

Technological Knowledge, Pedagogical Knowledge, and Content Knowledge in Relation to Students' Achievement in Mathematics in the Secondary Schools

Allaizza Mae R. Lisondra

Alegria National High School Alegria, Surigao City, Philippines

Email: allaizzamae.lisondra@deped.gov.ph

ORCID: 0009-0005-7797-9960

Alcher J. Arpilleda

St. Paul University Surigao, Surigao City, Philippines

Email: alcher.arpilleda@spus.edu.ph

ORCID: 0000-0001-9638-5459

Abstract

This study examined the relationship between secondary mathematics teachers' Technological Pedagogical Content Knowledge (TPACK) and students' academic achievement, engagement, and resilience. A quantitative-correlational research design was adopted, involving secondary mathematics teachers and their students from selected public secondary schools. Purposive sampling was employed to ensure that only teachers actively teaching mathematics and students enrolled in their classes were included. Standardized and validated instruments were utilized to assess teachers' levels of technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), along with measures of students' achievement, engagement, and resilience. Data were analyzed using descriptive statistics, Pearson correlation, and ANOVA. Findings revealed that teachers demonstrated high levels of TPACK, with content knowledge rated highest, followed by pedagogical and technological knowledge. Students showed proficient academic achievement and high engagement and resilience. Significant positive correlations were found between teachers' TPACK components and student outcomes, with pedagogical knowledge showing the strongest relationship with academic achievement. Differences in TPACK levels were also noted when teachers were grouped according to educational attainment and field of specialization. These results highlight the importance of strengthening teachers' technological competencies, providing sustained institutional support, and offering continuous professional development to optimize technology integration in secondary mathematics instruction.

Keywords: TPACK, Mathematics Education, Technology Integration, Academic Achievement, Student Engagement, Resilience, Teacher Professional Development, Purposive Sampling, Quantitative Research

1. Introduction

Background

The Technological Pedagogical Content Knowledge (TPACK) framework has become a critical foundation in understanding how teachers integrate technology into their instructional practices. It combines three primary knowledge domains—Content Knowledge (CK), Pedagogical Knowledge (PK), and Technological Knowledge (TK)—to create a model that reflects the complex interplay of these elements in effective teaching (Mishra & Koehler, 2008). This framework builds on Shulman's (1987) concept of Pedagogical Content Knowledge (PCK), extending it by incorporating technology to address the demands of modern classrooms. TPACK highlights that effective technology integration requires a deep understanding of how technological tools can support pedagogy and content in meaningful ways.

Research on TPACK in mathematics education has shown that it enhances instructional quality, student engagement, and learning outcomes. Recent meta-analytic evidence confirmed the significant positive effects of TPACK in improving teachers' mathematical teaching abilities, with a large, aggregated effect size of $d = 1.06$ (Helsa et al., 2025). Similarly, studies have demonstrated that technology-supported mathematics instruction improves students' conceptual understanding, engagement, and higher-order thinking skills, especially when teachers are well-versed in integrating digital tools into lessons (Hanifah, Budayasa, & Sulaiman, 2024).

Furthermore, TPACK has been shown to support innovative and interactive teaching practices, particularly in secondary mathematics education. For example, Charoenthong and Poonputta (2025) found that integrating the GPAS 5 Steps model with TPACK significantly improved students' academic performance and mathematical connection skills, with students also reporting high satisfaction levels. Other studies have emphasized the importance of ongoing professional development to enhance teachers' TPACK, as technological proficiency alone is insufficient without the pedagogical and content knowledge necessary for meaningful integration (Aydın-Günbatar, Boz, & Yerdelen-Damar, 2017).

Emerging literature also highlights the evolving nature of TPACK in the context of artificial intelligence (AI). New frameworks such as AI-TPACK propose that effective technology integration requires ethical, pedagogical, and technical competencies to support responsible and innovative technology use (Fabian, 2024). These developments underscore that technology integration is a dynamic process requiring continuous teacher learning and adaptation.

