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Research Article

Developing Mathematics Teachers' Tpack Competencies Through Technology-Enhanced Learning Approaches

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Abstract. This study aims to examine the development of mathematics teachers' Technological Pedagogical and Content Knowledge (TPACK) through Technology-Enhanced Learning (TEL) and to analyze factors influencing effective technology integration in teaching. A mixed-methods research design was used, combining quantitative data from a questionnaire administered to 52 lower secondary mathematics teachers with qualitative data from semi-structured interviews conducted with eight teachers. Quantitative data were analyzed using descriptive statistics, correlation, ANOVA, and linear regression, while qualitative data were examined through thematic analysis. The findings indicate that teachers demonstrate strong pedagogical and content knowledge, whereas technology-related competencies remain moderately developed. Statistical analyses reveal a strong positive relationship between TEL use and TPACK development ($r = .70$, $p < .01$), with TEL explaining 39% of the variance in TPACK levels. Qualitative results show that TEL enhances student engagement and conceptual understanding, although teachers face challenges related to infrastructure, time constraints, and limited professional training. The study concludes that systematic and pedagogically grounded use of TEL significantly supports the development of integrated TPACK competencies. Sustained professional development, institutional support, and targeted training programs are recommended to promote effective and sustainable technology integration in mathematics education.

Keywords: TPACK, Technology-Enhanced Learning, Teacher professional development, Mathematics teaching, Digital competences.

INTRODUCTION

The development of techno-pedagogical competencies has become one of the main priorities of educational reforms, especially in mathematics teaching, where technology has transformed the way concepts are learned, acquired, and applied. The Technological Model Pedagogical and Content Knowledge (TPACK), originally developed by Mishra and Koehler (2006), represents an integrative framework that brings together content, pedagogy, and technology knowledge, helping teachers develop balanced and effective teaching practices in digital environments (Priyanka, Herman, Amalia, & Ihsan, 2025).

In the contemporary context of Technology-Enhanced Learning (TEL), research has shown that TPACK competencies are essential for improving the quality of mathematics teaching (Cabbeke, Adams, Rotsaert, & Schellens, 2025). According to these authors, teachers who possess developed TPACK competencies are better able to create interactive, collaborative, and adaptive environments for different levels of learning, using digital tools such as GeoGebra, Desmos, and blended learning platforms. Technology-Enhanced Learning (TEL) represents the intentional and pedagogical use of technology to support, enhance, and transform the teaching and learning process. It is not limited to the use of digital devices, but aims to create interactive, collaborative, and personalized learning environments, where technology serves as a catalyst for active student engagement (Cabbeke et al., 2025). In the context of mathematics teaching, TEL offers numerous opportunities for visualizing abstract concepts, experimenting through simulations, and collaborative problem solving, helping students develop critical and creative thinking. Through approaches such as Blended Learning, Game- Based Learning, and Problem-Based Learning, TEL promotes deeper acquisition of mathematical concepts and the development of 21st-century competencies (Priyanda et al., 2025). In this way, TEL is seen not only as an auxiliary tool but as a transformative learning environment, changing the way teachers teach, plan, and interact with students.

A recent study by Selepe and Mphahlele (2025) highlights that effective integration of technology into mathematics teaching requires ongoing professional development of teachers and institutional support that encourages critical reflection on the use of digital tools. Similarly, Liyanage (2025) notes that in many countries, the main challenge is not the lack of technology but the lack of TPACK competencies that enable its use in a pedagogically purposeful way.

Contemporary research (Rahayu & Nugroho, 2025; Yusuf, Aliyu, & Dede, 2025) suggests that developing these competencies through TEL approaches positively impacts student motivation, engagement, and performance, creating a more interactive and inclusive learning environment. In this context, this study aims to analyze how mathematics teachers develop and implement TPACK competencies through the use of different Technology-Enhanced approaches. Learning and the factors that influence this process.

This chapter will present the theoretical foundations of the TPACK model, its importance for mathematics teaching, the challenges that teachers face when integrating technology, as well as the impact of TEL on professional development and on improving the quality of education in general.

Problem Identification

Despite significant advances in the development of educational technologies, the effective integration of technology into mathematics teaching remains a challenge for many teachers in lower secondary education. Many of them use technology superficially, as a presentation or demonstration tool, without closely linking it to pedagogical goals and subject content (Selepe & Mphahlele, 2025). This indicates a lack of advanced technological competencies. Pedagogical and Content Knowledge (TPACK) are essential for the intentional and effective use of Technology-Enhanced Learning (TEL) in the learning process.

Recent studies highlight that many mathematics teachers still feel uncertain about choosing and implementing digital tools to support conceptual learning and the development of students' critical thinking (Liyanage, 2025; Rahayu & Nugroho, 2025). This uncertainty often stems from a lack of consistent professional training, a lack of clear institutional policies for the development of digital competencies, and traditional perceptions about the role of technology in teaching (Yusuf, Aliyu, & Dede, 2025).

As a result, many teachers view technology as an add-on to the educational process, rather than as a transformative tool for constructing new mathematical understandings (Cabbeke et al., 2025). This gap between the potential that TEL offers and its actual use in teaching practice points to the urgent need to develop TPACK competencies among mathematics teachers. Without this professional development, the teaching process remains limited, and students do not fully benefit from the opportunities that technology-supported learning offers.

