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Understanding TPACK Implementation in STEM Mathematics Education: A Phenomenological Study of Indonesian Senior High School Teachers

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Abstract

The successful integration of technology in STEM-based mathematics education depends on teachers' Technological Pedagogical Content Knowledge (TPACK). However, most studies have examined teachers' TPACK through surveys and intervention-based research, offering limited insight into how teachers experience and apply TPACK in classroom practice. This study explored Indonesian senior high school mathematics teachers' lived experiences of understanding, implementing, and supporting TPACK in STEM-based mathematics instruction. A qualitative descriptive study with a phenomenological orientation was conducted with twelve mathematics teachers from six Indonesian provinces selected through purposive criterion sampling. Data was collected between November and December 2026 over a two-month period using semi-structured interview guidelines developed by researchers and validated by experts. Data were analysed inductively following Bogdan and Biklen's qualitative data analysis procedures. The findings revealed that teachers understood TPACK as an integrated instructional framework, enacted it by using digital technologies to support concept visualisation, inquiry-based learning, and formative assessment, and perceived school support, practice-oriented professional development, and collaborative teacher communities as essential for effective implementation. These findings suggest that successful TPACK implementation depends on the interaction between teachers' professional knowledge, instructional practice, and institutional support. This study contributes to the TPACK literature by providing a phenomenological perspective on teachers' experiences of technology integration in STEM-based mathematics education. The study further highlights the importance of sustained professional learning, collaborative teacher communities, and institutional support in enabling meaningful technology integration in STEM-based mathematics classrooms.

Keywords: TPACK, phenomenology, STEM, mathematics education, mathematics teachers, senior high school

1. Introduction

The demands of 21st-century education increasingly require mathematics learning to move beyond procedural fluency toward meaningful problem solving supported by technology. Within STEM education, mathematics is expected to help students apply concepts flexibly in real-world contexts while developing higher-order thinking skills. Prior research indicates that technology can support this shift by fostering conceptual understanding and mathematical meaning-making rather than merely facilitating routine tasks (Hoyles, 2018; Naidoo & Reddy, 2023; Ran et al., 2022). Empirical evidence further shows that technology-integrated mathematics instruction enhances students' problem-solving abilities and overall mathematical competence (Baccaglini-Frank & Lisarelli, 2023; Lu & Xie, 2024; Risnanosanti & Ristontowi, 2019). Consequently, mathematics instruction is increasingly expected to be implemented through STEM-based approaches that integrate technology in purposeful and meaningful ways.

Despite its potential, STEM-based mathematics instruction is complex and highly contextual. Its implementation varies across classrooms due to differences in instructional models, student characteristics, school culture, and institutional conditions. Studies across Asian and global contexts reveal that STEM effectiveness is strongly shaped by teachers' instructional decisions, professional judgment, and classroom practices rather than curriculum design alone (Le et al., 2021; Wahono et al., 2020; Zhang & Zhou, 2023). These findings highlight the pivotal role of teachers in translating STEM principles into meaningful mathematics learning experiences.

Previous research consistently shows that teachers' professional knowledge and experience influence the enactment of STEM-based mathematics instruction. Teachers' perceptions of their pedagogical and technological competence shape curriculum interpretation, instructional strategies, and responses to classroom challenges (Dong et al., 2020; Margot & Kettler, 2019). In developing contexts, instructional practices are further shaped by beliefs about learning, assessment demands, and resource limitations, all of which directly affect students' learning experiences (Aslam et al., 2023). Collectively, these studies emphasise that effective STEM-based mathematics instruction depends on teachers' ability to integrate content, pedagogy, and technology in context-sensitive ways.

This integration is conceptually framed within the TPACK framework. However, existing TPACK research has largely focused on measuring teachers' knowledge levels or evaluating implementation outcomes through survey-based or design-oriented approaches (Khong et al., 2023; Miguel-Revilla et al., 2020; Tseng et al., 2022). While informative, such studies offer limited insight into how teachers experience, interpret, and construct TPACK within the everyday realities of STEM-based mathematics classrooms, particularly in culturally and institutionally specific contexts. Limited attention has been paid to teachers' lived experiences and meaning-making processes underlying TPACK implementation, despite evidence that school culture and professional context strongly shape instructional practices (Sellami et al., 2022; Sokha, 2024; Wang et al., 2020).

Given that STEM-based mathematics instruction is enacted through teachers' situated practices, beliefs, and interactions within specific cultural and institutional environments, understanding TPACK requires close attention to how teachers experience, perceive, and assign meaning to this integration in their professional lives. From this perspective, phenomenology is particularly appropriate, as it seeks to explore participants' lived experiences, the subjective meanings they construct, and how individuals perceive, understand, and make sense of a phenomenon in everyday contexts. Accordingly, understanding TPACK in STEM-based mathematics learning requires attention to teachers' subjective experiences and contextual meaning-making processes.