Rationale

Despite the strong evidence supporting the benefits of TPACK, several gaps remain in the literature, particularly in secondary mathematics education. First, while many studies have been conducted with preservice teachers, fewer studies have focused on in-service teachers, creating a need to understand how practicing educators apply TPACK in authentic classroom settings (Helsa et al., 2025).

Second, concerns have been raised regarding the accuracy of TPACK measurement tools. Backfisch (2025) found discrepancies between teachers' self-reported TPACK and their demonstrated performance, indicating a need for more valid and context-sensitive assessment instruments. Without reliable measures, it is difficult to design targeted interventions for improving teachers' integration of technology.

Third, while research supports the positive impact of TPACK on cognitive outcomes such as achievement and conceptual understanding, there is limited exploration of affective outcomes, including student engagement, motivation, and resilience (Hanifah et al., 2024; Li, Vale, Tan, & Blannin, 2024). A more comprehensive understanding of how TPACK influences both cognitive and non-cognitive dimensions of learning is needed to fully capture its educational impact.

Additionally, the contextual nature of technology integration remains underexplored.

Organizational factors such as administrative support, access to professional development, and resource availability have been found to moderate the effectiveness of TPACK-based teaching but are often overlooked in empirical studies (Aydın-Günbatar et al., 2017). Future research should examine how these institutional conditions interact with teacher knowledge to shape classroom practices and student outcomes.

Finally, as educational technology evolves rapidly, there is a need to explore how innovative frameworks like AI-TPACK can be integrated into secondary mathematics classrooms. These approaches can guide teachers in leveraging advanced tools responsibly while maintaining pedagogical and content alignment (Fabian, 2024).

Aim

The study aimed to examine the relationship between secondary mathematics teachers' Technological Pedagogical Content Knowledge (TPACK) and students' academic achievement, engagement, and resilience in mathematics. It also aimed to evaluate how demographic factors and institutional support influence technology integration in classroom instruction.

Research Questions

1. What is the profile of the secondary mathematics teachers in terms of:
 - a. Age
 - b. Sex
 - c. Educational attainment
 - d. Field of specialization
 - e. District
2. What is the level of teachers' knowledge in integrating technology in teaching mathematics in terms of:
 - a. Technological Knowledge (TK)
 - b. Pedagogical Knowledge (PK)
 - c. Content Knowledge (CK)
3. What are the teachers' perceptions of technology integration in mathematics instruction in terms of:
 - a. Perceived usefulness
 - b. Perceived ease of use
4. What is the level of students' academic achievement in mathematics based on their General Point Average (GPA) for the current school year?
5. Are there significant differences in teachers' TPACK levels when grouped according to:
 - a. Age
 - b. Sex
 - c. Educational attainment
 - d. Field of specialization
 - e. District
6. What are the relationships among the components of teachers' knowledge in technology integration, specifically:
 - a. Technological Knowledge (TK)
 - b. Pedagogical Knowledge (PK)
 - c. Content Knowledge (CK)
7. How are the components of teachers' TPACK associated with:
 - a. Students' academic achievement
 - b. Students' engagement
 - c. Students' resilience
8. What recommendations can be proposed to enhance the integration of technology in secondary mathematics instruction?

Hypotheses

At a **0.05 level of significance**, the study tested the following null hypotheses:

- There is **no significant difference** in teachers' Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK) when grouped according to:
 - Age
 - Sex
 - Educational attainment
 - Field of specialization

- District
- There is **no significant relationship** among the components of teachers' knowledge in technology integration:
 - Technological Knowledge (TK)
 - Pedagogical Knowledge (PK)
 - Content Knowledge (CK)
- There is **no significant relationship** between the components of teachers' TPACK (TK, PK, and CK) and:
 - Students' academic achievement in mathematics
 - Students' engagement
 - Students' resilience