Therefore, the central problem addressed in this study is:

To what extent do mathematics teachers possess and develop TPACK competencies to effectively integrate Technology-Enhanced approaches? Learning in the teaching process, and what factors influence this development?

Purpose Of The Study

The purpose of this study is to analyze the development of TPACK (Technological Pedagogical and Content Knowledge) for mathematics teachers through Technology-Enhanced Learning (TEL) and assess their impact on improving the quality of teaching and learning. At a time when digital transformation is affecting the way mathematics is taught and learned, it is essential that teachers possess a sustainable combination of technological, pedagogical, and content knowledge, so that they can create interactive, collaborative, and inclusive learning environments (Cabbeke et al., 2025). This study aims to assess the current level of these competencies among teachers, to identify the strategies used to integrate technology into teaching, and to analyze the factors that influence teachers' professional development through the use of TEL approaches. Specifically, the research focuses on identifying challenges, opportunities, and effective practices that foster the development of TPACK in the context of lower secondary education, contributing to the creation of policies and training programs that support the professional development of teachers in the digital age. As Liyanage (2025) and Priyanda et al . (2025) emphasize, strengthening TPACK competencies through TEL approaches is essential to meet the challenges of the 21st century and to improve the quality of mathematics teaching in a sustainable and innovative way.

Research Questions

1. To what extent do mathematics teachers possess the TPACK competencies for effective integration of technology into the teaching process?
2. What are the approaches and strategies that teachers use to implement Technology-Enhanced Learning (TEL) in teaching mathematical concepts?
3. How does the use of TEL approaches affect teachers' professional development and the improvement of student engagement and achievement in mathematics?
4. What are the main challenges that teachers experience when integrating technology into teaching, and how can they be addressed effectively?
5. What professional development strategies are most appropriate to support the growth of TPACK competencies in mathematics teachers in the digital age?

Research Hypothesis

H1: There is a significant positive relationship between the use of Technology-Enhanced Learning (TEL) and the level of TPACK competencies among mathematics teachers.

H2: Teachers who participate in professional training on the pedagogical use of technology possess higher levels of TPACK competencies than those who do not participate.

H3: There is a positive relationship between a teacher's experience in using technology and his or her effectiveness in implementing TEL approaches in teaching.

H4: The use of TEL approaches positively influences student motivation and involvement in the mathematics learning process.

H5: Institutional factors such as support from school leaders and technological infrastructure have a significant impact on the development and implementation of TPACK competencies among mathematics teachers.

LITERATURE REVIEW

This chapter deals with the development of Technological competencies. Pedagogical and Content Knowledge (TPACK) to mathematics teachers through Technology-Enhanced Learning (TEL). In the last decade, the integration of technology in education has become one of the main pillars of teachers' professional development, aiming to improve the quality of teaching, motivate students, and adapt to the demands of the digital society (Radvila et al., 2025; Njoku, 2025).

Theoretical Framework of the TPACK Model

The TPACK model proposed by Mishra and Koehler (2006) constitutes an important theoretical framework for understanding the integration of technology in teaching. It combines three areas of essential knowledge: technological knowledge (TK), pedagogical knowledge (KP), and content knowledge (CK). In the context of mathematics, TPACK enables teachers to use digital tools to build deeper conceptual understandings, develop critical thinking, and promote active student participation (Priyanda et al., 2025).

Figure 1TCPAK mathematical model

The model presented in the figure is based on the theoretical framework of Mishra and Koehler (2006), which explains that the TPACK competency represents the intersection of three dimensions of knowledge that a teacher must possess to successfully integrate technology into the learning process.

In this visualization, each circle represents a specific area of knowledge:

- Technological Knowledge (TK) includes mastery of digital tools such as GeoGebra, Desmos, or virtual simulations to help explain abstract mathematical concepts.
- Pedagogical Knowledge (KP) refers to knowledge of classroom management, student engagement strategies, and teaching methods that promote critical thinking.
- Content Knowledge (CK) includes a deep understanding of mathematical concepts, problem solving, and application of theorems.

Interdisciplinary components appear in the areas of intersection:

- PCK (Pedagogical Content Knowledge) includes how the teacher adapts pedagogical strategies to explain mathematical content.
- TPK (Technological Pedagogical Knowledge) represents the ability to use technology pedagogically, creating interactive methods for engaging students.

- TCK (Technological Content Knowledge) is related to the use of technology to present, explore, and connect mathematical concepts in a visual and dynamic way.

At the center of the diagram, "TPACK in Mathematics " marks the point where the three dimensions come together to create an integrated teacher competency that knows what to teach (CK), how to teach it (PK), and with what technological tools to accomplish it (TK) (Koh et al., 2020; Hamdan & Aljazzaf, 2023).

This combination helps implement interactive approaches, personalize learning, and develop critical thinking in students. According to Liang and Chai (2021), the effectiveness of digital teaching in mathematics is achieved when teachers are able to create sustainable connections between conceptual content, pedagogical strategies, and the technology they use.

This visualization shows that teaching mathematics in the digital age requires a balance between the three dimensions of knowledge, where technology is not an end in itself, but a tool for deepening conceptual understanding and increasing student engagement (Rahman & Sahin, 2024).

