowledge**	**Technological Pedagogical Knowledge**
Correlation Coefficient	0.38	0.24	0.41
df	111	111	111
p-value	<0.001	0.011	<0.001

Table 2 shows the correlation of technology-enhanced teaching, as measured by Pedagogical Content Knowledge (PCK), Technological Content Knowledge (TCK), and Technological Pedagogical Knowledge (TPK), with academic performance in mathematics. The findings show a statistically significant positive correlation for all three aspects. In particular, there was a positive correlation between academic performance in mathematics and PCK ($\rho = .38$, $p < .001$), TCK ($\rho = .24$, $p = .023$), and TPK ($\rho = .41$, $p < .001$), which showed that the higher the level of technology-related knowledge for teaching, the better the performance in mathematics.

The findings show that as the perceived level of teacher expertise in these aspects increases, the academic performance of the students also improves. Moreover, TPK had the highest correlation with academic performance, followed by PCK and TCK.

Table 3. Multiple Regression Predicting Mathematics Academic Performance

Predictor	**β**	**t**	**p**
Pedagogical Content Knowledge	.33	3.99	< .001
Technological Content Knowledge	.18	2.09	.038
Technological Pedagogical Knowledge	.37	4.47	< .001
Model Summary: $R^2 = .34$, Adjusted $R^2 = .33$, $F(3,109) = 18.70$, $p < .001$			

Together in a multiple regression analysis, the three predictors accounted for a total of 34% of the variance in mathematics outcomes, which is a strong explanatory fit. Technological Pedagogical Knowledge was found to be the strongest individual predictor ($\beta = .37$, $p < .001$), which implies that the ability to effectively combine technology with pedagogical knowledge is a key determinant of mathematics outcomes. Pedagogical Content Knowledge was also found to be a strong individual predictor ($\beta = .33$, $p < .001$), which implies that the ability to effectively combine pedagogical knowledge with content knowledge is a key determinant of mathematics outcomes. Technological Content Knowledge was found to have a weaker but still significant predictor effect ($\beta = .18$, $p = .038$), which implies that technological knowledge alone is a less significant determinant of mathematics outcomes compared to its combination with pedagogical knowledge. The low intercorrelations among the predictors imply that there is no multicollinearity among the predictors, which implies that each knowledge type has a unique contribution to make to academic outcomes.

The strong positive correlations between PCK, TCK, and TPK indicate that technology-enhanced mathematics teaching is most effective when these components work as an integrated system rather than as separate components. Structural equation modeling studies indicate that core knowledge bases (CK, PK, TK) affect composite constructs (PCK, TCK, TPK), which are strong predictors of overall TPACK and technology integration in mathematics classrooms (Li & Li, 2024; Mansour et al., 2024; Zeynivandnezhad et al., 2023). Reviews also stress that the integration of these components, including contextual and learner knowledge, is more important than technological knowledge or content knowledge in effective digital teaching (Li & Li, 2024; Kholid et al., 2023; Aqib et al., 2025; Hanifah et al., 2024).

The correlation between PCK and achievement of .38 is consistent with the finding that high-quality PCK supports teachers in anticipating misconceptions, designing powerful representations, and creating tasks that enhance conceptual understanding and problem-solving, leading to positive outcomes (Priyanda et al., 2025; Hanifah et al., 2024; Belayneh, 2025). Discussion of PCK and topic-specific PCK suggests that in technology-rich contexts, PCK has a direct impact on conceptual understanding, cognitive engagement, and equity of participation, rather than a polishing effect on delivery (Belayneh, 2025). Survey research in secondary mathematics education has also found that pedagogical knowledge is frequently the TPACK component most closely linked with academic achievement, consistent with your finding that PCK is an important predictor of performance (Lisondra & Arpilleda, 2025).

The weaker but positive correlation for TCK ($\rho = .24$) is in line with studies that found mathematics specific technological knowledge has a supportive role in learning only when it is closely aligned with content goals and curriculum (Mansour et al., 2024; Zeynivandnezhad et al., 2023; Li et al., 2025). Structural models of STEM and AI TPACK suggest that content related technological knowledge (TCK or AI TCK) has the strongest indirect effect, by influencing more integrative constructs that combine pedagogy and technology, rather than being a strong predictor by itself (Mansour et al., 2024; Ning et al., 2024). Case and qualitative research also suggest that teachers are more confident with generic technology than with technology to transform specific mathematical ideas, which has a limited direct effect on achievement unless it is strongly supported by PCK and TPK (Pagiling et al., 2024; Li et al., 2025).