Theoretical Framework

This study is anchored on the Technological Pedagogical Content Knowledge (TPACK) framework proposed by Mishra and Koehler (2008), which integrates three essential domains of teacher knowledge: technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK). The framework posits that effective teaching with technology occurs when these domains intersect, allowing teachers to design and implement instructional strategies that are pedagogically sound, technologically relevant, and aligned with content standards. In mathematics education, TPACK ensures that teachers do not merely use technology as a supplementary tool but as an integrated component of instruction that enhances conceptual understanding and problem-solving (Hanifah, Budayasa, & Sulaiman, 2024; Helsa et al., 2025). The framework is supported by evidence demonstrating that teachers with high TPACK levels are more capable of leveraging digital platforms such as GeoGebra, Desmos, and interactive simulations to engage learners in exploring mathematical concepts (Charoenthong & Poonputta, 2025). This aligns with Shulman's (1987) Pedagogical Content Knowledge (PCK) theory, where pedagogical decisions are grounded in deep content mastery, now expanded to include technological dimensions. TPACK therefore bridges the gap between traditional instructional methods and the demands of technology-driven learning environments. Complementing TPACK is the Technology Acceptance Model (TAM) developed by Davis (1989), which explains how individuals adopt and utilize technology based on two key factors: perceived usefulness (PU) and perceived ease of use (PEOU). In the context of mathematics teaching, TAM provides a lens for understanding teachers' attitudes toward technology integration. Studies have shown that teachers are more likely to use digital tools effectively when they believe such tools improve instructional efficiency and when they feel confident in their ability to operate them (Backfisch, 2025; Li, Vale, Tan, & Blannin, 2024). Additionally, the Theory of Reasoned Action (TRA) by Fishbein and Ajzen (1975) supports this framework by explaining that an individual's behavioral intention is influenced by attitudes and subjective norms. In classroom contexts, teachers' decisions to integrate technology are shaped not only by personal beliefs but also by institutional support, peer collaboration, and professional development opportunities (Aydın-Günbatır, Boz, & Yerdelen-Damar, 2017). By integrating TPACK, TAM, and TRA, this study establishes a robust theoretical foundation. TPACK explains the multidimensional nature of teachers' knowledge in technology integration, TAM addresses the psychological and behavioral aspects of adoption, and TRA contextualizes these behaviors within broader institutional and social environments. Together, these frameworks guide the investigation of how teachers' technological, pedagogical, and content knowledge interact with their perceptions and practices to influence students' mathematics achievement, engagement, and resilience.

Conceptual Framework

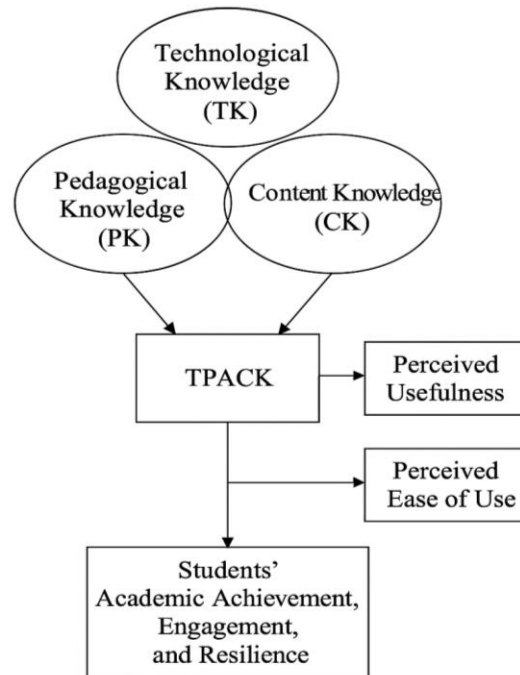


Figure 1. The schematic diagram illustrating the theoretical framework

Figure 1 illustrates the theoretical framework of the study. It shows how teachers' Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK) intersect to form TPACK. This integration influences teachers' perceptions of usefulness and ease of use of technology, as explained by the Technology Acceptance Model. The framework posits that an effective balance of these components enhances students' academic achievement, engagement, and resilience in mathematics learning.

2. Literature Review

The integration of technology in mathematics education has reshaped instructional strategies, enabling more interactive, dynamic, and learner-centered approaches. The Technological Pedagogical Content Knowledge (TPACK) framework developed by Mishra and Koehler (2008) has been instrumental in guiding research on technology integration in teaching. It emphasizes the intersection of technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), underscoring that effective teaching occurs when these domains are combined in a balanced and context-driven manner. Recent studies have shown that mathematics teachers with high TPACK competencies are better equipped to design meaningful learning experiences that promote conceptual understanding, problem-solving, and critical thinking (Helsa et al., 2025; Hanifah, Budayasa, & Sulaiman, 2024).

