



TEACHERS' TPACK DEVELOPMENT THROUGH THE IMPLEMENTATION OF E-MODULES BASED ON REALISTIC MATHEMATICS EDUCATION (RME)

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ABSTRACT

Aim/Purpose	This study aims to investigate how the TPACK of junior high school mathematics teachers develops through the implementation of RME-based e-modules.
Background	Despite the growing integration of digital tools in education, many mathematics teachers struggle to effectively integrate technology, pedagogy, and content.
Methodology	This study employed a qualitative approach involving six junior high school mathematics teachers (T1–T6) in Banda Aceh, Indonesia. The research instruments consisted of TPACK observation sheets and interview guidelines. Data were collected through observations, interviews, and teacher reflections conducted continuously after each lesson in collaboration with the observers.

Accepting Editor Aaron M. Glassman | Received: March 2, 2026 Revised: June 7, August 5, August 22, 2026 | Accepted: September 19, 2026.

Cite as: Johar, R., Khairunnisak, C., Zubaidah, T., Rohaizati, U., Pajarina, & Phonna, K. U. (2026). Teachers' TPACK development through the implementation of E-modules based on realistic mathematics education (RME). *Journal of Information Technology Education: Innovations in Practice*, 25, Article 40.
<https://doi.org/10.28945/5882>

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Contribution	This study provides new empirical insights into how continuous mentoring and reflection can enhance teachers' TPACK in implementing RME-based e-modules.
Findings	The results of the study show that all teachers experienced improvements in PCK, TPK, and TCK in implementing RME-based e-modules. The process of design, training, implementation, mentoring initiated through training and followed by implementation, observation, and reflection played an important role in helping teachers connect the components of TPACK, resulting in more meaningful, student-centered learning focused on conceptual understanding.
Recommendations for Practitioners	Mathematics teachers need to participate in continuous professional development programs that integrate mentoring, classroom teaching practice, and reflection to strengthen teachers' TPACK.
Recommendations for Researchers	Researchers are encouraged to develop professional development programs that integrate mentoring, classroom teaching practice, and reflection to strengthen teachers' TPACK.
Impact on Society	This study highlights the importance of practice-based continuous professional development in promoting meaningful technology integration in mathematics education.
Future Research	Future research could explore the long-term impact of TPACK development in various educational contexts by involving a larger number of participants and employing diverse research approaches.
Keywords	TPACK, realistic mathematics education, e-modules, teacher professional development

INTRODUCTION

The development of digital technology in the 21st century has significantly transformed educational paradigms, including mathematics education. Educational technology has great potential to support and enhance student learning by providing more interactive and meaningful instructional materials. Although technology can support and improve student learning, integrating it effectively into specific subject areas remains a complex endeavor (Herring et al., 2016). These challenges are reflected in teachers' limited ability to effectively combine technological tools with appropriate pedagogical strategies and mathematical content, which may hinder the development of meaningful technology-enhanced learning. Previous studies have identified several barriers to technology integration in education, including limited technological resources (Agyei & Voogt, 2011; Bingimlas, 2009; Hew & Brush, 2007) and insufficient teacher knowledge related to pedagogy, content, and technology (Chai et al., 2011; Donnelly et al., 2011). These findings suggest that the primary challenge lies not only in the availability of technological resources but also in teachers' capacity to integrate technology in pedagogically and mathematically meaningful ways.

In mathematics classrooms, teachers frequently struggle to select appropriate digital tools, design technology-supported learning activities, and connect technology with student-centered pedagogical approaches. As a result, technology is often used merely as a presentation tool rather than as a means of supporting students' conceptual understanding and mathematical reasoning. These challenges indicate weaknesses in teachers' Technological Pedagogical Content Knowledge (TPACK), which is essential for integrating technology, pedagogy, and mathematical content into effective instructional practices. Teachers need the ability to connect technological knowledge with pedagogical approaches that align with the content's characteristics. In other words, teachers must integrate technological

skills with pedagogical strategies related to content, which is referred to as TPACK (Angeli & Valanides, 2005; Chai et al., 2010). TPACK has become one of the most widely discussed frameworks in educational technology research due to its critical role in guiding teachers to integrate technology effectively into classroom instruction (e.g., Hew et al., 2019; Niederhauser & Lindstrom, 2018; Zou et al., 2022).

To strengthen teachers' TPACK, technology-based instructional materials such as e-modules have emerged as a promising alternative. Previous studies have shown that e-modules integrated with appropriate pedagogical approaches can enhance both teaching quality and student learning outcomes. For instance, Safitri et al. (2025) reported that technology-based e-modules have strong potential to support learning, although further improvements are needed in instructional design and TPACK integration. Similarly, Faradina et al. (2025) found that problem-based learning modules integrated with TPACK significantly improved students' learning outcomes. These findings suggest that technology-enhanced instructional materials, when combined with sound pedagogical principles, can serve as an effective means of strengthening teachers' TPACK. One promising approach is the implementation of e-modules based on Realistic Mathematics Education (RME), which emphasizes meaningful learning through contextual mathematical activities and active student engagement.

RME is a pedagogical and didactical philosophy that serves as a foundation for designing teaching materials, instructional designs, teacher and student behaviors, and interactions in mathematics teaching and learning (Bakker, 2004). Through RME-based instructional design, teachers can guide students to reinvent mathematical concepts as they progressively mathematize their activities (Treffers, 1987). Therefore, the implementation of RME-based e-modules has the potential not only to support students in developing a more meaningful understanding of mathematical concepts but also to enhance teachers' TPACK by facilitating the effective integration of technology, pedagogy, and content knowledge. Furthermore, efforts to strengthen teachers' TPACK through the implementation of RME-based e-modules align with Sustainable Development Goal 4 (SDG 4), which emphasizes inclusive, equitable, and high-quality education in the digital era.

Several studies have examined teachers' TPACK in classroom instruction. For instance, Santos and Castro (2021) demonstrated that TPACK plays a critical role in the effectiveness of technology-integrated instruction. Sheffield et al. (2015) found that applying the TPACK framework in science education effectively enhanced pre-service teachers' abilities and confidence in inquiry-based learning. Previous studies have underscored the importance of TPACK in supporting the effective integration of technology across diverse educational contexts. Despite extensive research on TPACK, limited studies have examined how RME-based e-modules support teachers' TPACK development in real classroom settings. This study provides empirical evidence on how structured mentoring and the classroom implementation of RME-based e-modules enhance teachers' TPACK. Therefore, the research question guiding this study is: How do the PCK, TPK, and TCK of junior high school mathematics teachers improve through the implementation of RME-based e-modules?

LITERATURE REVIEW

TEACHERS' TECHNOLOGICAL PEDAGOGICAL CONTENT KNOWLEDGE (TPACK)

The TPACK framework is grounded in the concept of Pedagogical Content Knowledge (PCK) introduced by Shulman (1986, 1987). It emphasizes the dynamic interaction among technological, pedagogical, and content knowledge in instructional practice (Koehler & Mishra, 2008). These knowledge domains continuously interact and influence teachers' decisions when integrating technology into classroom instruction. Consequently, the development of TPACK depends not only on teachers' technological proficiency but also on their ability to connect technology with appropriate pedagogical strategies and subject matter content.

Previous research has shown that factors such as teachers' perceptions of technology usefulness and their confidence in using digital tools influence instructional decision-making related to technology integration. For example, Ozden et al. (2024) found that pre-service teachers' perceptions of technology usefulness and their self-efficacy in using digital tools significantly affected their technology-based lesson planning. In addition, several studies have reported improvements in teachers' TPACK through effective technology use (Marino et al., 2009; Meika et al., 2026). However, these improvements do not result solely from technology use; rather, they require sustained support through professional training, classroom practice, and reflective activities. In this context, e-modules can serve not only as digital instructional materials but also as technological tools that support teachers in integrating content knowledge and pedagogical approaches into classroom practice, fostering the development of TPACK.