The ideal condition for implementing TPACK capabilities is when teachers can master technological knowledge, pedagogy, and mathematics content in a balanced, integrated manner, and are supported by continuous training, professional collaboration, and adequate access to technology. Teachers can combine content knowledge, pedagogy, and technology in harmony, not just mastering each separately, but being able to adapt the use of technology to learning strategies and teaching materials (Mansour et al., 2024). Teachers can design, implement, and evaluate mathematics learning by harmoniously combining technology, pedagogical strategies, and content understanding (Patahuddin et al., 2016). The use of technology not only as a tool, but also to deepen understanding of concepts and increase student engagement through dynamic visualisation, interactive simulations, and structured digital assignments, teachers actively participate in training, reflection, and collaboration to update TPACK knowledge and skills, as well as be able to overcome new technological challenges (Pazilah et al., 2025; Y. Zhang et al., 2023). To maximise the implementation of TPACK capabilities, adequate technological infrastructure and access to digital learning resources are essential, as are institutional support and school policies, to create an environment that supports TPACK-based learning innovations.

The main challenges teachers face in implementing TPACK in STEM-based mathematics learning include insufficient training, limited resources, variations in competencies, learning design difficulties, and a lack of institutional support. The lack of specialised training focused on integrating technology into mathematics and STEM is a major obstacle; teachers often do not receive relevant, sustainable professional development (Kholid et al., 2023). Other research reports gaps in access to and quality of technological resources, significant differences between school contexts (e.g., cities and villages), and variations in TPACK competencies and teachers' digital skills that lead to minimal or suboptimal use of technology in STEM-based mathematics learning (M. Li et al., 2025a; Wohlfart & Wagner, 2023). Studies on STEM-TPACK in mathematics education also show that teachers and prospective teachers have difficulty designing integrated learning activities, face contextual and policy challenges, and feel inadequate institutional support, hence the need for stronger training and systemic support program design.

The main reason for this research is to uncover the gap between the theoretical framework of TPACK and the reality of teachers in the integration of technology in the classroom. This gap arises because top-down STEM integration policies tend to assume that technological mastery is theoretically automatically directly proportional to success in the classroom. In fact, teachers' pedagogical decisions in the field are greatly influenced by subjective perceptions, school social dynamics, and independent adjustment to infrastructure limitations. If TPACK were measured only through quantitative instruments or technical indicators alone, the internal factors and local contexts that determine the real success of technology integration would remain unobserved.

To address this gap, this study adopts a phenomenological approach to explore how senior high school mathematics teachers in Indonesia experience and make sense of TPACK within STEM-based instruction. Specifically, the study investigates teachers' experiences in understanding the TPACK framework, implementing TPACK in STEM-oriented mathematics classrooms, and interpreting the factors that support such implementation. The following research questions guide the study: (1) How do teachers experience and understand the TPACK framework in STEM-based mathematics instruction? (2) How do teachers experience the implementation of TPACK in classroom-based STEM-oriented mathematics instruction? Moreover, (3) What meanings do teachers attribute to the supporting factors influencing the implementation of TPACK in STEM-based mathematics instruction?

This research makes an important contribution to the treasure trove of science and STEM educational practice by conceptualizing TPACK no longer just as a static cognitive knowledge framework, but as a dynamic, context-bound, and socio-culturally negotiated lived practice by teachers. Empirically, this study presents an in-depth portrait of how technology is integrated by high school mathematics teachers in six provinces in Indonesia, thus providing a perspective that complements the dominance of quantitative studies. In practice, this teacher-centered understanding provides a concrete foundation for policymakers, principals, and training providers to design more realistic and field-need-based teacher professionalism development programs, as well as formulate sustainable STEM curriculum implementation strategies in developing countries.

1.1 STEM-Based Mathematics Instruction

STEM-based mathematics instruction is commonly conceptualised as an interdisciplinary and student-centred approach that emphasises the application of mathematical knowledge to authentic, real-world problems. (Metpattarahiran, 2021; Nhung & Hanh, 2021). Rather than positioning mathematics as an isolated subject, STEM frameworks highlight its role as an analytical and modelling tool that supports inquiry, technological application, and engineering design processes (Chuchalin & Zamyatin, 2021; Palacios, 2022). When meaningfully integrated, STEM-based mathematics learning has been shown to enhance student engagement, contextual understanding, and problem-solving competence (Douglas et al., 2025; Horváth & Farkas, 2025).

In practice, STEM implementation in mathematics classrooms typically follows silo, embedded, or integrated models (Roehrig et al., 2021). While silo and embedded approaches are more accessible, they often limit interdisciplinary coherence or conceptual depth (Goovaerts et al., 2019; Larkin & Lowrie, 2023). Integrated STEM approaches, by contrast, explicitly connect mathematics with science, technology, and engineering through problem-based and project-oriented learning, positioning mathematics as a conceptual foundation rather than a procedural tool (Baker & Galanti, 2017; Dominguez et al., 2023). However, the effectiveness of such integration largely depends on teachers' instructional decisions, professional knowledge, and classroom contexts, underscoring the importance of examining how teachers experience and enact STEM-based mathematics instruction.

1.2 TPACK as a Framework for STEM-Based Mathematics Instruction

The integration of content, pedagogy, and technology in STEM-based mathematics instruction is commonly framed through the lens of Technological Pedagogical Content Knowledge (TPACK) (Koehler & Mishra, 2009) (Figure 1). TPACK emphasises the dynamic interaction among these knowledge domains, highlighting that effective technology integration is inherently context-sensitive and shaped by instructional goals, curricular demands, and classroom realities. Empirical studies across different educational systems demonstrate that the relative emphasis of TPACK components varies according to policy contexts, professional culture, and institutional conditions (Ning et al., 2024; Soler-Costa et al., 2021; Chen et al., 2022; S. Li et al., 2022).