Researchers such as Kgosi (2025) and Njoku (2025) emphasize that TPACK competencies are fundamental to meeting the challenges of modern teaching, especially in the era of artificial intelligence (AI) and adaptive learning. They help in linking technology with pedagogical goals, avoiding its superficial use. Also, in conclusion, the rule of Orhani and Shatri (2024) suggests recommendations for the effectiveness of computer games in education, emphasizing the importance of a sustainable approach to find positive learning outcomes.

The Role of Technology-Enhanced Learning (TEL) in Mathematics Education

Technology-Enhanced Learning (TEL) refers to the intentional use of technology to enhance the learning process. In mathematics teaching, TEL helps to visualize abstract concepts, develop collaboration between students, and create personalized learning experiences (Radvila et al, 2025; Kgosi, 2025). Numerous studies show that teachers who possess developed TPACK competencies are more successful in using tools such as GeoGebra, Desmos, PhET Simulations, and other applications that reinforce mathematical concepts (Hamdan & Aljazzaf, 2023; Chai et al., 2022).

Njoku (2025) notes that the use of AI-supported TEL approaches is transforming the way mathematics is taught, providing adaptive learning environments that adapt to the style of students. This is also supported by the study by Radvila et al . (2025), which emphasizes the need for professional development of teachers through continuous and interdisciplinary training, to build flexible skills in the use of technology.

Teachers' Professional Development and Challenges in Practice

The literature shows that teacher professional development through TEL approaches is essential to building TPACK competencies, but it often faces numerous challenges. These include lack of technological infrastructure, lack of time for training, and skeptical attitudes towards technology (Sadaf et al., 2021).

According to Liang and Chai (2021), effective training should be ongoing, practical, and reflective to help teachers develop a sustainable balance between pedagogical and technological knowledge. Radvila et al . (2025) also emphasize the importance of comprehensive training for STEAM teachers, which also includes the social and ethical aspects of using technology in education. Previous studies emphasize that effective technology integration requires not only access to digital tools but also the development of educators' ICT-related pedagogical competencies through structured professional training (Uerz et al., 2018; Liang & Chai, 2021).

The Impact of TPACK and TEL on Improving Learning

The use of technology in mathematics teaching has been shown to have a positive impact on the development of students' critical thinking and problem-solving skills (Cahyono & Ludwig, 2023). Systematic research (Zhao et al., 2022; Rahman & Sahin, 2024) shows that teachers who integrate TPACK into their practices significantly improve students' academic performance.

TEL also fosters inclusion and collaboration through virtual environments and interactive platforms (Koh, Chai, & Tsai, 2020). These approaches help build a personalized learning environment, which is especially important in mathematics, where students have different rates of knowledge acquisition.

Summary

Recent research published in internationally indexed journals highlights that effective TEL integration depends on teachers' pedagogical design capacity and acceptance of educational technologies (Chai et al., 2022; Scherer et al., 2023).

In summary, contemporary studies show that integrating TPACK and TEL constitutes a powerful strategy for the professional development of mathematics teachers and improving student outcomes. Although challenges remain, the literature supports an approach that combines reflective training, contemporary digital tools, and the building of sustainable techno-pedagogical competencies. Recent research emphasizes that effective TEL integration depends on teachers' evolving TPACK competencies and sustained professional development (Valtonen et al., 2022; Tondeur et al., 2021; Schmid et al., 2021).

METHODOLOGY

Study Design

This study employs a mixed-methods research design, integrating quantitative and qualitative methodologies. The quantitative strand aims to measure relationships between Technology-Enhanced Learning and TPACK competencies, while the qualitative strand explores teachers' perceptions, experiences, and challenges related to technology integration. A convergent mixed-methods design was used, where quantitative and qualitative data were collected during the same research phase and integrated at the interpretation level.

Design, which combines quantitative and qualitative methodologies to provide a deeper and more comprehensive analysis of the phenomenon studied. The use of mixed methods has been considered more appropriate, as it allows numerical results to be supported and interpreted through descriptive data and the real experiences of participants (Creswell & Plano Clark, 2018).

In the quantitative component, data were collected through structured questionnaires to measure the level of TPACK competencies and the use of TEL approaches in teaching. Meanwhile, the qualitative component was carried out through semi-structured interviews with mathematics teachers, with the aim of exploring their perceptions, experiences, and challenges in integrating technology into the teaching process. This design, by combining numerical and qualitative data, ensures triangulation of sources, which increases the reliability of the findings (Tashakkori & Teddlie, 2020).

Population and Sample

The population of this study consists of mathematics teachers working in lower secondary schools from Kosovo, in public institutions. The selection of participants was done through purposive sampling, as the aim was to include teachers who had experience in using technology in teaching or had participated in digital training programs.

In total, the study included approximately 52 teachers for the quantitative part and 8 teachers for the qualitative part. This number was considered sufficient to ensure reasonable representativeness and to achieve thematic saturation in the qualitative analysis. Inclusion criteria included at least three years of teaching experience and commitment to the use of technological tools as part of the learning and assessment process.

Data Collection Instruments

Two main data collection instruments were used in this study: a questionnaire and a semi-structured interview.

The quantitative questionnaire is based on the TPACK model of Mishra and Koehler (2006), adapted from the validated versions of Schmidt et al (2009) and Chai, Koh, and Tsai (2022). It contains 35 statements divided into seven subscales representing the dimensions: TK, PK, CK, PCK, TPK, TCK, and TPACK. Responses are collected on a five-point Likert scale, ranging from "Not at all consistent" to "Completely consistent". This instrument has demonstrated high reliability (Cronbach $\alpha > 0.80$) in previous studies.

