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Abstract

TPACK development for prospective mathematics teacher students is a crucial aspect in preparing educators who are able to integrate technology effectively in the learning process. This study aims to examine the development of TPACK for prospective mathematics teacher students and the most effective form of TPACK development for prospective mathematics teacher students. This study uses the Systematic Literature Review method. Data collection was obtained by documenting articles related to the development of TPACK for prospective mathematics teacher students. The articles obtained and used in this study were 7 Scopus indexed journal articles that had been published from 2010 to 2024 using the publish or perish application. However, after an in-depth review, only 4 articles contributed to the questions of this study. The results of the study indicate that the development of TPACK for prospective mathematics teacher students can be done using various methods or ways. Each method or method of developing TPACK for prospective mathematics teacher students certainly has its own advantages and disadvantages. By combining several of these methods, the development of TPACK for prospective mathematics teachers will be more effective, namely in the form of training or learning that involves technology in it with the target of producing products so that prospective mathematics teachers have a rich learning experience with technology to be applied in their classes later.

Introduction

In the context of today's modern education, the Technological Pedagogical Content Knowledge (TPACK) framework is very important to improve the quality of learning. TPACK integrates three main components, namely content knowledge, pedagogical knowledge, and technological knowledge. TPACK is related to teachers' skills in connecting the three main aspects, namely materials, technology and pedagogy (Quddus, 2019). By combining these three main components, teachers can design learning experiences that are more effective and relevant to the needs of students in today's digital era (Janah, 2022; Oktaviana & Yudha, 2022; Rahmatiah et al., 2022). The importance of TPACK in modern education is also seen from the need to develop 21st century skills known as 4C, namely communication, collaboration, critical thinking, and creativity (Fauziyah & Mahmudah,

2023; Mas'un & Saparudin, 2022). Research shows that mastery of TPACK can help teachers create a learning environment that encourages students to think critically and creatively, and collaborate effectively (Rahmadi, 2019; Rahmawati & Khoirurrosyid, 2022). For example, in STEM-based learning and digital learning, teachers who master TPACK can more easily integrate technology to improve student engagement and learning outcomes (Yuliardi et al., 2023).

TPACK also plays an important role in preparing teachers to face the challenges that arise due to rapid technological developments. In the era of the Industrial Revolution 4.0, teachers are required not only to master the content being taught, but also to be able to use technology effectively in the learning process (Lukman et al., 2022; Rismawati et al., 2021). TPACK does not focus on the use of technology, but rather on how to use it in the learning process effectively (Alqurashi et al., 2016). TPACK is also defined as the knowledge, abilities, and competencies of teachers related to the integration of technology in learning activities. Research shows that teachers who have a good understanding of TPACK can more easily adapt their teaching methods to take advantage of the latest technology, thereby improving the quality of education provided (Maharani et al., 2022; Rafi & Sabrina, 2019).

However, in reality, there are various challenges faced. Several studies have identified inhibiting factors, such as lack of access to technology and adequate training for teachers (Mas'un & Saparudin, 2022). Therefore, it is important for educational institutions to provide the necessary support, both in the form of training and technological infrastructure, so that teachers can develop and implement TPACK effectively in their learning (Hartati et al., 2019). TPACK is the most effective tool and method to explore teachers' abilities in terms of mastery of technology and their ability to use technology in learning (Hanik et al., 2022). One form of teacher skills that supports teacher professionalism is TPACK skills (Nurhayani et al., 2022). Overall, TPACK is a very relevant framework in modern education, because it can help teachers integrate technology in ways that support deeper and more meaningful learning. By developing TPACK, teachers not only improve their professionalism, but also contribute to the formation of a generation that is ready to face future challenges (Fauziyah & Mahmudah, 2023; Oktaviana & Yudha, 2022; Rahmatiah et al., 2022).