E-MODULE

E-modules function not only as digital learning resources but also as a means for teachers to simultaneously integrate technological and pedagogical aspects of instruction. Compared to printed modules, e-modules offer several advantages, including interactivity, ease of navigation, and the integration of multimedia elements such as videos, animations, and automated quizzes (Cynthia et al., 2023; Risnawati & Purwaningsih, 2025). Several previous studies have shown that implementing RME-based e-modules can enhance students' conceptual understanding and mathematical thinking skills. For example, Johar, Annisa, et al. (2025) reported that interactive RME-based e-modules improved students' understanding of algebraic expressions. In addition, RME-based digital learning resources grounded in real-life contexts, such as interactive worksheets themed around *qurban* (sacrifice), have been shown to significantly improve students' mathematical communication skills and their understanding of Islamic values (Johar, Ikhsan, et al., 2025). Several studies have reported the positive impact of digital learning resources on mathematics education. For example, interactive RME-based e-modules have been shown to improve students' understanding of algebraic expressions, while other context-based digital instructional materials have enhanced students' mathematical communication skills and conceptual understanding. Despite these promising findings, previous research has primarily focused on student learning outcomes rather than examining how teachers develop their TPACK through sustained classroom implementation, mentoring processes, and reflective practices. Consequently, there remains limited empirical evidence on how technology-based instructional materials can support the continuous development of teachers' TPACK in authentic mathematics classroom settings.

REALISTIC MATHEMATICS EDUCATION (RME)

From a TPACK perspective, RME offers a pedagogical approach that encourages teachers to design contextual and meaningful mathematical learning experiences. Previous studies have shown that implementing RME enhances teachers' PCK and promotes more meaningful mathematics instruction (Zubaidah et al., 2023). RME views mathematics as a human activity involving problem-solving, problem-posing, and the organization of instructional content (Freudenthal, 1973, 1991; Gravemeijer, 1994). Accordingly, mathematics learning is regarded as an active process in which students construct mathematical understanding through meaningful situations and progressive mathematization.

In technology-supported learning environments, these principles offer teachers opportunities to integrate content knowledge, pedagogical strategies, and technological tools simultaneously. In the context of e-module development, the presentation of contextual problems in e-modules should be designed using the emergent instructional design model proposed by Gravemeijer (1994). This model emphasizes heuristic learning that supports students in gradually achieving formal mathematical knowledge through four stages: *situations*, *model of*, *model for*, and *formal knowledge*. The *situations* stage involves mathematical activities related to daily life or imaginable problems that provide rich opportunities for mathematization (Gravemeijer, 1994; Gravemeijer et al., 2017; Gravemeijer & Stephan, 2002). Models play a crucial role in bridging informal, context-based understanding with formal

mathematics. A model used to represent a situation in a problem is referred to as a *model of*, while a *model for* emphasizes strategies rather than the problem context. At the level of formal knowledge, students can express mathematical generalizations or conclusions. These four levels help students solve problems informally and gradually develop their understanding into formal mathematical knowledge (Gravemeijer, 2020).

METHOD

RESEARCH DESIGN

This study employed a qualitative cross-case research design to describe and analyze the development of mathematics teachers' TPACK through the implementation of RME-based e-modules in classroom instruction. A qualitative approach enables researchers to capture teachers' perspectives, experiences, and the subjective meanings they construct within authentic instructional contexts (Creswell & Poth, 2018). Cross-case analysis systematically compares information across individual case studies and identifies commonalities, patterns, and themes that emerge across cases (Mynott & Kager, 2024).

PARTICIPANTS

The participants in this study were six mathematics teachers from five junior high schools in Banda Aceh, Indonesia, who implemented RME-based e-modules in their teaching. All participating teachers were female, with varying teaching experience. The participants were selected using purposive sampling based on their willingness to participate and their involvement in implementing the RME-based e-modules developed by the research team at the Research Center of Realistic Mathematics Education at Universitas Syiah Kuala (USK). Classroom observations were conducted by the research team (observers), with each teacher accompanied by one observer. Table 1 presents detailed information regarding the teachers' demographics.

Table 1. Teacher Demography

Teacher	T1	T2	T3	T4	T5	T6
Age	49 years old	40 years old	30 years old	44 years old	40 years old	52 years old
Working Experience	20 years old	16 years old	3 years old	21 years old	20 years old	27 years old
Grade Taught	Grades 7 and 8	Grades 7 and 8	Grade 7	Grade 8	Grade 8	Grades 8 and 9
Training Attended in the Past 10 Years	Curriculum 2013 (K-13)	In-service Teacher Professional Education (PPG), Implementation of GeoGebra, Implementation of Autograph	PISA Question Development, GetMath Application, Implementation of Deep Learning, Implementation of Autograph	Realistic Mathematics Education (RME), Implementation of GeoGebra, Implementation of Deep Learning, Implementation of Autograph	Creating instructional videos using the Snapshot application	Teacher and Principal Performance Management on the Merdeka Mengajar Platform
Technology or Applications Designed or Used in Mathematics Instruction	Power Point	GeoGebra	Geogebra, Canva, Quizziz, Kahoot, GetMath	Canva, GeoGebra, Autograph, Quizziz	GeoGebra	Instructional videos from YouTube

The research has been approved by the Education and Culture Office of Banda Aceh City, Indonesia. This study was conducted in accordance with local regulations and institutional research ethics requirements. Written informed consent to participate in the study was obtained from all participants prior to the training, classroom observations, interviews, and video recordings. The identities of the participants and school information were kept confidential using coded identifiers (T1–T6).

INSTRUMENTS

The instruments consisted of a TPACK observation sheet (Koh & Chai, 2014) and an interview guideline. The observation sheet includes four PCK indicators, five TPK indicators, and three TCK indicators. The instruments were adapted through a process of translation, contextual adjustment, and alignment with the research objectives. The e-module, observation sheet, and TPACK interview instrument were validated by fifteen validators consisting of mathematics education lecturers and teachers. The analysis results showed that the overall average score of the instruments was 4.35 out of 5, indicating that they met the criteria of being highly valid.

PROCEDURES

The research flow diagram is presented in Figure 1.