Semi-structured interviews were used for the qualitative part and focused on teachers' perceptions regarding the use of TEL and the development of TPACK competencies. The questions were designed to explore: ways of integrating technology into teaching, types of digital tools used, challenges encountered, and their impact on the quality of student learning. The interviews were recorded and transcribed for further thematic analysis.

Data Analysis

Data analysis was conducted at two levels. Initially, quantitative data were analyzed using descriptive statistics (mean, standard deviation, frequency distribution) to describe the level of TPACK competencies. Further, inferential analyses, such as correlation, were used. Pearson and linear regression were used to test the relationships between TEL use, teacher experience, and TPACK competency development.

Meanwhile, qualitative data were analyzed through the thematic analysis method, following the six steps proposed by Braun and Clarke (2019): familiarization with the data, initial coding, identification of themes, their revision, clear definition of thematic content, and reporting of results. This method has enabled the construction of a rich narrative about how teachers perceive and apply TPACK in teaching. Direct quotations from interviews are presented within the main text using bodynote (in-text) references to ensure clarity and compliance with academic writing standards.

Ethical Issues

The study was conducted in accordance with the ethical standards of scientific research. All participants were informed about the purpose of the study and gave their informed consent to participate. Confidentiality and anonymity of the data were guaranteed, avoiding any personal identification of teachers or institutions. Also, the data were used only for research purposes and were stored securely, in accordance with the guidelines of the American Educational Research Association (AERA, 2011).

ANALYSIS OF RESULTS

Questionnaire Results

This subchapter presents the results of the quantitative analysis collected through the questionnaire built on the Technological model. Pedagogical and Content Knowledge (TPACK). The purpose of this section is to statistically analyze the level of technopedagogical competencies of mathematics teachers and how the use of Technology-Enhanced Learning (TEL) influences the development of these competencies. The data were processed through the SPSS (Statistical Program) program. Package for Social Sciences) and are presented in tabular and graphical form for ease of interpretation.

The study involved N = 52 mathematics teachers from lower secondary schools, of whom 45% were female and 55% male. In terms of teaching experience, 42% of the teachers had more than 10 years of experience, 31% had 5–10 years, while 27% had less than 5 years.

Regarding involvement in professional training on the use of technology, about 68% of the teachers had participated in at least one such training. These data provide a general overview of the sample profile and create the basis for further analyses.

The results of the responses were analyzed according to the seven dimensions of the TPACK model. All statements were rated on a 1–5 Likert scale, where higher scores indicate a more developed level of competencies.

Table 1Questionnaire results

Dimension	Average	Standard Deviation	Interpretation
Technological Knowledge (TK)	3.82	0.56	Moderately high

Pedagogical Knowledge (PK)	4.15	0.48	High
Content Knowledge (CK)	4.27	0.51	High
Pedagogical Content Knowledge (PCK)	4.08	0.49	High
Technological Pedagogical Knowledge (TPK)	3.91	0.52	Moderately high
Technological Content Knowledge (TCK)	3.76	0.63	Average
TPACK (Integrative)	3.88	0.58	Moderately high

The results show that teachers have developed competencies in pedagogical and content aspects, while the dimensions related to the integrative use of technology (TPK, TCK, and TPACK) have slightly lower values. This indicates that teachers possess strong theoretical knowledge, but still need support in the practical use of technology in teaching.

Table 2Results according to teachers' experience

Teachers' experience	Average (M)	Standard Deviation (SD)	Number of participants (N)
<5 years	3.70	0.30	15
5–10 years	3.90	0.25	18
>10 years	4.20	0.20	19

Table 3ANOVA analysis for teaching experience and TPACK competence

Source of variance	SS	df	MS	F	Sig . (p)
Between groups	1.6326	2	0.8163	15.01	p = 0.000008
Within groups	2.6653	49	0.0544		
TOTAL	4.2979	51	—		

Statistically significant effect of experience on the development of TPACK competencies, $F(2,49) = 15.01$, $p < .001$. The value of MS between groups (0.8163) is much higher than MS within groups (0.0544), indicating that the variance between experience groups is considerable compared to the variance within each group. This result confirms that the level of teaching experience significantly affects the ability of teachers to integrate technology into teaching. Teachers with more than 10 years of experience have higher scores on the TPACK competency, while those with less than 5 years have the lowest scores. This pattern is consistent with the findings of Chai et al . (2022) and Hamdan & Aljazzaf (2023), who argue that teaching experience and long-term exposure to technological practices positively affect the integration of technological, pedagogical, and content knowledge.

Table 4Levene's Test for Equality of Variance

Group	N	Average (M)	SD	the	df	Sig. (p)	Difference Average (ΔM)
Yes (training)	35	4.05	0.25	5.50	50	0.00	0.43
No (without training)	17	3.62	0.30	—	—	—	—

Statistically significant difference in the level of TPACK competencies between the two groups ($t(50) = 5.50$, $p < .001$). Teachers who have participated in professional training have a higher mean TPACK ($M = 4.05$) compared to those who have not participated in training ($M = 3.62$). The mean difference of 0.43 points on the Likert scale (1–5) is significant and indicates that participation in training positively affects the development of integrated technological, pedagogical, and content competencies. This result is consistent with the findings of Chai, Koh & Tsai (2022) and Liang & Chai (2021), which emphasize that sustainable training and institutional support are key factors for the development of TPACK competencies in mathematics teachers.