In line with the challenges outlined above, the integration of technology in mathematics learning also faces various challenges that need to be overcome to improve the effectiveness and efficiency of the teaching and learning process. One of the main challenges is the readiness of teachers to use technology effectively. Technology can improve the effectiveness and efficiency of mathematics learning, but it also poses challenges in terms of teacher adaptation and competence in managing and using technology (Ansar & Asrirawan, 2020; Darmayunata et al., 2021; Gumilar & Hermawan, 2021; Munawaroh et al., 2021). Research shows that teachers often lack adequate skills in operating the technological devices needed for mathematics learning, which can hinder the implementation of technology in the classroom (Oktaviyanthi et al., 2017; Samo et al., 2019; Taufan et al., 2023). In addition, the lack of professional training and support for teachers is also an inhibiting factor in technology integration (Restiana & Pujiastuti, 2019).

On the other hand, students' attitudes towards the use of technology in mathematics learning also play an important

role. Research shows that students' positive attitudes towards technology can increase their engagement in learning (Lijie et al., 2020; Purwaningrum & Faradillah, 2020). However, if students find it difficult to use technology or do not see its relevance to learning, this can have a negative impact on their motivation and learning outcomes. Therefore, it is important for educators to create a learning environment that supports and facilitates the use of technology in a way that is interesting and relevant to students (Satriawati et al., 2022; Sugestiana & Soebagyo, 2022).

In addition to challenges at the teacher and student level, technological infrastructure is also an important issue. Access to adequate devices and internet connections is essential to support technology-based learning. In many areas, especially in disadvantaged areas, access to technology is still limited, resulting in gaps in the quality of education (Setyawan et al., 2023). Therefore, efforts to improve technological infrastructure in schools are essential so that all students can benefit from technology integration in mathematics learning (Restiana & Pujiastuti, 2019). However, the success of implementing this technology is highly dependent on the ability of teachers to integrate the technology into existing curricula and teaching methods (Oktaviyanthi et al., 2017; Taufan et al., 2023). For example, the potential of Artificial Intelligence (AI) education in mathematics teaching highlights the urgent need for comprehensive professional development programs designed to equip teachers with the skills and knowledge needed to effectively integrate AI tools such as ChatGPT into the curriculum (Magat & Sangalang, 2024). Thus, ongoing training and professional development for teachers becomes essential to address these challenges and ensure that technology can be optimally used in mathematics learning.

The TPACK framework has emerged as an important model for understanding the integration of technology into instructional practices across educational contexts globally. TPACK synthesizes three primary forms of knowledge: technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), emphasizing the interaction between these domains to improve educational outcomes. The evolution of TPACK has been influenced by a variety of factors, including pedagogical shifts, technological advances, and contextual adaptations, which have been widely documented in the recent literature.

The TPACK framework has undergone significant adaptation to accommodate diverse educational contexts reflecting the increasing role of technology in 21st-century education. For example, Habiyaremye discusses how the framework has evolved from Pedagogical Content Knowledge (PCK) to TPACK, highlighting its effectiveness in mathematics instruction and its adaptability across subjects and technologies (Habiyaremye et al., 2023). This adaptability is important because it allows educators to adjust their instructional strategies to meet the unique needs of their students and the demands of their educational environment. Additionally, the global trend toward digital pedagogy necessitates a deeper understanding of TPACK among educators. As Goradia notes, the rapid development of information technology has shifted higher education toward the adoption of digital pedagogy, making the TPACK framework increasingly relevant (Goradia, 2018). This shift is further supported by Niess' findings, which emphasize the importance of TPACK in preparing teachers to navigate the complexities of teaching with technology (Niess, 2011). The development of a practical and integrated knowledge base on the use of ICT should be a visible component of teacher education programs (Aslan & Bekereci-Sahin, 2024). Based on this explanation, the purpose of this study was to examine in depth the development of TPACK in pre-service

mathematics teacher students.

Method

This study uses the Systematic Literature Reviews (SLR) method, which is a way of synthesizing scientific evidence to answer specific research questions in a transparent and reproducible manner, while attempting to include all published evidence on the topic and assessing the quality of this evidence (Lame, 2019). The data used in the SLR study consists of research questions, search process, define inclusion and exclusion criteria, define the quality assessment (QA) checklist, data collection, data analysis, deviation from protocol (Carrera-Rivera et al., 2022; Triandini et al., 2019). With the following provisions:

Research Question

One possible way to help provide an overview of the scope of the SLR is to use the PICOC method as shown in Table 1.