Within mathematics education, TPACK has been associated with teachers' ability to select appropriate digital tools, design interactive learning activities, and support students' conceptual understanding. Studies report that TPACK-informed instructional practices—such as dynamic visualisation, simulations, and structured digital tasks—can enhance student engagement and learning outcomes (Bueno et al., 2021; Chatmaneerungcharoen, 2024a; Priyanda et al., 2025). Nevertheless, despite its widespread adoption as a guiding framework, TPACK enactment remains highly variable across teachers and educational contexts, suggesting that possessing the TPACK concept does not guarantee coherent implementation in practice.

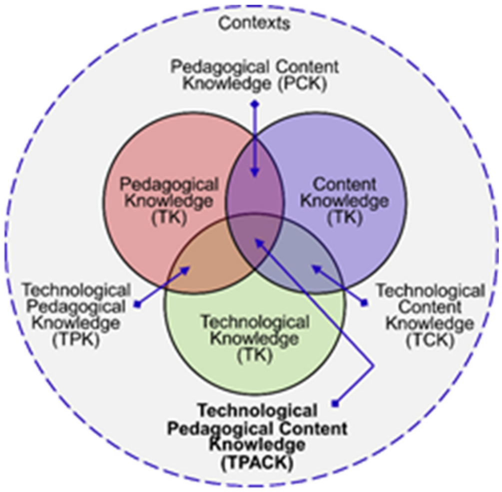

Figure 1. TPACK Framework and Its Knowledge Components (Koehler & Mishra, 2009)

1.3 Challenges and Gaps in Teachers' TPACK Implementation within STEM Contexts

Existing research identifies persistent challenges in implementing TPACK within STEM-based mathematics instruction. Teachers often encounter difficulties in connecting mathematical concepts to science, technology, and engineering in authentic, transdisciplinary ways (Chai et al., 2019; Dolgopolovas & Dagiene, 2024). Imbalances among TPACK components are also common, with teachers often demonstrating stronger technological knowledge than pedagogical or content knowledge, resulting in fragmented integration (Hanifah et al., 2024; Mansour et al., 2024b). In many cases, technology is still used as a supplementary tool rather than as a medium for knowledge construction and collaboration (Y. Helsa, 2023).

Structural constraints further complicate TPACK implementation. Limited access to sustained professional development, insufficient institutional support, time constraints, and unequal technological resources remain persistent barriers (Kholid et al., 2023; Viberg et al., 2020b; Wahono et al., 2025). However, much of the existing evidence is derived from survey-based assessments, competency measurements, or intervention-focused studies. While these approaches document challenges and outcomes, they offer limited insight into how teachers personally experience, interpret, and construct TPACK within the everyday realities of STEM-based mathematics classrooms. Consequently, there remains a critical need for research that moves beyond measuring TPACK competence toward examining teachers' lived experiences and contextual meaning-making processes. This gap is particularly salient in culturally and institutionally specific contexts, such as Indonesian senior high schools, where school culture, professional norms, and systemic constraints strongly shape instructional practice.

2. Method

This study employed a qualitative descriptive approach with a phenomenological orientation to explore Indonesian senior high school mathematics teachers' experiences of TPACK integration in STEM-based mathematics instruction. A phenomenological orientation was selected because the study focused on understanding how teachers experienced and interpreted TPACK integration within their professional practice rather than evaluating instructional effectiveness (Crawford, 2019; Lindseth & Norberg, 2022; M. Zhang & Fang, 2022). By staying close to the data in its natural context, The study adopted a phenomenologically informed design that emphasised teachers' lived experiences in authentic educational settings while allowing flexible thematic interpretation. This approach directly aligned with the study's focus on teachers' understanding of TPACK, its implementation in STEM mathematics instruction, and the factors that facilitate or constrain its integration, thereby ensuring both operational clarity for future replication and contextual depth in revealing teachers' subjective perspectives (M. Li et al., 2025b; M. Li & Li, 2024).

This study was conducted in the context of Indonesian senior high school mathematics education, where recent curriculum reforms have promoted technology integration and STEM-oriented learning. The participants were twelve mathematics teachers (n = 12) from six provinces: West Java, Central Java, Yogyakarta, East Java, West Sumatra, and West Nusa Tenggara, selected based on prior evidence of STEM implementation in mathematics education (Laksmiwati et al., 2024). The sample size of 12 participants was considered methodologically correct because the recommended pre-insertion range for qualitative research with phenomenological types was 3 to 25 participants (Creswell & Poth, 2016; Polkinghorne, 1989). In addition, the qualitative literature shows that in-depth interviews conducted on 12 participants are sufficient to achieve valid data, where no new thematic insights emerge regarding the shared experiences experienced by the participants (Guest et al., 2006; Hennink & Kaiser, 2022). This can allow the research to capture the diverse regional perspectives of the six provinces, while maintaining the depth needed for meaningful qualitative analysis. Using purposive criterion sampling, participants were required to (1) teach mathematics at the senior high school level, (2) have at least two years of teaching experience, (3) have implemented STEM-based mathematics instruction, and (4) consent to participate in in-depth interviews. Meanwhile, exclusion *criteria* are applied to eliminate teachers who: (1) have never implemented STEM-based learning in the classroom, (2) only use technology for administrative purposes or one-way presentations without any pedagogical integration of mathematics, and (3) are not actively teaching during the study. The determination of this criterion is very crucial to ensure the accuracy of the participants (*sample appropriateness*) and maintain the depth and relevance of the qualitative analysis. Data collection continued until no new insights emerged, indicating data saturation. Participants' demographic characteristics are presented in Table 1.