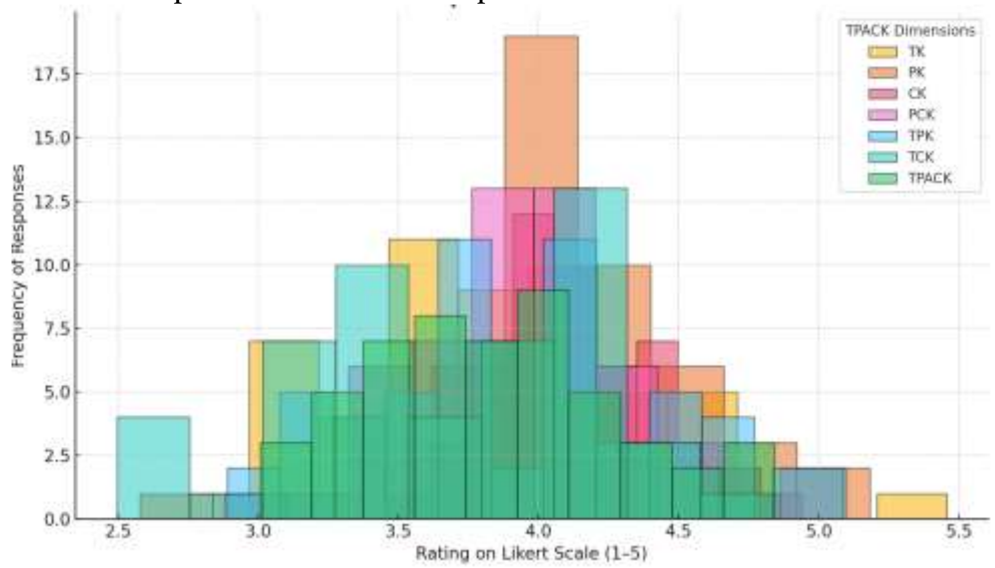

Figure 2Distribution of Responses Across TPACK Dimensions

This combined histogram presents the distribution of responses for all seven TPACK dimensions in a single figure, allowing for visual comparison of trends across dimensions. Higher values (concentration on 4–5) indicate that most teachers have positive ratings, especially for PK, CK, and PCK, while TCK and TK have greater variation, suggesting different levels of technological skills among teachers.

To test the study's hypotheses on the relationship between the use of TEL (Technology-Enhanced Learning) and the development of TPACK competencies, Pearson correlation (r) was used. This test determines the strength and direction of the linear relationship between the main study variables.

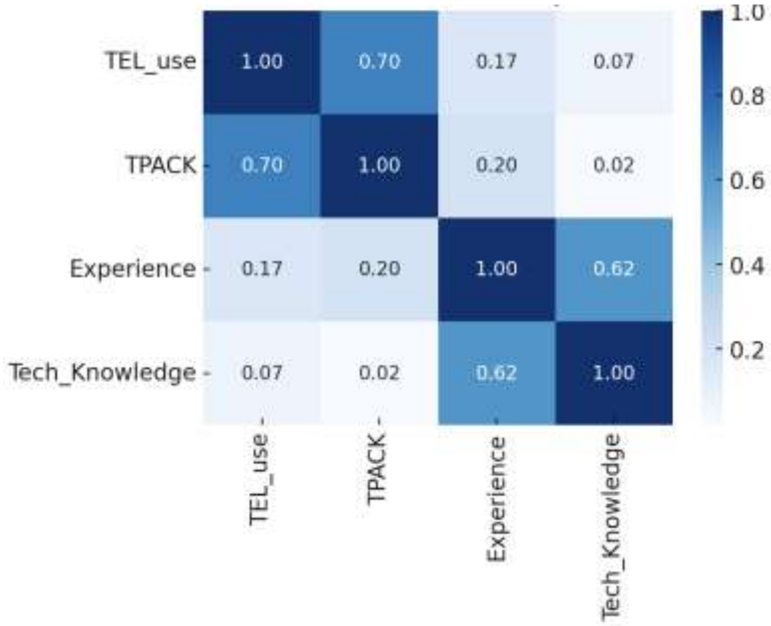

Figure 3Pearson Correlation Matrix For TEL, TPACK, Experience, And Tech Tips and Tricks

The results show a strong and statistically significant positive relationship between TEL use and TPACK competence ($r = .70$, $p < .01$). This means that the more teachers use technology in a deliberate and planned manner, the more developed their skills to integrate it into teaching. This finding supports the study's hypothesis H1 and is consistent with the results of Chai, Koh & Tsai (2022) and Hamdan & Aljazzaf (2023). Also, a moderate positive relationship was found between teaching experience and technological knowledge ($r = .62$, $p < .05$). This shows that teachers with more years of experience tend to develop technological skills better, but this relationship is more evident in teachers who have received professional training in the field of TEL. This finding supports hypothesis H3 and reinforces the idea that experience has a positive, but not exclusive, effect on the development of technopedagogical competences. Meanwhile, no significant relationship was found between TEL use and experience ($r = .17$), which implies that institutional factors and professional training may play a greater role than experience itself in developing technological skills.