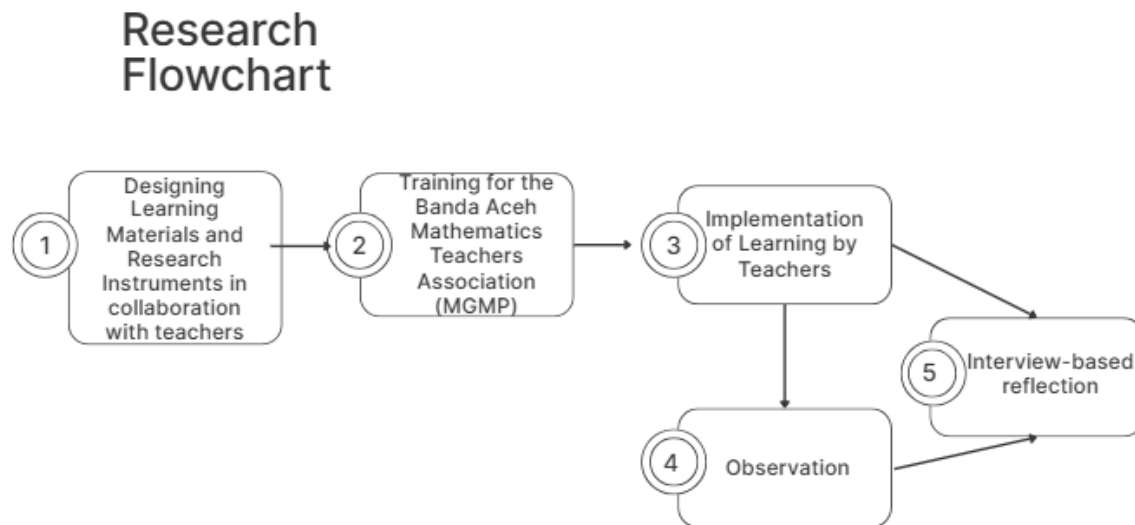


Figure 1. Research Flow Diagram

Figure 1 presents the research flow. This study was carried out through five stages, beginning with the design of instructional materials and concluding with reflection. The first stage involved designing instructional materials and research instruments. At this stage, the e-modules used in this study were developed by the Research Center of Realistic Mathematics Education at Universitas Syiah Kuala and are available on the GetMath platform (<https://getmath.id/>). GetMath Platform has been transformed to GetSmart (<https://getsmart.id/login>). These e-modules cover four topics: fractions, algebraic expressions (Johar, Annisa, et al., 2025), gradients (Johar et al., 2023), and quadratic functions. They are complemented by learning trajectories in the form of iceberg models, live worksheets, introductory videos, and interactive assessments. During implementation, teachers also used various supporting applications, such as GeoGebra, Autograph, and the educational game Mario Bros, enabling students to learn through visual and exploratory experiences. These teachers were involved in validating the learning tools.

The second stage was teacher training, which involved members of the Banda Aceh Mathematics Teachers Association (*Musyawarah Guru Mata Pelajaran*, MGMP). The training focused on RME principles, including guided reinvention and progressive mathematization, didactic phenomenology, and self-developed models. The learning trajectory related to student activities was designed based on the iceberg model, which consists of *situations*, *model of*, *model for*, and *formal knowledge*, using GeoGebra and Autograph. Six volunteer teachers were selected as research subjects and implemented the designed e-modules in their classrooms. At this stage, the teachers also provided feedback and discussed the developed teaching materials as part of the refinement process. During implementation, teachers were allowed to make modifications according to their students' needs.

In the third stage, the six teachers implemented the RME-based e-modules in their respective classrooms. Each instructional meeting lasted 2×45 minutes or 3×45 minutes. During the implementation process, the researchers, acting as observers, accompanied the teachers to monitor lesson delivery.

The fourth stage consisted of classroom observations conducted by observers during lessons taught by the six teachers to assess their TPACK. Data were collected through a TPACK observation sheet, interviews, and video recordings. Observations were conducted by the research team and supported by video recordings during classroom learning. The video recordings were used to document classroom interactions, teachers' instructional practices, and the use of technology throughout the learning activities.

The fifth stage consisted of collaborative reflection between teachers and observers. Reflection was conducted after each meeting to identify successes, challenges, and obstacles encountered during instruction. This process included evaluating the alignment of learning activities with the learning trajectories, analyzing the effectiveness of technology integration, and discussing students' responses and understanding of the material. Interview-based reflection was conducted after each learning implementation session for approximately 20–30 minutes and focused on teachers' experiences, challenges faced, and perceptions of technology integration. The interview guide consisted of open-ended questions aligned with the TPACK framework. The results of the reflection were used to improve lesson plans for subsequent sessions, adjust teachers' pedagogical strategies, and optimize the use of RME-based e-modules. Moreover, collaborative reflection served as an important data source for analyzing the quality of implementation and the development of teachers' TPACK throughout the study. Figure 2 shows the interface of the GetMath platform, which serves as the host for the RME-based e-modules.

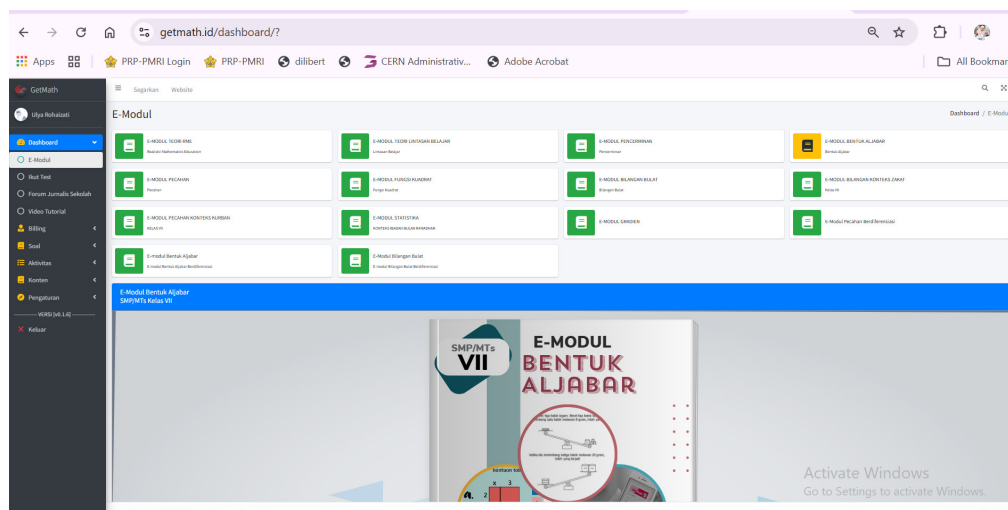


Figure 2. The GetMath platform displaying an RME-based e-module

Figure 3 illustrates the iceberg model of fraction addition and subtraction. RME facilitates students' conceptual understanding through a progressive learning process that moves from concrete experiences to abstract mathematical reasoning. The process begins with the *situations* stage, in which students are presented with real-world problems relevant to daily life or readily imaginable. Next, in the *model of* the stage, students construct visual representations of the situations to develop a more concrete understanding of fractions.

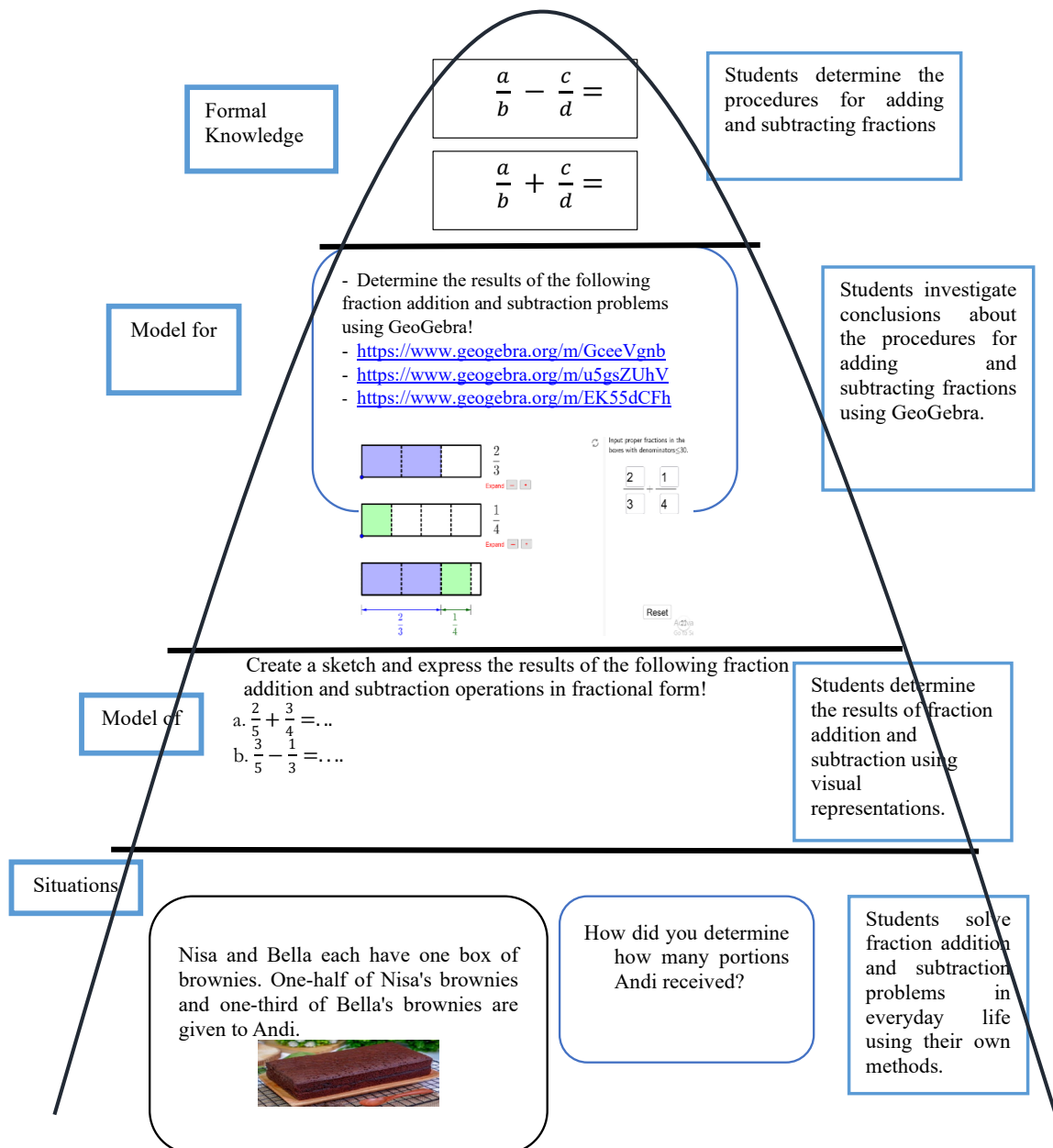
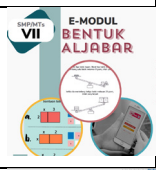