Table 1. PICOC (Population, Intervention, Comparison, Outcome, and Context)

Population (P)	Pre-Service mathematics teacher students
Intervention (I)	TPACK Development
Comparison (C)	Comparing various TPACK developments of prospective mathematics teacher students
Outcomes (O)	TPACK of prospective mathematics teacher students
Context (C)	TPACK of prospective mathematics teacher students in the implementation of ICT-assisted mathematics learning

The research questions to be answered in this SLR are arranged in Table 2 below.

Table 2. Research Question

ID	Research Question	Motivation/purpose/benefit
RQ1	How is the development of TPACK for prospective mathematics teacher students?	Examining the development of TPACK of prospective mathematics teacher students
RQ2	What is the most effective form of TPACK development for prospective mathematics teacher students?	Identifying the most effective form of TPACK development for prospective mathematics teacher students

Search Process

The first step the author took was to discuss the title for this SLR. Along with the rapid development of technology use in the world of education, it is appropriate for prospective mathematics teacher students to have TPACK in order to integrate technology into their learning. Therefore, the author decided to explore further the development

of TPACK of prospective mathematics teacher students carried out in various countries. Relevant keywords from the title, abstract, and appropriate authors obtained to conduct this review are Analysis of the Development of Technological Pedagogical Content Knowledge of Prospective Mathematics Teacher Students in Various Countries. These keywords are then combined with the Boolean operator "AND" to form a search string used in the identification process as a literature search strategy. This literature search strategy is shown in Table 3.

Table 3. Search Keywords

Database/Search Result	Keyword String
Scopus	"Technological Pedagogical Content Knowledge" AND "Pre-Service Mathematics Teacher" AND "Development"

The identification stage begins with searching for relevant articles to review. The search was conducted through Scopus using the keywords listed in Table 3, namely "Technological Pedagogical Content Knowledge" AND "Pre-Service Mathematics Teacher" AND "Development". At this stage, the author only uses these keywords to calculate the results from each search engine. By using the help of Publish or Perish software, the identified results were 7 articles from Scopus. The last search was conducted on December 10, 2024 which will be filtered. This PRISMA protocol is illustrated in Figure 1.