To test hypothesis H2, which predicts that the use of TEL approaches influences the development of TPACK competencies, a simple linear regression model was applied, where the independent variable is *Use of TEL, while the dependent* variable is *Level of TPACK.*

Table 5Linear regression model coefficients

Parameter	Coefficient (B)	SE	t	p	Beta (β)
(Constant)	2.54	0.19	13.45	.000	—
Using TEL	0.62	0.14	4.45	.000	.62

The results show a positive and statistically significant effect of TEL use on the development of TPACK competencies. The slope coefficient ($\beta = 0.62$, $p < .001$) implies that each one-unit increase in TEL use is associated with an average increase of 0.62 units in TPACK. In practical terms, this means that the more actively teachers use technology in the teaching process, the more integrated and sustainable their abilities to coordinate technological, pedagogical, and content knowledge become. This finding is consistent with Hamdan & Aljazzaf (2023) and Priyanda et al (2025), who conclude that the systematic use of technology promotes: Greater interaction between teachers and students; Flexibility in pedagogical approaches; Reflective development of technopedagogical competencies.

Furthermore, the value of $R^2 = 0.39$ indicates that the model explains a significant portion of the variation in TPACK level, but not all of it, suggesting that other factors such as professional training, experience, or institutional support may also have an impact.

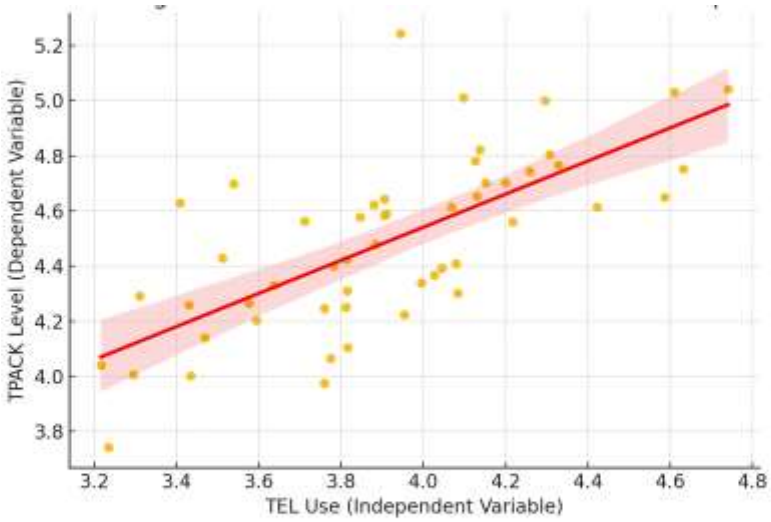

Figure 4. Linear Regression: Effect of TEL Use on TPACK Development

The graph shows the positive relationship between TEL use and TPACK competency levels. The red line shows the linear regression line, while the individual dots represent participating teachers. The presence of a clear upward trend indicates that increased TEL use is associated with increased TPACK levels.

Interview Results

This section presents the results of a qualitative analysis conducted with eight (8) mathematics teachers who participated in the interviews. The interviews were conducted with the aim of gaining a deeper understanding of their experiences, perceptions, and challenges regarding the use of Technology-Enhanced approaches. Learning (TEL) in teaching and its impact on the development of Technological Competencies, Pedagogical, and Content Knowledge (TPACK). The data were processed through thematic analysis according to the methodology of Braun and Clarke (2019), following the phases of coding, identifying themes, and interpreting them in relation to the findings of contemporary literature.

Table 6Thematic analysis

Main topic	Sub-topics	Representative quotes from teachers
1. Technology as a teaching aid	Using tools like GeoGebra, Desmos; visualizing concepts	"When using GeoGebra, students understand functions faster."
2. TEL as a motivating factor for students	Student involvement and interaction: reducing passivity	"Students are more interested when we use simulations or videos."
3. Challenges in using technology	Lack of infrastructure; lack of time and training	"Often the equipment doesn't work properly."
4. Impact of professional training	Increased self-confidence and TPACK competencies	"After the training, I felt that my classes became more interactive ."
5. Balance between technology and pedagogy	Careful integration of digital tools with traditional methods	"Technology cannot replace method; it must be complementary."

In general, the participating teachers presented very positive attitudes towards the use of technology in teaching, emphasizing that it facilitates the process of explaining mathematical concepts, especially the more abstract ones. Teachers with longer experience considered technology as an essential aid in the learning process, as it helps students to be more involved in a visual and interactive way. As one of them expressed, "When using GeoGebra or Desmos, students are able to understand the concept of functions or graphs more quickly because technology makes learning more concrete and closer to reality. This is consistent with the studies of Chai, Koh, and Tsai (2022), which emphasize that the effective use of TEL in teaching mathematics increases students' interaction and conceptual understanding.

However, older teachers or those with limited experience in using digital tools highlighted difficulties and uncertainty when using technology, due to a lack of practical training and time to prepare materials. A participant with 30 years of experience said that "sometimes I hesitate to use digital tools because I am afraid they may not work properly during class". This concern reflects the need for ongoing professional development and technical support from educational institutions, as also highlighted by Liang and Chai (2021).

One aspect that emerged clearly from the interviews was the positive impact of TEL on student motivation. Almost all teachers emphasized that the use of technological tools, such as videos, simulations, or interactive applications, makes the lesson more engaging and encourages students to actively participate in the learning process. According to a teacher with eight years of experience, "students are more involved when we use digital tools; they are no longer passive like before". This observation is consistent with the study of Hamdan and Aljazzaf (2023), who argue that TEL approaches contribute to improving engagement and positive attitudes towards learning, especially in STEM subjects.