Figure 3. The iceberg model illustrates the designed fraction-learning activities for fraction addition and subtraction.

Then, in the *model for* stage, students begin to identify patterns and rules in performing fraction addition and subtraction through structured exercises. Finally, at the *formal knowledge* stage, students can

generalize their findings into symbolic forms and understand the formal procedures for fraction addition and subtraction. Throughout this process, the teacher does not merely present mathematical procedures; rather, they facilitate students in generalizing concepts based on their discoveries. These learning stages integrate content, pedagogy, and technology. Details of this integration are presented in Table 2.

Table 2. Content, pedagogy, and technology used in the RME-based e-module.

Topics	Content					Pedagogy Used	Technology Used	E-Module Cover
	Meeting 1	Meeting 2	Meeting 3	Meeting 4	Meeting 5			
Fraction E-Module	Introduction to Fractions	Comparing Fractions	Addition and Subtraction of Fractions	Multiplication of Fractions	Division of Fractions	Principles of RME	GeoGebra	
Algebraic Expressions E-Module	Introduction to Algebraic Expressions	Addition of Algebraic Expressions	Addition of Algebraic Expressions	Multiplication of Algebraic Expressions	Multiplication of Algebraic Expressions	Principles of RME	GeoGebra	
Gradient E-Module	Discovering the meaning of gradient	Determining the types of gradients	Interpreting speed–distance–time graphs and their relationship to the gradient			Principles of RME	Autograph	
Quadratic Function E-Module	Graphing quadratic function graphs based on project assignments	Graphing quadratic function	Solving contextual problems related to quadratic function graphs			Principles of RME	GeoGebra and Mario Bros Game	

DATA ANALYSIS

This study utilized multiple data sources: observation sheets, interviews, and video recordings. The collected data were analyzed using the three stages proposed by Miles and Huberman (1994), namely data reduction, data display, and conclusion drawing. Data analysis began with data reduction through a coding process applied to the observation notes, interview transcripts, and video recordings. The coding process was conducted based on the indicators of the TPACK components, limited to PCK, TPK, and TCK aspects. Initial codes were identified from teachers' instructional practices, technology integration, classroom interactions, and pedagogical strategies. They were then grouped into categories representing the development of teachers' TPACK during the implementation process. The categorized data were subsequently presented in narrative form, supported by quotations from interview transcripts at each learning meeting, and linked to PCK indicators (PCK 1–4), TPK (TPK 1–5), and TCK (TCK 1–3) (Koh & Chai, 2014).

Triangulation was conducted by comparing findings from classroom observations, interview results, and video recordings to ensure the consistency and credibility of the research findings. The video recordings were reviewed repeatedly to verify the observational data and to minimize researcher bias. The data analysis yielded a more comprehensive and valid depiction of the development of teachers' TPACK competencies during the implementation of the RME-based e-module.

RESULTS

The six teachers participating in this study integrated various technological tools into their instruction, including Liveworksheets, contextual introductory videos closely related to daily life, and GeoGebra provided through the GetMath platform. The findings were derived from classroom observations, video recordings, and reflective interviews conducted after instruction to identify patterns in the development of TPK, TCK, and PCK during classroom implementation. Data were analyzed through a coding process that examined recurring instructional practices, teacher reflections, and classroom interactions. Subsequently, cross-case comparisons were conducted among Teachers T1–T6 to identify similarities and differences in the development of these knowledge domains.

IMPROVEMENT OF PEDAGOGICAL CONTENT KNOWLEDGE (PCK)

In the first meeting, T1 was hesitant in determining when to provide explanations, when to give examples, and how to stimulate students' understanding through open-ended questions. For example, when students gave an incorrect answer in an activity involving shaded regions representing the fraction $\frac{1}{2}$ (Figure 4), T1 immediately provided the correct answer without probing students' reasoning.

Which shaded region represents the fraction $\frac{1}{2}$?

Instruction: Choose the pictures below that you think are the correct answers.

Figure 4. Activity 1 of the first meeting related to shaded regions representing the fraction $\frac{1}{2}$

Similarly, in the second meeting on comparing fractions, when students were asked to place the symbols $<$ or $>$ between the fractions $\frac{2}{5}$ and $\frac{2}{9}$, T1 asked, “Which fraction has a greater value, $\frac{2}{5}$ or $\frac{2}{9}$?” Several students simultaneously answered $\frac{2}{9}$. T1 did not provide feedback on this incorrect response and merely asked the students to “just write it in the live worksheet.” T1 also tended to give the correct answer directly, without probing students' reasoning, so misconceptions were not optimally addressed.

In the third and fourth meetings, which covered fraction addition, subtraction, and multiplication, T1 addressed misconceptions and helped students overcome learning difficulties. However, in the fifth meeting on fraction division, T1 still struggled to explain the conceptual meaning of fraction operations, such as “how many $\frac{1}{4}$ are in $\frac{1}{2}$ ” (Figure 5). Based on the interviews, T1 experienced difficulties in visualizing the concept of fraction division. T1 was unable to determine how many one-fourth units are within one-half. T1 also struggled to connect conceptual understanding with visual representations in fraction operations, as illustrated in the following excerpt from the interview.



Figure 5. Activity “How many $\frac{1}{4}$ are in $\frac{1}{2}$?”

O: What was the most challenging part for you?

T1: Determining how to represent the fractions visually, whether I should draw the one-half first or the one-fourth. I also occasionally confused the expressions “one-half divided by one-fourth” or “one-fourth of one-half.” which made the concept difficult for me to explain.

O: All right. During yesterday’s mentoring session, we tried a step-by-step approach. Which part did you find helpful?

T1: What helped me most was the sequence you suggested: first draw a rectangle and divide it into four equal parts to represent one-fourth. Then, shade two parts to show one-half. This visualization enabled me to clearly see that there are two one-fourths in one-half.