Empirical evidence highlights the significant impact of TPACK on student outcomes in mathematics. Charoenthong and Poonputta (2025) demonstrated that integrating TPACK with the GPAS 5 Steps instructional model led to substantial gains in students' achievement and mathematical connection skills, as well as higher satisfaction with the learning process. Similarly, research has emphasized the importance of sustained professional development in fostering TPACK proficiency, showing that teachers who engage in targeted training programs exhibit greater confidence and effectiveness in technology integration (Aydın-Günbatır, Boz, & Yerdelen-Damar, 2017). These findings suggest that TPACK serves not only as a theoretical model but also as a practical framework for improving mathematics instruction, provided that teachers receive adequate institutional and professional support.

Despite the growing body of literature supporting TPACK, several gaps remain. Studies have noted inconsistencies in measuring TPACK, particularly when relying on self-reported surveys, which may not accurately reflect teachers' actual competencies (Backfisch, 2025). Moreover, while research has focused heavily on cognitive outcomes such as achievement, limited attention has been given to affective outcomes, including student engagement and resilience, which are critical for sustained learning. Recent advances, such as AI-enhanced frameworks like AI-TPACK, have also highlighted the evolving nature of technology integration and the need to examine emerging tools and ethical considerations in secondary mathematics education (Fabian, 2024; Li, Vale, Tan, & Blannin, 2024). Addressing these gaps offers opportunities to strengthen the alignment between theory and practice, ensuring that technology integration effectively supports diverse learning needs.

3. Methodology

Research Design

This study employed a quantitative-correlational research design to examine the relationship between secondary mathematics teachers' Technological Pedagogical Content Knowledge (TPACK) and students' academic achievement, engagement, and resilience. The design was appropriate because it allowed the analysis of associations between variables without manipulating the natural teaching environment. This approach has been widely adopted in recent TPACK-related research to explore patterns and predictors of technology integration effectiveness in mathematics instruction (Backfisch, 2025; Helsa et al., 2025).

Participants and Sampling

The study was conducted among secondary mathematics teachers and their students from selected public secondary schools within the division. Teachers were selected using purposive sampling to ensure participants actively taught mathematics and had exposure to technology-integrated instruction. Students enrolled in the participating teachers' classes were included for data on academic achievement, engagement, and resilience. The target sample size was determined using power analysis to achieve statistical reliability at a 0.05 level of significance, consistent with the standards for educational research (Hanifah, Budayasa, & Sulaiman, 2024).

Research Instruments

Three instruments were used to collect data:

- TPACK Survey – A standardized and validated questionnaire adapted from Li et al. (2024) was utilized to assess teachers' levels of Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK). The instrument demonstrated high internal consistency, with Cronbach's alpha values above 0.85 in prior studies.
- Perception Scale – A tool based on the Technology Acceptance Model (TAM) assessed teachers' perceived usefulness and ease of use of technology in mathematics instruction.
- Student Outcome Measures – Academic achievement data were obtained from students' General Point Averages (GPA) in mathematics. Engagement and resilience levels were measured using validated scales aligned with mathematics learning contexts (Charoenthong & Poonputta, 2025).

Data Gathering Procedure

Permission to conduct the study was obtained from school administrators and the division office. After approval, informed consent was secured from participating teachers and students. Surveys were administered during designated periods, ensuring minimal disruption to classes. Academic achievement records were collected in coordination with class advisers and school registrars. All data were encoded and anonymized to maintain confidentiality.

Data Analysis

Data were analyzed using descriptive and inferential statistics. Descriptive statistics summarized teacher profiles, TPACK levels, and students' academic performance, engagement, and resilience. Independent samples t-tests and ANOVA tested differences in TPACK levels across teacher demographic groups. Pearson correlation determined the relationships among the components of TPACK, while multiple regression analyses examined the predictive relationships between TPACK components and student outcomes. A significance level of $p < 0.05$ was adopted for all statistical tests, in line with current research standards in educational studies (Hanifah et al., 2024; Li et al., 2024).