Table 1. Demographic Characteristics of the Participants

Category	Subcategory	n	%
Gender	Male	3	25
	Female	9	75
Age	25–30	4	33.3
	31–40	3	25
	41–50	2	16.7
Educational Background	Bachelor's degree (S1)	8	66.7
	Master's degree (S2)	4	33.3
Teaching Experience (years)	1–5	5	41.7
	6–10	3	25
	11–15	1	8.3
	16–25	3	25
N		12	100

The semi-structured interview protocol was developed based on the study objectives, the TPACK framework, and previous research on technology integration in STEM mathematics education. The protocol was reviewed by two experts in mathematics education and educational technology to evaluate its relevance and clarity. A pilot interview involving two mathematics teachers was subsequently conducted, resulting in minor revisions to question wording and sequencing. The final protocol consisted of open-ended questions and probing prompts designed to facilitate in-depth exploration of teachers' experiences.

Data were collected through in-depth semi-structured interviews, which are commonly employed in phenomenological research to elicit rich descriptions of lived experiences (Yuksel-Arslan et al., 2016). The data collection process took place over a two-month period, from November to December 2026. The interviews explored teachers' experiences with their understanding of TPACK, its implementation in STEM-based mathematics instruction, and the factors that support or constrain its application. All interviews were conducted online via Zoom, lasted approximately 45–60 minutes per session, and were scheduled according to participants' availability. The interviews were conducted in Indonesian to allow participants to express their experiences comfortably and authentically. With participants' consent, all interviews were audio-recorded and transcribed verbatim. To enhance depth and credibility, time triangulation was applied by conducting the interviews in two stages with a 2- to 3-week interval between sessions, allowing participants to reflect further on their experiences and refine their perspectives (Denzin, 2017). The interview protocol is summarized in Table 2.

Table 2. Interview Questions

Focus Area	Questions
Teachers' understanding of TPACK	Could you please describe your experiences in understanding TPACK from both theoretical and practical perspectives?
Teachers' implementation of TPACK	Could you please explain your experiences in implementing TPACK in STEM-based mathematics instruction?
Supporting factors for TPACK implementation	What factors do you perceive as facilitating the effective implementation of TPACK in STEM-based mathematics instruction?

Data analysis followed the qualitative data analysis procedures proposed by Bogdan & Biklen (2007) The analysis involved five main stages: data reduction, coding, theme development, relating themes, conclusion and interpretation (Figure 2). First, all interview recordings were transcribed verbatim. The researchers then immersed themselves in the data by reading and rereading the transcripts to gain a comprehensive understanding of participants' experiences. Initial codes were generated inductively from the data, followed by the development of subthemes and broader themes. To enhance analytic rigour, two researchers independently reviewed the emerging themes and engaged in reflective discussions to reach consensus. The final themes were refined, clearly defined, and interpreted to address the research questions.

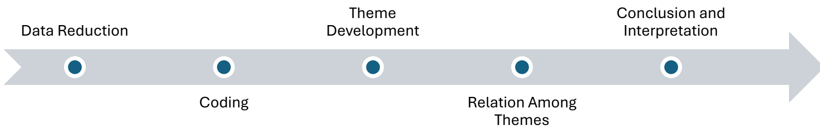

Figure 2. Data Analysis Model

To ensure the trustworthiness of the findings, this study applied strategies aligned with qualitative research rigour. Credibility was enhanced through prolonged engagement with the data and time triangulation across two interview stages to verify response consistency over time (Creswell & Poth, 2016). Dependability was supported by involving multiple researchers in the coding and theme development processes to achieve inter-coder agreement and minimize subjective bias (Miles et al., 2014). An audit trail documenting analytical decisions was maintained throughout the study (Korstjens & Moser, 2018). Participant confidentiality was strictly preserved, and all data were used solely for academic and research purposes. All participants provided informed consent prior to data collection. They were informed that their participation was voluntary and that their identities would remain confidential. The data collected were used exclusively for research purposes and did not affect participants' professional roles or future decisions.

3. Results

This section presents the findings of the thematic analysis of teachers' understanding and implementation of TPACK in STEM-based mathematics instruction. Following Bogdan and Biklen's thematic analysis procedures, the interview data were coded and organised into recurring themes. The findings are presented in four areas: teachers' theoretical understanding, practical understanding, experiences of TPACK implementation, and perceived supporting factors

3.1 Teachers' Understanding of TPACK in STEM-Based Mathematics Instruction

3.1.1 Theoretical Understanding

Teachers' theoretical understanding of TPACK in STEM-based mathematics instruction was explored through their descriptions of how technology, pedagogy, and mathematics content should work together in teaching. The thematic analysis identified three interrelated themes: (1) Teaching Approach, (2) Technology Integration, and (3) Teacher Competence. Together, these themes show how teachers understood TPACK as a foundation for effective STEM-based mathematics instruction. Table 3 presents the themes and their relationships.