O: Based on your current reflection, do you feel it is easier to explain this to students?

T1: Yes.

Through the assistance provided by the observer and followed by the reflection, T1 began to understand the importance of distinguishing between the operations “ $\frac{1}{2}$ divided by $\frac{1}{4}$ ” and “ $\frac{1}{4}$ of $\frac{1}{2}$,” which increased T1’s confidence in explaining fraction concepts more consistently in the subsequent meetings. T1 then re-explained the activity “how many $\frac{1}{4}$ are in $\frac{1}{2}$ ” before the final test was administered. This mentoring and reflection process supported T1 in using a visual approach to guide students in fraction division. T1’s performance was associated with indicators PCK1 and PCK4.

In meetings one to three, T2 was able to guide students in understanding fraction concepts, comparing fractions, and performing addition and subtraction of fractions through structured activities. However, in multiplication and division of fractions, several limitations were identified in explaining the conceptual meaning of fraction operations. In meeting four, T2 did not guide students in interpreting the multiplication $\frac{1}{2} \times \frac{1}{3}$ as “half of one-third.” Similarly, in meeting five, T2 was unable to explain $\frac{1}{2} \div \frac{1}{4}$ as “how many one-fourths are in one-half.” T2 still relied more on procedural approaches than on conceptual explanations to support students’ understanding. Through the observer’s assistance and reflection, T2 then re-guided students to understand the conceptual meaning of fraction multiplication and division before the posttest. T2’s performance was associated with indicator PCK3.

Across all meetings, T3 and T5 consistently guided students in algebraic expressions and slope topics. Both were able to help students construct understanding from contextual situations to more formal representations. T3 used a concrete context, a basket-and-ball analogy, to address students’ misconceptions in distinguishing between $2y$ and $2 + y$. Meanwhile, T5 combined explanations using the whiteboard with graphical visualization for students who still had difficulty determining coordinates and distinguishing changes in the x-axis and y-axis when applying the slope formula. The performance of T3 and T5 was associated with indicator PCK1.

In the first meeting, T4 often provided direct answers and offered limited opportunities for students to independently explore problem-solving strategies. T4 was asked to explain the problem shown in

Figure 6, which involved interpreting a distance–time graph. In the section of the graph showing a distance of 100 km between 2 and 4 hours, T4 did not recognize that this segment represented a period when the vehicle was stationary. Reflection activities are illustrated in the following excerpt from the interview.

O: By the way, for the problem in Figure 6, how do you interpret the flat section of the graph at a distance of 100 km between 2 and 4 hours?

T4: Previously, I thought the vehicle was still moving but at a low speed. However, After reviewing it, I realized that the vehicle was not moving.

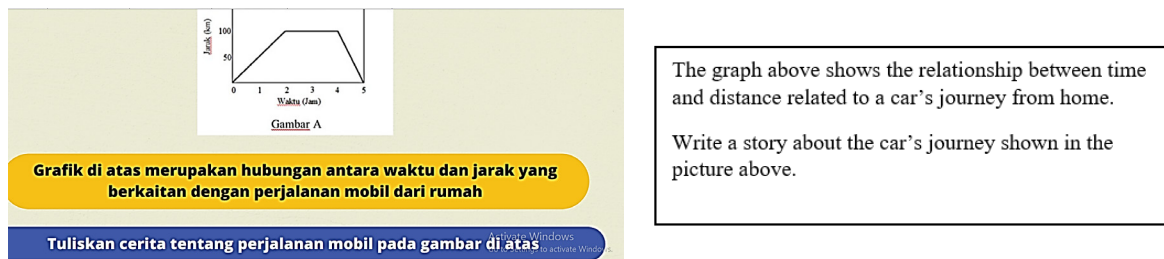


Figure 6. Activity on the relationship between

Through mentoring sessions followed by reflective discussions, T4 began to practice questioning strategies to connect graphical representations with contextual situations. This collaborative reflection process enhanced T4's understanding of how to interpret the relationship between slope, distance, and time more accurately, as well as how to apply it conceptually and pedagogically in classroom instruction. Accordingly, T4's performance was categorized under indicator PCK2.

In the first meeting, T6 did not facilitate students' engagement with a project-based activity involving the measurement of water-spray trajectories generated by a hose. Instead, T6 focused solely on guiding students to complete distance and pressure values in the Liveworksheet. However, the activity was originally designed to help students develop initial understanding before learning about quadratic function graphs. In the second meeting, T6 incorrectly explained the relationship between variable values and function values. Nevertheless, through mentoring by the observer followed by reflection in the subsequent meeting, T6 re-explained the concept of graphing quadratic functions and guided students to examine how variations in function coefficients affect the shape of the graph. This improvement reflected T6's development in relation to indicator PCK2.

IMPROVEMENT OF TECHNOLOGICAL PEDAGOGICAL KNOWLEDGE (TPK)

During the first meeting in T1's classroom, the use of Liveworksheets was not implemented effectively because T1 encountered difficulties in independently accessing the fraction e-module and introductory videos available on the GetMath platform. Spontaneously, a student assisted T1 in activating the e-module, enabling the lesson to proceed as planned. Based on post-lesson reflection, T1 stated, "I was confused about how to open the e-module and the video." This reflection indicates that at the initial stage T1 was not yet developed sufficient proficiency in using technology as an instructional tool. Following this lesson, the observer provided further guidance to the teacher in using the e-module, so that in the subsequent meetings T1 gradually improved in utilizing technology to support student learning. T1's performance was associated with indicator TPK1.

Teachers T2, T3, and T5 had previously used GeoGebra in mathematics instruction because students were more interested in learning and could independently discover more information. Based on the post-lesson reflection, T2 stated that "through GeoGebra, students can visualize the addition of fractions with different denominators, increasing their motivation." Regarding slope, T5 stated that with GeoGebra "I can facilitate students to explore the properties of slopes after they derive the slope formula from two points." In relation to Liveworksheets, these three teachers did not experience difficulties and guided students in group activities. According to T5, one advantage of Liveworksheets is

that “it provides real-time feedback to students, helping me correct their answers so I can immediately provide follow-up actions based on that feedback.” T3 added that Liveworksheets also supports guided practice and classroom interaction. The performance of T2, T3, and T5 was associated with indicators TPK3 and TPK5.

Across the three meetings, T4 integrated Autograph into classroom instruction to support students’ exploration of slope concepts. The technology was used to facilitate activities in which students drew line segments with different slope values and interacted with graphical representations during learning activities. However, observational data also showed limitations in T4’s pedagogical use of technology. T4 often provided direct answers, giving students limited opportunities to independently explore problem-solving strategies. As a result, students had fewer opportunities to actively construct conceptual understanding through guided learning experiences. Through the observer’s mentoring followed by reflection, T4 gradually began implementing questioning strategies in classroom instruction, encouraging students to investigate mathematical situations independently. Overall, T4 showed improvement in TPK through increased awareness of how technology can support student-centered rather than teacher-centered learning. T4’s performance was associated with indicator TPK2.

In the first meeting, T6 had not yet been able to guide students in graphing water-jet trajectories and plotting coordinate points in GeoGebra. In the second meeting, there was improvement in technology use, as T6 was able to guide students in exploring changes in quadratic function graphs using a Mario Bros game-based activity (Figure 7). In subsequent meetings, T6 also guided students in exploring changes in the shapes of quadratic function graphs as coefficient values varied, using GeoGebra (Figure 8). T6’s performance was associated with indicator TPK4.