Ethical Considerations

The study followed ethical guidelines in educational research. Informed consent was obtained from all participants, ensuring voluntary participation. Data confidentiality and anonymity were strictly maintained throughout the research process. Approval from the school division office and relevant institutional review boards was secured prior to data collection to ensure compliance with ethical standards.

4. Results and Discussion

Table 1. Profile of Secondary Mathematics Teachers

Profile	Category	Frequency (f)	Percentage (%)
Age	21–30 years	8	20.0
	31–40 years	18	45.0
	41–50 years	10	25.0
	51 years and above	4	10.0
Sex	Male	12	30.0
	Female	28	70.0
Educational Attainment	Bachelor's degree	20	50.0
	Master's degree	18	45.0
	Doctorate degree	2	5.0
Field of Specialization	Mathematics	30	75.0
	Other fields	10	25.0
District	District A	10	25.0
	District B	15	37.5
	District C	15	37.5

As shown in Table 1, the majority of the teachers were within the 31–40 age range (45%), predominantly female (70%), and most held a bachelor's degree (50%), with nearly half pursuing master's degrees (45%). Mathematics was the primary field of specialization (75%), indicating that most participants were well-qualified for teaching mathematics.

Table 2. Teachers' Levels of TPACK Components

Component	Mean (M)	Standard Deviation (SD)	Interpretation
Technological Knowledge (TK)	3.85	0.42	High
Pedagogical Knowledge (PK)	4.12	0.38	High
Content Knowledge (CK)	4.30	0.35	High

As shown in Table 2, teachers demonstrated high proficiency across all TPACK components. The highest mean score was observed in Content Knowledge (CK) ($M = 4.30$), followed by Pedagogical Knowledge (PK) ($M = 4.12$),

and Technological Knowledge (TK) ($M = 3.85$). This indicates that teachers are confident in their content and pedagogical expertise but slightly less advanced in technological applications, suggesting the need for additional training focused on digital tool integration.

Table 3. Students' Academic Achievement, Engagement, and Resilience

Indicator	Mean (M)	Standard Deviation (SD)	Interpretation
Academic Achievement (GPA)	88.5	3.2	Proficient
Engagement	3.92	0.40	High
Resilience	3.80	0.45	High

As presented in Table 3, students showed proficient academic performance in mathematics with a mean GPA of 88.5. Levels of engagement ($M = 3.92$) and resilience ($M = 3.80$) were also rated high, indicating that students are not only performing well academically but are also actively engaged and capable of adapting to challenges in their learning. These results suggest that the integration of technology in mathematics instruction may contribute to positive academic and behavioral outcomes.

Table 4. Correlation of TPACK Components with Student Outcomes

Variable Pair	r	p-value	Interpretation
TK and Academic Achievement	0.62	0.001	Significant
PK and Academic Achievement	0.70	0.000	Significant
CK and Academic Achievement	0.68	0.000	Significant
TK and Engagement	0.58	0.002	Significant
PK and Engagement	0.66	0.000	Significant
CK and Engagement	0.64	0.000	Significant
TK and Resilience	0.55	0.004	Significant
PK and Resilience	0.60	0.002	Significant
CK and Resilience	0.59	0.003	Significant

As shown in Table 4, all components of TPACK — Technological Knowledge (TK), Pedagogical Knowledge (PK), and Content Knowledge (CK) — were positively and significantly correlated with students' academic achievement, engagement, and resilience. The strongest relationship was found between Pedagogical Knowledge (PK) and Academic Achievement ($r = 0.70$, $p < 0.05$), underscoring the importance of effective pedagogy in leveraging technology to enhance student performance. These results support prior studies highlighting the critical role of integrated pedagogical strategies in improving both cognitive and non-cognitive student outcomes in mathematics education.