Table 3. Results of Theoretical Understanding Analysis

Representative Excerpt	Theme	Relation among Themes
"*TPACK, as far as I know, is an approach that combines three important aspects in teaching: knowledge of technology, pedagogy (teaching methods), and content (subject matter).*" (JB1)	Teaching Approach	Teachers' theoretical understanding of TPACK reflects three interconnected dimensions: understanding TPACK as a teaching approach, integrating technology with pedagogy and content, and recognising TPACK as an essential professional competence for effective mathematics instruction.
"*Learning related to technology, where content and applications are linked to the teaching process, involves integration of technology into learning. The teaching material is integrated with technology to make it more engaging.*" (JB2)	Technology Integration	
"*Content, Pedagogy, and Technology knowledge (TPACK) is a framework that describes the types of knowledge a teacher must have to successfully integrate technology effectively into the teaching process*." (NTB2)	Teacher Competence	

As shown in Table 3, teachers conceptualized TPACK from three closely related perspectives: as a teaching approach, as the integration of technology, pedagogy, and content, and as a form of professional competence required for effective mathematics instruction. Collectively, these themes reflect a holistic view of technology integration in which pedagogical approaches, technological integration, and professional competence are regarded as inseparable elements of effective mathematics instruction. Rather than viewing TPACK merely as the use of digital technologies, teachers understood it as an integrated instructional framework that combines technological, pedagogical, and content knowledge to support meaningful STEM-based mathematics learning.

The first theme, Teaching Approach, demonstrates that teachers understood TPACK as a comprehensive instructional approach that simultaneously integrates technology, pedagogy, and mathematics content. Rather than treating these knowledge domains separately, participants described TPACK as a unified framework for planning and delivering instruction. This understanding suggests that teachers recognized the importance of balancing technological resources with appropriate pedagogical strategies to achieve meaningful learning outcomes.

The second theme, Technology Integration, highlights teachers' awareness that technology should be purposefully integrated into classroom instruction rather than used merely as an additional teaching tool. Participants emphasized that technological applications should complement mathematical content and instructional methods to enhance student engagement, facilitate concept exploration, and improve learning experiences. This perspective reflects teachers' recognition that effective technology integration depends on pedagogically meaningful implementation.

The third theme, Teacher Competence, indicates that teachers viewed TPACK as a professional competency required for effective STEM-based mathematics instruction. Participants describe TPACK as the knowledge needed to select appropriate technologies, design technology-supported learning activities, and integrate technological, pedagogical, and content knowledge into coherent instructional practice. This finding suggests that teachers associate successful technology integration with professional expertise rather than technological skills alone.

3.1.2 Practical Understanding

Teachers' practical understanding of TPACK in STEM-based mathematics instruction was explored through participants' descriptions of how they applied technological, pedagogical, and content knowledge in their instructional practice. The thematic analysis generated three interrelated themes: (1) Teacher Competence, (2) Framework, and (3) Teacher Knowledge. Together, these themes illustrate how teachers translated their conceptual understanding of TPACK into practical classroom implementation. These themes and their relationships are presented in Table 4.

Table 4. Results of Practical Understanding Analysis

Representative Excerpt	Theme	Relation among Themes
"*I understand it as the teacher's ability to use technology in the right way so that the material and teaching methods can be more effective and engaging*." (JB1)	Teacher Competence	Teachers' practical understanding of TPACK is reflected in three interconnected dimensions: teachers' competence in using technology effectively, TPACK as a framework for planning and implementing instruction, and the professional knowledge required to integrate technology, pedagogy, and mathematics content in classroom practice.
"*A theoretical framework that explains how teachers should integrate technology into their teaching by combining knowledge of technology, pedagogy (teaching methods), and content (mathematics material) to create effective and innovative learning experiences through the use of technological tools.*" (YG2)	Framework	
"*I understand TPACK as a way of thinking that helps teachers design, implement, and evaluate learning that balances technology, pedagogy, and content.*" (JT1)	Teacher Knowledge	

As presented in Table 4, teachers described the practical application of TPACK through three complementary perspectives: the ability to use technology effectively in teaching, the role of TPACK as a framework for instructional design, and the professional knowledge needed to integrate technology with pedagogy and mathematics content. Together, these perspectives portray TPACK as a practice-oriented framework that guides teachers in making informed instructional decisions throughout the teaching process. The findings emphasise that technology integration is most effective when supported by professional competence, thoughtful instructional planning, and a balanced understanding of technological, pedagogical, and content knowledge. Consequently, teachers' practical understanding extends beyond knowing the principles of TPACK to applying those principles in ways that enhance the quality of STEM-based mathematics instruction.

The first theme, Teacher Competence, demonstrates that teachers regarded TPACK as the professional ability to use technology purposefully to support mathematics learning. Participants emphasised that technology should function as an instructional medium that enhances the effectiveness of teaching methods, facilitates students' understanding of mathematical concepts, and promotes more engaging learning experiences. This finding suggests that teachers associated successful technology integration with pedagogically appropriate technology use rather than with the mere availability of digital tools.