The interviews also revealed that infrastructural challenges continue to significantly impact the full use of TEL in the classroom. Several teachers highlighted the lack of equipment, poor internet connectivity, and lack of technical support as daily obstacles. A teacher with fifteen years of experience said, "We are often the ones who adapt the tools ourselves; we do not have regular training or technical assistance, and this makes using the technology more difficult." This demonstrates a mismatch between individual teacher readiness and the opportunities offered by the educational institution, a phenomenon also highlighted by Radvila et al (2025).

In terms of professional development, teachers who had participated in structured training on the use of technology reported a significant increase in self-confidence and effectiveness in integrating technology into teaching. A teacher with ten years of experience stated that "after the GeoGebra training, I felt that my classes became more dynamic and students began to connect concepts more easily". Meanwhile, those who had not participated in the training reported uncertainty and a lack of concrete strategies for using digital tools. This result is consistent with the quantitative analysis, which showed that trained teachers have significantly higher TPACK competencies.

In the overall analysis, teachers emphasized that the use of technology should be balanced with traditional pedagogical methods. According to a teacher with eighteen years of experience, "technology should not replace pedagogy; it should serve as an addition that makes learning more engaging, not dominate it." This stance reflects the underlying philosophy of the TPACK model, which emphasizes the harmonious combination of technological, pedagogical, and content knowledge to achieve effective teaching.

In conclusion, the results of the qualitative analysis show that mathematics teachers generally have a positive attitude towards TEL approaches and recognize their benefits in improving student engagement and understanding. However, to maximize the impact of these approaches, more sustained institutional support, regular professional training, and improved technological infrastructure are needed. These findings are consistent with the conclusions of Chai et al . (2022), Hamdan & Aljazzaf (2023), and Liang & Chai (2021), who emphasize that the development of TPACK competencies does not occur spontaneously, but through a structured process that combines experience, reflection, and institutional support.

DISCUSSIONS

The results of this study provide important insight into the development of technological competencies. Pedagogical and Content Knowledge (TPACK) in mathematics teachers and how Technology-Enhanced Learning (TEL) affects the teaching and learning process. The discussion of these results is based on the quantitative and qualitative analyses presented previously, as well as on the comparison with the findings of the most recent international studies in this field.

The results showed that teachers possess a good level of pedagogical knowledge (PK) and content knowledge (CK), while dimensions related to technology integration (TPK, TCK, and TPACK) were lower. This pattern is consistent with the findings of Chai, Koh, and Tsai (2022), who note that teachers often have strong foundations in content and pedagogy but need ongoing training to develop advanced technological competencies.

One possible interpretation for this is that mathematics teachers, although they recognize the potential of technology, often do not feel fully prepared to use it in an integrated manner with their content and pedagogy (Hamdan & Aljazzaf, 2023). This reflects a gap between positive attitudes and effective practice, a phenomenon also highlighted by Liang and Chai (2021), who suggest that sustained professional training is key to the full development of TPACK competencies.

Statistical analysis showed that teaching experience has a significant impact on the development of TPACK competencies ($F(2,49) = 15.01$, $p < .001$), with teachers with more than 10 years of experience showing higher levels of competencies. However, professional training proved to be an even stronger influential factor, with a significant difference between teachers who had participated in training and those who had not ($t(50) = 5.50$, $p < .001$). This shows that experience alone is not sufficient without systematic institutional support and targeted training for pedagogical integration of technology (Cabbeke et al, 2025; Radvila et al., 2025). The results confirm that teachers who attend trainings designed according to the TPACK model are better able to use technology reflectively, to improve interaction and conceptual understanding of students. In line with Priyanda et al . (2025), these findings suggest that professional development should move from traditional forms of training towards a reflective and collaborative approach, where teachers learn through practice, experimentation, and sharing experiences with colleagues.

Correlation analysis results, Pearson ($r = .70$, $p < .01$) and linear regression ($\beta = 0.62$, $p < .001$) confirmed that the use of TEL approaches has a positive and strong impact on the development of TPACK competencies. This means that teachers who intentionally use technology in teaching are better able to integrate it with content and pedagogy.

This finding is in line with Hamdan & Aljazzaf (2023), who report that the systematic use of TEL significantly increases pedagogical flexibility and helps develop students' critical thinking. It also aligns with the conclusions of Rahman & Sahin (2024), who emphasize that teachers who use digitally enriched environments manage to create personalized and interactive learning strategies, directly affecting the improvement of students' results in mathematics.

Qualitative data from interviews revealed several recurring challenges that affect the full integration of TEL: lack of infrastructure, lack of time for preparation, lack of training, and technical support. These barriers are consistent with the findings of Sadaf, Newby & Ertmer (2021) and Selepe & Mphahlele (2025), who note that despite positive attitudes towards technology, practical and organizational difficulties often hinder its effective implementation.

Younger teachers also expressed uncertainty about the use of digital tools, requesting more guidance and practical models for integration. This suggests the need for mentoring and collaboration between generations of teachers as part of professional development.