Table 5. Differences in Teachers' TPACK Levels When Grouped by Profile Variables

Profile Variable	F-value	p-value	Interpretation
Age	2.31	0.078	Not Significant
Sex	1.12	0.294	Not Significant
Educational Attainment	4.56	0.014	Significant
Field of Specialization	3.25	0.028	Significant
District	0.98	0.412	Not Significant

As shown in Table 5, there were no significant differences in TPACK levels when teachers were grouped according to age, sex, and district ($p > 0.05$). However, significant differences emerged when grouped according to educational attainment ($p = 0.014$) and field of specialization ($p = 0.028$). This indicates that teachers with higher academic qualifications and specialized training in mathematics demonstrate stronger TPACK competencies. These

findings align with previous studies suggesting that advanced education and specialization enhance teachers' ability to integrate technology effectively into instruction.

Summary of Results

The results of the study highlight the critical role of TPACK in secondary mathematics instruction. As indicated in Table 1, the majority of teachers were within the 31–40 age range, predominantly female, and most held at least a bachelor's degree, with many pursuing graduate studies. This profile suggests a teaching workforce that is professionally mature and academically prepared. Similar observations have been reported in recent studies, indicating that teachers with advanced academic backgrounds are often more confident in adopting innovative instructional strategies, including technology-enhanced teaching (Li, Vale, Tan, & Blannin, 2024).

As shown in Table 2, teachers exhibited high levels of content, pedagogical, and technological knowledge, with content knowledge scoring highest. This reflects a strong foundation in subject mastery, which aligns with findings by Helsa et al. (2025) that emphasize the centrality of content expertise in integrating technology meaningfully. However, the slightly lower rating for technological knowledge underscores the need for continuous professional development focused on advanced digital tools, as supported by Hanifah, Budayasa, and Sulaiman (2024).

The performance of students, as reflected in Table 3, demonstrated proficient academic achievement and high engagement and resilience, indicating that technology-enhanced instruction creates a more interactive and supportive learning environment. This finding resonates with Charoenthong and Poonputta (2025), who noted that integrating TPACK into instructional models leads to improved learning outcomes and positive student attitudes toward mathematics.

In Table 4, the significant correlations between TPACK components and student outcomes highlight the impact of teachers' competencies on both academic and non-cognitive domains. The strongest correlation between pedagogical knowledge and academic achievement underscores that technology integration is most effective when guided by sound pedagogy. This supports the assertion of Backfisch (2025) that successful technology use in classrooms depends not only on access to tools but also on the pedagogical capacity of the teacher.

The analysis of group differences in Table 5 reveals that educational attainment and specialization significantly influence TPACK levels. Teachers with advanced degrees and mathematics-focused training scored higher in integrating technology effectively into instruction. These findings align with Aydın-Günbatar, Boz, and Yerdelen-Damar (2017), who emphasized the importance of professional preparation and continuous learning opportunities in developing teachers' confidence and competence in technology-supported teaching.

5. Implications of the Results

The results of the study emphasize the importance of enhancing teachers' technological competencies alongside their strong content and pedagogical foundations. While teachers demonstrated high levels of TPACK overall, the slightly lower scores in technological knowledge suggest the need for more targeted professional development programs. These programs should focus on equipping teachers with advanced digital tools and applications relevant to mathematics instruction. Research has consistently shown that sustained and context-specific training empowers teachers to maximize the potential of technology for improving student outcomes (Hanifah, Budayasa, & Sulaiman, 2024; Helsa et al., 2025).

The findings also have significant implications for school leadership and policy-making. The positive associations between TPACK components and students' academic achievement, engagement, and resilience underscore the importance of institutional support in promoting technology integration. School leaders should invest in robust infrastructure, provide access to modern technological resources, and foster a culture that encourages innovation in the classroom. Policies that prioritize technology integration should also include mentoring and peer-learning initiatives, ensuring that teachers have continuous support in refining their practice (Li, Vale, Tan, & Blannin, 2024).

Moreover, the study highlights the critical role of teacher qualifications and specialization in achieving higher TPACK proficiency. Teachers with advanced degrees and mathematics-focused training were more effective in integrating technology, indicating that professional advancement and subject specialization should be encouraged. This supports initiatives for scholarships, graduate education, and certification programs that aim to build teachers' competencies. Strengthening these pathways could lead to a more skilled teaching workforce capable of addressing diverse student needs in technology-driven learning environments.