The highest correlation for TPK ($\rho = .41$) is strongly supported by both quantitative and qualitative research that has identified TPK as a key lever for engaging and inquiry-oriented digital mathematics teaching. Large-scale survey research and structural models reveal high correlations between TPK, PCK, and TCK, with TPK strongly predicting teachers' use of discovery learning and multiple representations in mathematics (Hidayat et al., 2024; Zeynivandnezhad et al., 2023; Li et al., 2025). Systematic reviews of TPACK and pedagogical reasoning suggest that teachers with highly developed TPK are more skilled at tool selection, designing interactive learning tasks, and simulating and visualizing instruction in ways that promote engagement and conceptual understanding (Priyanda et al., 2025; Sartika et al., 2025). Empirical research on classroom technology use also finds that higher levels of TPK and TPACK are linked to more sophisticated technology use and improved student outcomes, supporting your interpretation that TPK-related expertise has the strongest correlation to performance in technology-enhanced environments (Sartika et al., 2025; Plantado, 2023; Patalinghug & Arnado, 2021). Various studies in mathematics education have indicated that it is the integrated technological pedagogical competence and not technology alone that is most strongly associated with students' mathematical performance. Descriptive-correlational study at the primary level revealed that the Technological Pedagogical Knowledge of teachers was the highest TPACK construct and directly proportional to learners' mathematics achievement, similar to the strong unique effect of TPK in the current study (Patalinghug & Arnado, 2022). Action research in the classroom also indicates that the implementation of TPACKoriented lesson designs yields great improvements in students' mathematical capabilities in each successive cycle, suggesting that technology-pedagogy integration can lead to clear performance improvement and not merely self-assessed competence (Thalhah & Irma, 2024). The current studies on the conceptual level all agree that the key to effective technology integration in mathematics education is the complementary fusion of pedagogy and technology and that TPK/PCK are the core pathways through which technology impacts learning and not technological proficiency alone (Priyanda et al., 2025; Li & Li, 2024; Kholid et al., 2023; Habiyaremye et al., 2023). On the other hand, research on teacher knowledge and student achievement suggests that knowledge components may be mediated by the quality of instructional enactment. Large-scale multilevel studies in mathematics revealed that there was no direct relationship between teachers' content knowledge and pedagogical content knowledge and students' learning progress when the quality of instructional enactment and teachers' perception-interpretation-decision skills were controlled, with the process variables fully mediating the relationship between knowledge and achievement (Blömeke et al., 2022). This is consistent with structural models of TPACK, which have demonstrated that technological, pedagogical, and content knowledge influence higher-order composites (such as TPK, TCK, and PCK), which in turn influence actual technology integration and instructional practice, rather than student achievement being accounted for by any one knowledge domain (Mansour et al., 2024; Li & Li, 2024; Ning et al., 2024).

The moderate level of explained variance (34%) is thus in line with previous studies: teacher knowledge and its technological-pedagogical integration explain a significant, yet partial, part of mathematics achievement, while the remaining variance is attributed to contextual, instructional, and personal variables (Kholid et al., 2023; Blömeke et al., 2022; Li & Li, 2024). The low intercorrelations and differential predictive roles of TPK, PCK, and TCK in the current model reflect structural and correlational findings that TPACK components possess discriminant validity and play distinct roles in technology-enhanced mathematics instruction (Mansour et al., 2024; Li & Li, 2024; Plantado, 2023; Ning et al., 2024).

This study offers a strong empirical assessment of the predictive value of TPACK domains on mathematics outcomes and thus a clear scientific rationale for a paradigm shift in digital learning from general ICT competence to comprehensive pedagogical capability. The results show a complex learning environment, in which students overall are positive about the pedagogical integration of technology (TPK) and the pedagogical knowledge of content (PCK), but a strong disciplinary barrier in the area of Technological Content Knowledge (TCK). This suggests that technology is actually used more effectively as a general engagement tool than as a specialized medium for the representation of complex mathematical concepts.

Despite these mixed views, all three domains continue to be significantly and positively related to academic achievement. It is worth noting that Technological Pedagogical Knowledge (TPK) has the strongest correlation and unique predictive effect, outperforming the effect of both isolated content and pedagogical knowledge. By showing that the combination of technology and pedagogy explains a large part of the variance in mathematics achievement, this study contributes to the field by reaffirming the theoretical underpinning of the TPACK model—that technology integration is most successful when situated within a sound pedagogical foundation, rather than solely within a technical one. Thus, these findings indicate to policymakers and curriculum developers that professional development needs to focus on content-specific technological integration, rather than generic technological training.

Although this study helps to illuminate that mathematics achievement is indeed a beneficiary of the informed and pedagogically sound use of technology, the remaining unexplained variance indicates important directions for future research. These may include longitudinal studies, some of which are already in progress, to see whether TPACK-focused interventions lead to long-term improvements in mathematical achievement. Additionally, future research should seek to incorporate qualitative observations of classroom practice to help triangulate the manner in which these perceived domains are enacted. In any case, this study highlights the importance of technology being integrated through the prism of a teacher's pedagogical reasoning, and not simply for technical proficiency's sake, but in order to achieve a deeper level of conceptual understanding.

CONCLUSION

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