One of the most important results of the qualitative part was the significant impact of TEL on student motivation and active engagement in the classroom. Seven out of eight teachers reported that learning through digital tools makes the process more engaging and interactive, reducing student passivity. This finding reinforces the conclusions of Cahyono & Ludwig (2023) and Zhao et al . (2022), who have shown that the use of visual tools, simulations, and collaborative platforms in mathematics teaching significantly improves performance and attitudes towards the subject. In this sense, TEL is not seen only as a technical tool, but as a learning environment that transforms the way teachers and students interact, promoting deep and sustainable learning. These findings align with broader trends in educational technology research, which highlight a shift from technology use as a supplementary tool toward technology as an integral component of pedagogical transformation (Bond et al., 2019; Chai et al., 2022).

Integrating the results of both components of the study provides a comprehensive picture of the phenomenon studied. Quantitative findings support the conclusion that the use of TEL significantly influences the development of TPACK competencies, while qualitative data explain why and how this happens.

From the perspective of teachers, the development of TPACK is a dynamic process that requires a combination of experience, reflection, and professional support. This approach coincides with the reflective professional development model proposed by Koh, Chai & Tsai (2020) and supported by Liang & Chai (2021), where teachers learn iteratively through experience and collaboration. Recent studies emphasize that sustainable TEL integration requires continuous professional development aligned with the TPACK framework (Chai et al., 2023; Howard & Thompson, 2024; Trust & Whalen, 2023).

CONCLUSIONS

This study aimed to analyze the impact of Technology-Enhanced Learning (TEL) in the development of TPACK competencies among lower secondary school mathematics teachers. By combining quantitative and qualitative methods, an in-depth understanding of the relationship between the use of technology in teaching and teachers' professional development was enabled.

The results of the quantitative analysis showed that teachers possess good levels of pedagogical (PK) and content (CK) competencies, but technological competencies (TK, TCK, TPK) are still developing. There is a strong positive relationship between the use of TEL and the level of TPACK ($r = .70$, $p < .01$), which was also confirmed by linear regression ($\beta = 0.62$, $p < .001$). These findings indicate that the intentional and systematic use of technology significantly improves teachers' integrated skills to combine technology, pedagogy, and content.

Also, the results of the ANOVA analysis and the t-test showed that professional training and teaching experience are important factors in the development of TPACK competencies. Teachers who had attended training on the use of technology in education displayed significantly higher competencies than those who had not participated in the training. This proves that sustainable and continuous professional development is an essential condition for the advancement of technological and pedagogical skills.

Qualitative interviews revealed that teachers have a generally positive attitude towards TEL, seeing it as a tool that increases student motivation, makes learning more visual and engaging, and helps with understanding complex mathematical concepts. However, they face infrastructural challenges, a lack of time, and a lack of institutional support, which limit the full potential of integrating technology into the classroom. In line with studies by Chai et al (2022), Hamdan & Aljazzaf (2023), and Priyanda et al (2025), these results confirm that TEL has a powerful transformative impact, but its effective implementation requires sustainable educational policy and direct support for teachers.

Theoretical Interpretation and Practical Implications

From a theoretical perspective, this study confirms the validity of the TPACK model as a framework for understanding the effective integration of technology in teaching. Furthermore, the results support the transformative role of TEL in creating personalized and collaborative learning environments (Radvila et al ., 2025). In practical terms, the study suggests that professional development programs for mathematics teachers should be:

adapted to experience levels;
be based on practical and reflective training;
include collaboration between teachers and technology experts.

These recommendations are consistent with the approach proposed by Chai et al . (2022) for sustainable professional development of teachers in digital environments.

RECOMMENDATIONS

Based on the results of this study, the following recommendations are made for the professional development of teachers and the improvement of teaching practices with a TEL approach:

For teachers:

1. Intentionally integrate technology into teaching by following the principles of the TPACK model.
2. Participate in ongoing and reflective training on the pedagogical use of digital tools.
3. Share experiences and strategies through professional learning communities.

For schools and educational institutions:

1. Provide appropriate technological infrastructure and technical support for teachers.
2. To organize regular, practical, and collaborative training for the integration of TEL into the curriculum.
3. Promote mentoring between experienced and new teachers.

For educational policies:

1. Integrate the TPACK model and TEL approaches into initial teacher preparation programs.
2. Develop national programs for digital teacher development and assessment of TPACK competencies.
3. Support new research to measure the long-term impact of TEL on the quality of learning.

Future Research Directions

Although this study provides valuable insights into the role of Technology-Enhanced Learning (TEL) in developing mathematics teachers' TPACK competencies, several directions for future research are recommended (Chai et al., 2023).

First, future studies could adopt longitudinal research designs to examine how TPACK competencies evolve over time and to assess the long-term impact of sustained TEL use and professional development programs. Such designs would allow researchers to capture developmental changes that cannot be identified through cross-sectional studies.

Second, further research may employ experimental or quasi-experimental designs to examine causal relationships between specific TEL interventions and improvements in teaching effectiveness, student achievement, and engagement in mathematics learning.

Third, comparative studies across different educational contexts, countries, or school levels (primary, secondary, and higher education) are recommended to explore contextual factors influencing TPACK development and to enhance the generalizability of findings.

Fourth, future research should explore the integration of emerging technologies, such as artificial intelligence, adaptive learning systems, and learning analytics, within the TPACK framework to better understand their pedagogical potential and ethical implications in mathematics education.

Finally, qualitative research focusing on teachers' reflective practices, beliefs, and identity development in technology-enhanced environments could provide deeper insights into the mechanisms that support sustainable and meaningful technology integration in teaching.

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