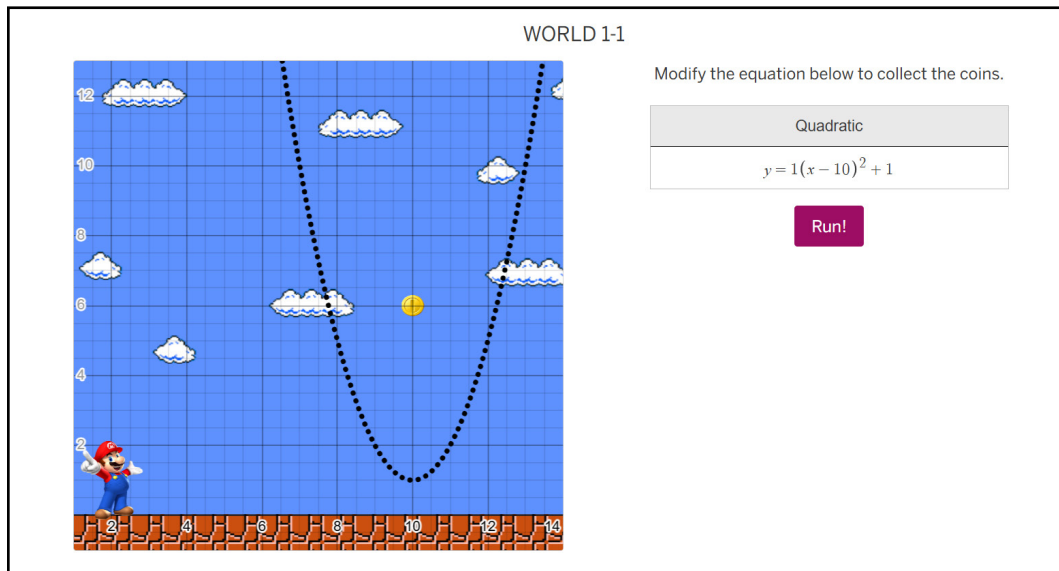


Figure 7. T6 facilitating students in graphing quadratic function using the Mario Bros game

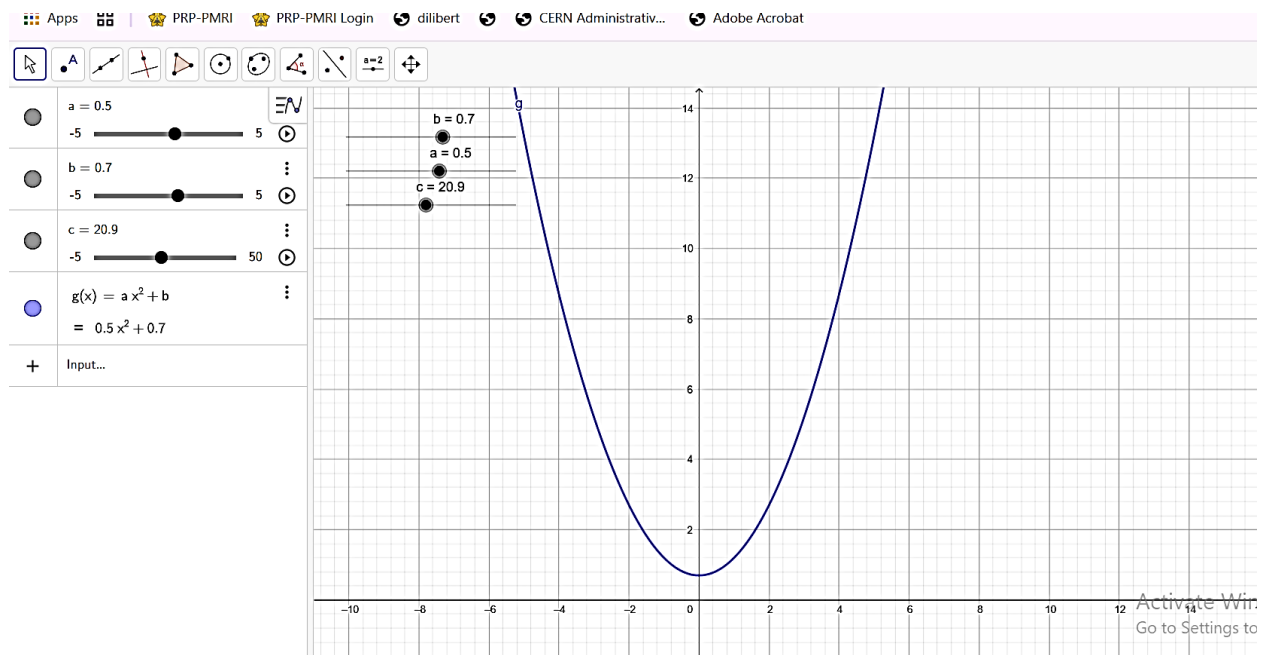


Figure 8. Exploring changes in the shapes of quadratic function graphs based on variations in coefficient values.

IMPROVEMENT OF TECHNOLOGICAL CONTENT KNOWLEDGE (TCK)

In the first meeting, T1's ability to use the e-module and videos on the GetMath platform was limited; therefore, the technology could not yet be used to support students' understanding of comparing fractions. One reason was that T1 had never used technology in teaching before. Through mentoring and post-lesson reflection, T1 began understanding the functions of various features on the GetMath platform. As a result, in subsequent meetings, T1 was able to use the e-module and introductory videos independently. T1 also used Liveworksheets and GeoGebra to support students in exploring addition and subtraction of fractions and in connecting these concepts to real-life contexts, as shown in Figure 9. The same improvement was also observed in the teaching of fraction multiplication and division. T1's performance was associated with indicators TCK2 and TCK3.

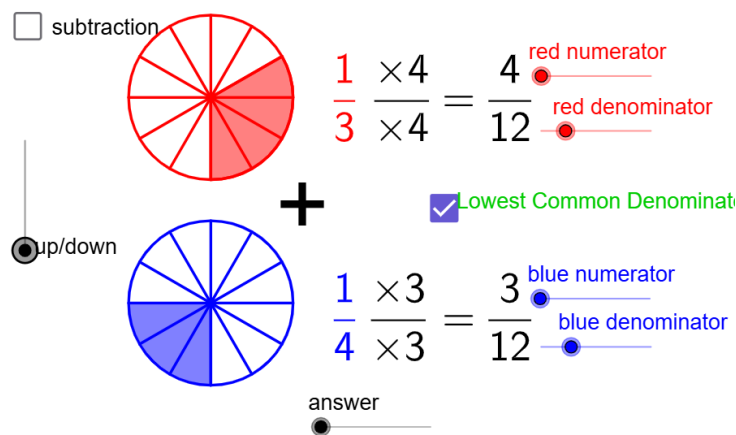


Figure 9. Addition of fractions 1/3 and 1/4 using GeoGebra

During the first three meetings, T2 used Liveworksheets in conjunction with GeoGebra to guide students in exploring the concepts of comparing, adding, and subtracting fractions. However, conceptual challenges became evident during the fourth and fifth meetings. In the fourth meeting, T2 experienced difficulty using visual representations to explain the operation $1/2 \times 1/3$. Instead of explaining it as “half of one-third,” T2 relied primarily on procedural rules. T2 stated, “I was confused about which part to draw first. I thought that since the operation was $1/2 \times 1/3$, I should draw $1/2$ first. Because I was not confident with the drawing, I used the usual method, multiplying the numerator by the numerator and the denominator by the denominator.”

Following the mentoring and post-lesson reflection, T2 developed a better understanding of the visual representation of $1/2 \times 1/3$ and subsequently used this representation to explain the concept to students in the following lesson. A similar issue emerged during the fifth meeting, when T2 explained fraction division procedurally by inverting the second fraction and multiplying it by the first fraction, without providing a conceptual interpretation of the operation. During the reflection session, T2 acknowledged her uncertainty in connecting symbolic procedures with visual meaning, stating, “I am still unsure about applying it in the classroom because I am afraid of drawing it incorrectly and confusing the students.” Based on post-lesson interviews, T2 also explained that although the researcher had provided conceptual explanations of fraction division during the training, T2 still lacked confidence in implementing them. Accordingly, T2’s performance was associated with indicator TCK3.