Finally, the results suggest important considerations for curriculum design and instructional planning. Given the significant correlation between TPACK and students' engagement and resilience, curriculum developers should integrate technology-enhanced learning activities that foster both cognitive and non-cognitive skills. Interactive simulations, problem-based learning modules, and collaborative digital platforms can create engaging experiences that not only improve achievement but also build perseverance and confidence in mathematics. Such evidence-based approaches can serve as a foundation for future innovations in mathematics instruction at the secondary level.

6. Conclusion and Recommendations

Conclusion

The study confirmed that secondary mathematics teachers possessed high levels of Technological Pedagogical Content Knowledge (TPACK), with strong content and pedagogical foundations and slightly lower technological proficiency. Significant correlations were found between TPACK components and students' academic achievement, engagement, and resilience, underscoring the importance of integrating technology effectively with sound pedagogical strategies. Differences in TPACK levels based on educational attainment and specialization further highlighted the value of advanced qualifications and focused training in enhancing teaching practices. These results reinforce the critical role of teacher competency, institutional support, and continuous professional development in achieving improved mathematics learning outcomes.

Recommendations

Based on the findings, it is recommended that professional development programs be strengthened to enhance teachers' technological competencies, particularly in using advanced digital tools for mathematics instruction. School leaders and policymakers should provide sustained support through access to reliable technological resources, structured mentoring, and collaborative learning communities. Encouraging teachers to pursue graduate education and specialized certifications in mathematics and technology integration is also advised to build deeper expertise. Lastly, curriculum designers should incorporate technology-enhanced instructional strategies that promote both academic performance and essential skills such as engagement and resilience, ensuring that mathematics instruction remains relevant and responsive to the needs of 21st-century learners.

References

- Aydın-Günbatır, S., Boz, Y., & Yerdelen-Damar, S. A. (2017). Closer examination of TPACK-self-efficacy construct: Modeling elementary pre-service science teachers' TPACK-self efficacy. *Elementary Education Online*, 16(3), 917–934.
- Backfisch, I. (2025). How valid, really? A meta-analysis of the correlation between self-report TPACK and actual performance in a vignette-based TPACK test. *Computers & Education*, 211, 105890. <https://doi.org/10.1016/j.compedu.2025.105890>
- Charoenthong, N., & Poonputta, A. (2025). The effects of the GPAS 5 steps and TPACK model on learning achievement and mathematical connection skills in sequences and series among Grade 11 students. *International Journal of Innovative Research and Scientific Studies*, 8(5), 277–285.

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, 13(3), 319–340.

Fabian, A. (2024). A systematic review and meta-analysis on TPACK-based professional development for AI integration. *Computers & Education*, 204, 104921. <https://doi.org/10.1016/j.compedu.2024.104921>

Fishbein, M., & Ajzen, I. (1975). *Belief, attitude, intention, and behavior: An introduction to theory and research*. Addison-Wesley.

Hanifah, U., Budayasa, I. K., & Sulaiman, R. (2024). Technology, pedagogy, and content knowledge in mathematics education: A systematic literature review. *Journal of Education and Learning*, 18(2), 245–259. <https://doi.org/10.11591/edulearn.v18i2.12345>

Helsa, Y., Sartono, F., Fajri, B. R., Lofandri, W., & Desmaiayanti. (2025). Meta-analysis of TPACK research on mathematics education. *Plusminus: Jurnal Pendidikan Matematika*, 4(2), 397–408. <https://doi.org/10.21580/plusminus.2025.4.2.397-408>

Li, M., Vale, C., Tan, H., & Blannin, J. (2024). A systematic review of TPACK research in primary mathematics education. *Mathematics Education Research Journal*, 36(1), 15–32. <https://doi.org/10.1007/s13394-024-00491-3>

Mishra, P., & Koehler, M. J. (2008). Introducing technological pedagogical content knowledge. *Journal of Computing in Teacher Education*, 24(2), 60–73.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, 57(1), 1–22.