The second theme, Framework, highlights teachers' perception of TPACK as a comprehensive framework that guides the planning, implementation, and evaluation of STEM-based mathematics instruction. Rather than viewing technology as an independent component, participants described TPACK as an integrated model that combines technological knowledge, pedagogical strategies, and mathematics content to support meaningful learning. This perspective indicates that teachers recognised the importance of systematic instructional design in achieving effective technology integration.

The third theme, Teacher Knowledge, indicates that teachers perceived TPACK as the professional knowledge required to integrate technology into classroom practice effectively. Participants described this knowledge as enabling teachers to make informed instructional decisions that balance technological, pedagogical, and content considerations throughout the teaching process. This finding suggests that teachers viewed successful STEM-based mathematics instruction as being grounded in the continuous development of integrated professional knowledge rather than in technological proficiency alone.

3.2 Teachers' Experiences in Implementing TPACK in STEM-Oriented Mathematics Classrooms

The analysis of teachers' experiences in implementing TPACK in STEM-oriented mathematics classrooms explored how teachers integrated technological, pedagogical, and content knowledge into their classroom practices. The thematic analysis generated three interrelated themes: (1) Concept Visualization, (2) Innovative Learning, and (3) Assessment. Together, these themes demonstrate how teachers employed TPACK to facilitate conceptual understanding, promote meaningful learning experiences, and monitor students' learning through technology. These themes and their relationships are presented in Table 5.

Table 5. Results of TPACK Implementation Analysis

Representative Excerpt	Theme	Relation among Themes
"*The implementation of technology can provide variation in learning to prevent boredom, but it must be carefully considered so that students can utilise technology effectively rather than becoming dependent on it. Technology is used to help students master lesson concepts and visualise abstract mathematical objects*." (JG1)	Concept Visualization	Teachers' implementation of TPACK is reflected in three interconnected dimensions: using technology to visualise abstract mathematical concepts, creating innovative and student-centred learning experiences, and employing digital technologies to support formative assessment and monitor students' learning.
"*I guide students to use GeoGebra or Desmos (technology) to visualise and manipulate mathematical models (content), test different parameters, and find optimal solutions*." (NTB2)	Innovative Learning	
"*Using technology as a tool for concept visualization, for example GeoGebra to help students understand geometry and function graphs; integrating technology into pedagogical strategies, such as project-based learning through platforms like Google Classroom for collaboration and discussion; providing interactive learning experiences using videos and digital quizzes (Quizizz, Kahoot, etc.); and supporting technology-based formative assessment, for example through Google Forms to quickly evaluate students' understanding*." (JT1)	Assessment	

Table 5 illustrates that teachers enacted TPACK through a range of instructional practices that integrated technology into different aspects of mathematics learning. Technology was consistently used to make abstract mathematical concepts more accessible, design learning experiences that encouraged active student participation, and generate formative evidence to monitor students' progress. These practices reveal that technology functioned as an integral component of classroom instruction rather than as an isolated instructional resource. Instead, teachers embedded digital tools within pedagogical activities to strengthen conceptual learning, facilitate meaningful classroom interaction, and support ongoing assessment throughout the learning process.

The first theme, Concept Visualisation, demonstrates that teachers used digital technologies to make abstract mathematical concepts more concrete and accessible for students. Participants described the use of applications such as GeoGebra and other digital platforms to support students' conceptual understanding while emphasising that technology should enhance learning rather than create dependency. This finding suggests that teachers recognised visualisation technologies as cognitive tools that facilitate mathematical reasoning and deepen conceptual understanding.

The second theme, Innovative Learning, highlights teachers' efforts to create engaging, interactive, and problem-solving-oriented learning environments through technology integration. Participants explained how digital applications enabled students to explore mathematical models, manipulate variables, and investigate alternative solutions within authentic STEM contexts. This perspective indicates that teachers viewed technology as a means of promoting active learning and inquiry-based instruction rather than simply delivering instructional content.

The third theme, Assessment, indicates that teachers integrated digital technologies into formative assessment to monitor students' understanding and provide timely feedback throughout the learning process. Participants described using platforms such as Google Forms, Quizizz, Kahoot, and Google Classroom to assess learning, facilitate collaboration, and evaluate students' conceptual development efficiently. This finding suggests that teachers perceived assessment as an integral component of TPACK implementation, where technology supports evidence-based instructional decisions and continuous improvement of student learning.

3.3 Perceived Supporting Factors in the Implementation of TPACK for STEM-Based Mathematics Instruction

The supporting factors required by teachers to strengthen their TPACK competence in STEM-based mathematics instruction were explored through participants' descriptions of the institutional, professional, and collaborative support that facilitated technology integration. The thematic analysis generated three interrelated themes: (1) School Support, (2) Practical TPACK Training, and (3) Active Teacher Communities. Together, these themes illustrate the essential conditions that enable teachers to implement TPACK effectively in STEM-based mathematics instruction. These themes and their relationships are presented in Table 6.