Across all meetings, T3 consistently utilized GeoGebra and Liveworksheets to help students understand algebraic concepts. T3’s prior experience using GeoGebra since university contributed to the smooth integration of technology in classroom instruction. T3 was able to connect algebraic multiplication with the area of a rectangle using GeoGebra (Figure 10). Accordingly, T3’s performance was associated with indicators TCK1 and TCK3.

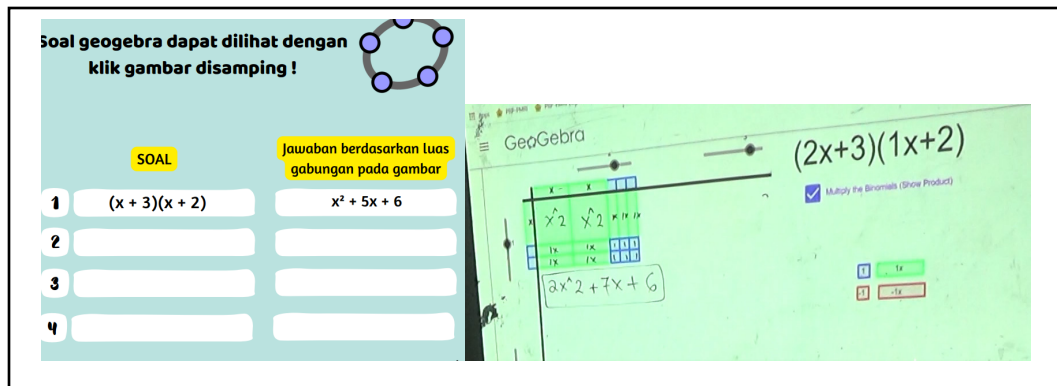


Figure 10. T3 guiding students in completing Activity 6 in the fifth meeting.

Across the three meetings, T4 and T5 also consistently used technology during slope instruction. GeoGebra and Autograph allowed students to explore the relationship between changes in slope and graphical representations on the coordinate plane (Figure 11). Based on the interview data, T5 recognized the important role of technology in strengthening students’ conceptual understanding, particularly in learning about slope. Specifically, T5 emphasized the value of technological tools for visualizing lines parallel to the y-axis and helping students understand why the slope of such lines is considered undefined. Accordingly, the performance of T4 and T5 was associated with indicators TCK2 and TCK3.

Draw several line segments using Autograph with various directions of slope and complete the following table!

direction of the line

rising from left to right

rising from left to right

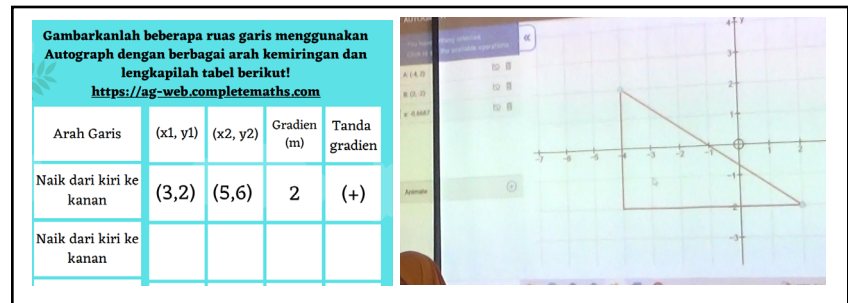


Figure 11. Teacher T5 facilitates students' use of Autograph to draw line segments.

In the first meeting, T6 was unable to use GeoGebra to introduce and visualize quadratic functions. However, through mentoring and reflection in subsequent sessions, T6 gradually developed the ability to integrate GeoGebra with mathematical content knowledge, enabling the technology to better support students' conceptual understanding of quadratic functions. In the post-lesson interview, T6 stated, "Usually I use PowerPoint in teaching, but I have never used GeoGebra before." This statement suggests that T6 initially had limited experience with mathematics software. Nevertheless, the observed progression across lessons indicates an improvement in T6's ability in selecting and using GeoGebra for instructional content. T6's performance was associated with indicators TCK2 and TCK3.

IMPROVEMENT OF TEACHERS' TPACK (T1–T6)

Based on the cross-case analysis of the six teachers involved in the study, improvements were found in the technological, pedagogical, and mathematical content aspects, with different characteristics across teachers. Table 3 presents the summary of these findings.

Table 3. Summary of Improvements in PCK, TPK, and TCK

Teacher	PCK	TPK	TCK
T1	Initially, T1 was hesitant to determine when to provide explanations and visualize the concept of fraction division. This circumstance improved through increased use of visual approaches (PCK1 and PCK4).	Initially, T1 was unable to guide students in accessing the fraction e-module and introductory videos. Through mentoring and reflection, T1 used technology as an active learning medium (TPK1).	Initially, T1's ability to use the e-module and introductory videos was limited, but it improved to the point that T1 could use the technology independently (TCK2 and TCK3).
T2	T2 was able to guide students in understanding fraction concepts, comparing fractions, and performing addition and subtraction through structured activities. However, in the multiplication and division of fractions, there were limitations in explaining the conceptual meaning. Through mentoring and reflection, T2 understood multiplication and division of fractions through visual approaches (PCK3).	T2 consistently integrated technology to enhance student motivation, facilitate feedback, and support both independent and collaborative learning (TPK3 and TPK5).	T2 was able to use GeoGebra for comparing, adding, and subtracting fractions, but experienced conceptual difficulties in multiplication and division. Through mentoring and reflection, T2 began understanding multiplication and division concepts visually (TCK3).

Teacher	PCK	TPK	TCK
T3	T3 consistently guided students in algebraic topics (PCK1).	T3 consistently used technology because it motivated students and supported feedback, student independence, and group work (TPK3 and TPK5).	T3 consistently used GeoGebra and Liveworksheet to support students' understanding of algebraic concepts (TCK1 and TCK3).
T4	Initially, T4 often provided direct answers. This was improved by applying questioning strategies to help students connect graphical forms with contextual situations (PCK2).	Initially, T4 used technology in a teacher-centered way by providing direct answers to students. Following mentoring and reflection, T4 demonstrated improvement by applying questioning strategies that encouraged students' active engagement (TPK2).	T4 consistently used GeoGebra and Autograph during slope instruction (TCK2 and TCK3).
T5	T5 consistently guided students in slope topics (PCK1).	T5 consistently used technology because it motivated students, provided timely feedback, and supported both independent learning and collaborative group work. (TPK3 and TPK5).	T5 consistently used GeoGebra and Autograph during slope instruction (TCK2 and TCK3).
T6	Initially, T6 did not guide students in project-based tasks, but it was improved by guiding students in graphing quadratic function and analyzing changes in graph shape from variations in function coefficients. (PCK2).	Initially, T6 was unable to guide students in graphing water trajectory using GeoGebra. Later, T6 demonstrated improvement by guiding students to explore changes in quadratic function graphs using GeoGebra (TPK4).	Initially, T6 was unable to use GeoGebra to introduce and visualize quadratic functions. Improvement was shown through effective use of GeoGebra in instruction (TCK2 and TCK3).

Table 3 indicates that all teachers experienced an improvement in their TPACK throughout the implementation of instruction. This development was facilitated through ongoing mentoring and reflective discussion that supported teachers in integrating technology, pedagogy, and mathematical content more effectively. Teachers with prior experience using educational technologies (T2, T3, and T5) demonstrated consistent ability in utilizing GeoGebra and Autograph to support instruction. In contrast, teachers with limited prior experience in technology integration (T1 and T6) showed notable improvement following mentoring sessions and reflective engagement with the observer. These findings suggest that mentoring and reflection played a significant role in supporting the development of teachers' TPACK, particularly among those with less experience in using technology for instructional purposes.