Table 6. Results of Analysis of Supporting Factors in TPACK Implementation

Representative Excerpt	Theme	Relationship among Themes
"*The school supports positively; the greatest support is that the internet network is quite smooth, although there are some places that are less optimal. The school also provides practical training for teachers regarding new technologies."* (JG1)	School Support	Teachers identified three interconnected supporting factors for successful TPACK implementation: institutional support through adequate facilities and professional development, practice-oriented TPACK training, and active teacher communities that promote collaboration and continuous professional learning.
"*Yes, I have gained knowledge from MGMP and Nusantara Mathematics, including a one-month course at KNUE that integrated the three knowledge domains. The course emphasised mathematics while demonstrating how technology and pedagogy could be combined in instruction*." (YT1)	Practical TPACK Training	
"*The mathematics community in schools should be more active in analysing which mathematics materials and technologies are most appropriate, so that mathematics lessons become more innovative*." (SM1)	Active Teacher Communities	

The findings presented in Table 6 highlight that teachers regarded successful TPACK implementation as being shaped not only by individual expertise but also by the broader professional environment in which they worked. Adequate institutional support provided the necessary infrastructure and learning opportunities, while practice-oriented TPACK training enabled teachers to translate theoretical knowledge into classroom practice. At the same time, active teacher communities created spaces for collaboration, reflection, and the exchange of instructional experiences. Taken together, these supporting factors illustrate that sustainable TPACK implementation is fostered through an educational ecosystem that continuously strengthens teachers' professional capacity to integrate technology into STEM-based mathematics instruction.

The first theme, School Support, demonstrates that teachers regarded institutional support as a fundamental prerequisite for implementing TPACK effectively. Participants emphasised the importance of adequate technological infrastructure, including reliable internet access and instructional facilities, together with opportunities for professional development provided by schools. This finding suggests that teachers perceived successful technology integration as being strongly influenced by the availability of both physical resources and institutional commitment to teacher development.

The second theme, Practical TPACK Training, highlights teachers' recognition of the importance of hands-on professional learning experiences that emphasise the practical application of TPACK in STEM-based mathematics instruction. Participants described workshops, professional courses, and teacher development programmes as valuable opportunities to strengthen their ability to integrate technology, pedagogy, and mathematics content in authentic classroom contexts. This perspective indicates that teachers considered experiential and practice-oriented training to be more beneficial than theoretical instruction alone in developing TPACK competence.

The third theme, Active Teacher Communities, indicates that teachers viewed collaborative professional communities as an important source of continuous learning and instructional improvement. Participants emphasised that collaboration within school-based and subject-specific teacher communities enabled them to exchange ideas, evaluate technology integration practices, and identify appropriate technological resources for mathematics instruction. This finding suggests that teachers regarded professional collaboration as an essential mechanism for sustaining innovation and strengthening TPACK implementation in STEM-based mathematics classrooms.

4. Discussion

This study aimed to explore Indonesian senior high school mathematics teachers' experiences of TPACK integration in STEM-based mathematics instruction, with particular attention to how teachers understood the TPACK framework, implemented it in classroom practice, and perceived the factors supporting its implementation. The findings provide a comprehensive understanding of teachers' experiences within the context of ongoing technology integration and STEM-oriented educational reform in Indonesia. This study generated three main findings regarding teachers' experiences of TPACK in STEM-based mathematics instruction. First, teachers understood TPACK as an integrated framework that combines technology, pedagogy, and mathematics content to guide lesson planning and classroom teaching. Second, teachers implemented TPACK by integrating digital technology into STEM-based mathematics instruction to support concept visualisation, inquiry-based learning, and formative assessment. Third, teachers perceived that successful TPACK implementation requires a supportive professional environment characterised by school support, practical TPACK training, and active teacher collaboration.

The first main finding indicates that teachers understood TPACK as an integrated framework that combines technology, pedagogy, and mathematics content to guide lesson planning and classroom teaching. Rather than viewing technology as a separate instructional tool, teachers perceived it as meaningful only when aligned with appropriate pedagogy and mathematics content. This finding supports the TPACK framework proposed by (Mishra & Koehler, 2006) and is consistent with (DiKmen & DemiRer, 2022) and (Priyanda et al., 2025b), who found that an integrated understanding of TPACK enables teachers to design more effective technology-supported instruction. However, it contrasts with studies reporting that teachers often emphasize technological knowledge while overlooking pedagogical and content knowledge, resulting in fragmented technology integration (Bueno et al., 2023; Habiyaremye et al., 2023; Sarı & Keser, 2021). This difference may reflect the Indonesian educational context, where post-pandemic digital transformation, the implementation of the Merdeka Curriculum, and continuous professional development through schools and TPACK-related training have strengthened teachers' integrated understanding of TPACK(Chang et al., 2025; Fitrah et al., 2025a; Thohir, et al., 2023; Zaenab, et al., 2024) From a theoretical perspective, this finding reinforces (Mishra & Koehler, 2006) proposition that effective technology integration depends on the interaction of technological, pedagogical, and content knowledge. It also aligns with constructivist learning theory (Bruner, 1961; Vygotsky, 1978), which emphasizes that knowledge is actively constructed through meaningful learning experiences, with technology serving as a tool to support students' exploration, interaction, and conceptual understanding. Therefore, the findings suggest that professional development should prioritize authentic STEM teaching practices that integrate technology, pedagogy, and mathematics content rather than developing these competencies separately.