DISCUSSION

This study found that all teachers (T1–T6) demonstrated improvements in their PCK, TPK, and TPK competencies despite their different characteristics. In the PCK aspect, improvements were evident in teachers' abilities to elicit students' understanding, identify misconceptions, and adjust instructional strategies. Teachers who initially tended to be procedural or provided limited opportunities for student responses developed through the use of open-ended questions, feedback, and contextual approaches. Meanwhile, some teachers consistently demonstrated strong PCK in constructing conceptual meaning and adapting instruction to students' needs. Teachers require professional development in the pedagogical application of these skills to make the teaching and learning process more meaningful (Carlson & Gadio, 2002). Suboptimal PCK resulted in teachers' TPACK remaining partial and focused primarily on technology use. These findings align with previous studies indicating a strong correlation between TPACK and PCK, where deep mastery of pedagogical and content knowledge serves as the foundation for meaningful technology integration (Dong et al., 2015; Scherer et al., 2017). However, after each lesson, observers conducted reflective discussions with teachers, leading to improvements in PCK in subsequent meetings. Overall, all teachers experienced improvements in TPACK, either gradually or consistently. This improvement was marked by greater integration of technology, pedagogy, and content into instructional practices. The observer-guided mentoring followed by reflective discussions helped teachers connect these three components, resulting in more meaningful, student-centered learning.

In the TPK aspect, some teachers initially used limited technology or lacked confidence in technology use. For example, one teacher was not confident in using instructional videos, so a student spontaneously assisted her by opening the e-module and the video. However, through continuous mentoring and reflection, technology use evolved to be more meaningful, not merely as a presentation tool but also as a medium for exploration and active student guidance. As noted by previous researchers, direct classroom observation provides rich information about the characteristics of effective teaching and learning (Good & Brophy, 2000), while the success of technology integration in instruction depends on the extent to which teachers plan the learning process (Harris & Hofer, 2009). Therefore, the next step was to observe how teachers implemented TPACK in classroom practice, followed by interviews to further elaborate the planning and implementation processes (Kereluik et al., 2010). In addition, reflection has also been identified as an important component in developing and evaluating effective TPACK within teacher education programs (Goktas et al., 2009; Pierson & Borthwick, 2010). Other teachers demonstrated relatively strong TPK mastery from the outset and consistently facilitated collaboration and student learning activities. The teachers' TPK was categorized as good because they frequently participated in training related to facilitating students' use of technology. The application of GeoGebra and Autograph, integrated into the GetMath platform, as seen in T2, T3, and T5 (Table 3), enabled them to acquire adequate knowledge to guide students in using technology for learning. Teachers' pedagogical beliefs, affective attitudes, and technological competencies also changed after participating in professional development programs (Benning et al., 2023). In line with those studies focusing on teachers' progress in professional development (PD) programs, this study further demonstrates how mentoring and reflection support the development of TPACK during classroom instruction.

In the TCK aspect, some teachers were initially inconsistent or experienced conceptual errors; however, after mentoring, observation, and reflection, technologies such as GeoGebra and Autograph were effectively used to visualize mathematical relationships, correct misconceptions, and deepen conceptual understanding. Other teachers demonstrated strong TCK from the initial meetings, using technology to connect symbolic, visual, and contextual representations. These teachers' TCK was considered good because they frequently integrated technology into the mathematical content, as shown by T3, T4, and T5 (Table 3). Mathematics teachers with high levels of TCK integrate the most appropriate technological tools to represent the mathematical topics they teach (Alshehri, 2012). TCK also refers to knowledge of how technology and content are reciprocally related (Mishra &

Koehler, 2006). However, this study shows that TCK development can also emerge gradually through repeated opportunities to visualize concepts, discuss misconceptions, and reflect on classroom learning experiences.

Furthermore, comprehensive development of teachers' TPACK is essential for supporting the effective design and implementation of RME-based mathematics learning modules (Aryani et al., 2026). Through the principles of guided reinvention and didactical phenomenology, RME encourages teachers to design contextual learning activities grounded in real-life situations relevant to students' experiences (Gravemeijer & Doorman, 1999). Consequently, the use of RME-based e-modules not only emphasizes teachers' technological competencies but also strengthens their pedagogical abilities in guiding students to rediscover mathematical concepts independently. Furthermore, CK requires special attention to reconnect RME with its philosophical foundations, ensuring a balance between theory and practice (Class, 2024).

Based on these findings, further improvement of teachers' TPACK requires systematic support from multiple stakeholders. Schools and education authorities need to play an active role in creating conducive environments and providing professional development opportunities that support technology integration in learning. Such training should involve using the GetMath platform as the primary resource and medium for implementing RME-based e-modules. Through these activities, teachers are expected to strengthen their integrative skills in meaningfully combining technology, pedagogy, and content. Continuous institutional support and practice-based training are expected to enhance teachers' confidence in innovation while reinforcing their capacity to create reflective, contextual, and 21st-century-relevant learning processes.

CONCLUSION

This study shows that all teachers (T1–T6) improved their PCK, TPK, and TCK competencies during the implementation of the RME-based e-module. These improvements varied across teacher, influenced by their initial experience with technology, understanding of mathematical content, and pedagogical practices. Teachers with limited experience in using technology showed development in utilizing e-modules, introductory videos, Liveworksheets, GeoGebra, and Autograph to support the learning process. In contrast, teachers with prior experience in using technology demonstrated more consistent integration of technology, pedagogy, and content throughout the learning process.

The findings indicate that mentoring with observers followed by reflection played an important role in supporting the development of teachers' competencies. In terms of PCK, teachers improved in identifying students' misconceptions, asking questions that promote conceptual understanding, and adjusting instructional strategies to students' needs. In terms of TPK, the use of technology evolved from merely a tool for delivering information into a means of facilitating exploration, interaction, and active student engagement in learning. Meanwhile, in TCK, teachers increasingly start using technology to visualize mathematical concepts, connect symbolic, visual, and contextual representations, and help students build deeper conceptual understanding.

Overall, this study demonstrates that TPACK development depends not only on technological proficiency but also on teachers' ability to integrate technology, pedagogy, and mathematical content into instructional practice. The implementation of an RME-based e-module supported by continuous mentoring and reflection was proven effective in strengthening teachers' TPACK competencies and promoting more contextual, reflective, and student-centered mathematics learning. Therefore, teacher professional development programs should be designed not only as technology training, but also through classroom-based mentoring and reflective practice to sustainably enhance teachers' competencies. This study has several limitations. First, the number of participants was limited to six teachers, which restricts the generalizability of the findings to broader school or regional contexts. Second, in this study, the research team developed the e-module containing introductory videos, Liveworksheets, GeoGebra, Autograph, and a Mario Bros game. Ideally, according to the TPACK

framework, such instructional materials should be developed by the teachers themselves during the training process. Furthermore, subsequent studies should more deeply examine the influence of teachers' initial technological competencies on TPACK development, for example, by grouping teachers by levels of digital literacy or teaching experience.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from Universitas Syiah Kuala. We also thank all participants for their valuable contributions to this study. Universitas Syiah Kuala (USK) supported this study under the Penelitian Profesor Grant (contract number: 166/UN11/SPK/PNBP/2021).

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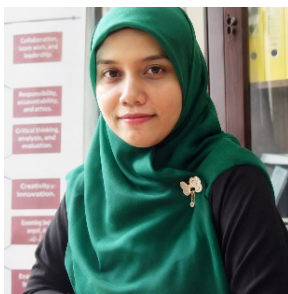
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