The second main finding highlights how teachers enacted TPACK by embedding digital technologies into STEM-based mathematics instruction to support concept visualization, inquiry-based learning, and formative assessment. Rather than serving as instructional supplements, digital tools became part of the learning process by helping students explore mathematical relationships, test ideas, and receive timely feedback. This finding is consistent with the TPACK framework (Mishra & Koehler, 2006) and the Cognitive Theory of Multimedia Learning (Mayer, 2005, 2021) which proposes that learning is enhanced when verbal and visual representations are meaningfully integrated. It also aligns with previous studies showing that technologies such as GeoGebra, Desmos, and digital assessment platforms improve conceptual understanding, mathematical reasoning, and student engagement in STEM education. However, other studies have reported that technology is often used primarily for content presentation, with limited opportunities for inquiry or formative assessment (Alptekin & Taneri, 2025; Børte et al., 2023). This difference may reflect the Indonesian educational culture, where recent curriculum reforms and collaborative teacher communities have encouraged more student-centred and technology-supported instructional practices (Abidin et al., 2021; Amiruddin et al., 2023; Bachtiar & Nirmala, 2023). Furthermore, the use of digital formative assessment supports the principles of Assessment for Learning (Black & Wiliam, 1998), which emphasizes the role of continuous feedback in improving learning. Overall, these findings suggest that effective TPACK implementation depends not only on access to technology but also on teachers' ability to design learning experiences in which technology strengthens conceptual understanding, inquiry, and ongoing assessment.

The third main finding underscores that successful TPACK implementation depends on a supportive professional environment in which school support, practice-oriented TPACK training, and active teacher collaboration work together to strengthen teachers' capacity for technology integration. Participants emphasised that institutional resources, continuous professional learning, and collaboration with colleagues are essential for sustaining effective STEM-based mathematics instruction. This finding is consistent with previous studies showing that school leadership, access to technological resources, and ongoing professional development are critical factors influencing teachers' TPACK development and classroom technology integration (Hsu & Chen, 2026; Mgeladze et al., 2024; Wang Lixia, 2024). However, some studies have reported that inadequate infrastructure, limited training opportunities, and weak professional collaboration continue to constrain teachers' ability to implement TPACK effectively (Dinçer, 2024; Nordgren et al., 2021). These differences may reflect the Indonesian educational context, where recent educational reforms have expanded teachers' access to digital infrastructure and professional learning programmes that encourage collaboration and technology integration (Hamsiah et al., 2024; Nisa et al., 2024; Rasmitadila et al., 2025). From a theoretical perspective, this finding aligns with Communities of Practice (Lave & Wenger, 1991; Wenger, 1998), which emphasises that professional knowledge is developed through participation in collaborative learning communities where teachers exchange experiences, solve instructional problems, and refine their practice. Therefore, strengthening TPACK requires individual professional competence, sustained institutional support, and collaborative professional networks that enable teachers to continuously adapt their instructional practices to the demands of STEM education.

This research has several limitations. First, this study focuses exclusively on teachers who are experienced in STEM learning, so they have not captured the perspective of teachers with limited STEM experience or no experience at all. Second, data is only collected through interviews. Although it produces in-depth insights, the implementation of classroom observation and documentation during learning can provide a more comprehensive understanding of learning practices in the classroom. Finally, these findings reflect the specific context of curriculum reform in Indonesia. Future research should include teachers with different levels of STEM and TPACK experience, particularly those with limited implementation experience, to broaden understanding of teachers' professional needs. Using multiple data sources, such as classroom observations, lesson plans, and students' perspectives, would also provide a more comprehensive picture of TPACK implementation. Comparative and longitudinal studies across different educational contexts are further recommended to examine how teachers' TPACK develops over time and across diverse settings.

5. Conclusion

This study examined how Indonesian senior high school mathematics teachers experienced the integration of TPACK within STEM-based mathematics instruction by exploring their understanding of the framework, its application in classroom practice, and the conditions that support its implementation. Overall, the findings demonstrate that successful TPACK integration is not determined by technological competence alone but by the close relationship between teachers' understanding of TPACK, its enactment in classroom instruction, and the professional environment that supports its use. Teachers perceived TPACK as an integrated framework for planning and teaching mathematics, applied digital technologies to enhance conceptual understanding, inquiry, and formative assessment, and emphasised the importance of institutional support, practice-oriented professional learning, and teacher collaboration for sustaining effective implementation. Collectively, these findings provide a more comprehensive understanding of how TPACK is experienced in STEM-based mathematics education and contribute to the literature by integrating teachers' conceptual understanding, instructional practice, and contextual support within a single qualitative framework in the Indonesian educational context.

The findings of this study offer practical implications for teacher education institutions, schools, and educational policymakers. First, teacher education programs should strengthen integrated TPACK preparation by providing authentic STEM learning experiences that connect technology, pedagogy, and mathematics content. Second, school administrators need to support teachers by enhancing technological infrastructure, offering practice-oriented professional development, and fostering collaboration through professional learning communities like MGMP. Finally, policymakers should prioritize instructional practice over mere technical skills in technology integration initiatives, ensuring that professional development directly enhances classroom teaching.

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Author contributions

IK, S, and SH were responsible for the conceptualization and design of the research. IK was responsible for data collection and drafting the initial manuscript. Formal analysis was conducted by IK and FE. S, SH, and FE critically reviewed and revised the manuscript. All authors have read and approved the final version of the manuscript for publication.

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Obtained.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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