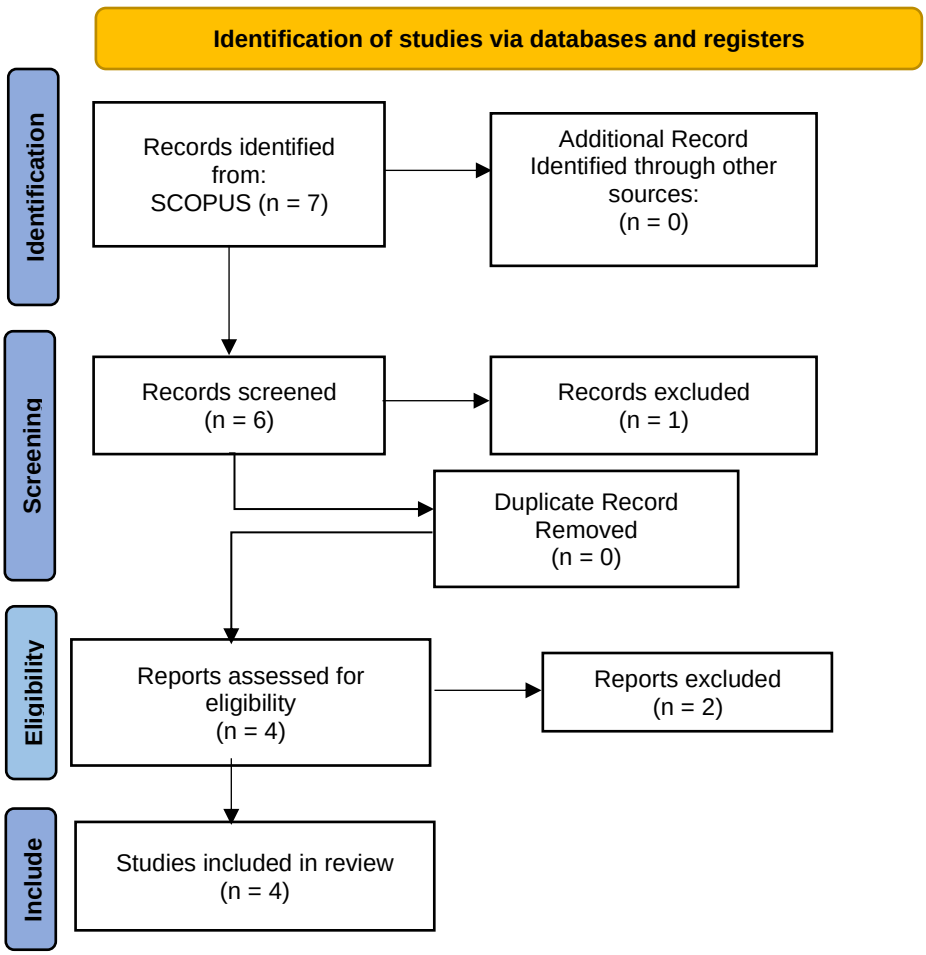

Figure 1. Export PRISMA Data

Inclusion and Exclusion Criteria

The screening stage begins by eliminating duplications from the identification results. Next, we sort the data based on the article title, year of publication, document type, language, and article accessibility. The article title must be relevant to the author's topic, namely Analysis of the Development of Technological Pedagogical Content Knowledge of Prospective Mathematics Teacher Students. The year of publication is set between 2010 and 2024 to ensure relevant and up-to-date research, considering that technological advances are developing rapidly. The type of document selected is an original study published in a scientific journal. The language used is English for research standardization, and its accessibility is limited to full-text articles with free access. This sorting process is carried out through each search engine, and the details are stated in the inclusion and exclusion criteria in Table 4.

Table 4. Selection Criteria (Inclusion and Exclusion)

Inclusion criteria	1. Articles used are only those related to the Development of Technological Pedagogical Content Knowledge of Prospective Mathematics Teacher Students 2. Only journal studies will be included 3. Articles published in 2010-2024 4. Articles written in English
Exclusion criteria	1. Articles not related to the Development of Technological Pedagogical Content Knowledge of Prospective Mathematics Teacher Students 2. In addition to journal studies 3. Articles published outside of 2010-2024 4. Articles not written in English

The selection of primary studies was carried out through a two-stage screening procedure. In the first stage, only the abstract and title of the studies were considered. In the second stage, the full text was read. It is important to note that an inclusive approach was used at both stages to avoid premature exclusion of studies. This means that if there was any doubt about a study, it was included.

Research Quality (Quality Assessment)

The data obtained from the SLR research will be analyzed using quality assessment criteria, which include the following aspects:

Table 5. Research Quality (Quality Assessment)

ID	Quality Assessment Criteria Questions
QA1	Was the journal article published in 2010-2024?
QA2	Does the journal article contain information related to the Development of Technological Pedagogical Content Knowledge of Prospective Mathematics Teacher Students?

For each question, quality assessment criteria will be used to evaluate each selected journal paper.

a. a. Y (Yes): for journal articles that meet the quality assessment criteria.
b. b. T (No): for journal articles that do not meet the quality assessment criteria.

Data Analysis

At this stage the data that has been collected will be analyzed to show:

a. TPACK development of prospective mathematics teacher students conducted in various countries from 2010-2024 (referring to RQ1).
b. The most effective form of TPACK development of prospective mathematics teacher students from 2010-2024 (referring to RQ2).

Deviation from Protocol

After evaluation, the author documents modifications related to deviations from protocol.

a. This study identifies the development of TPACK of prospective mathematics teacher students conducted in various countries and provides responses to research questions.
b. Collecting scientific publications to answer questions, ensure excellence, and provide necessary data.
c. This study aims to provide a more comprehensive picture of the development of TPACK of prospective mathematics teacher students conducted in various countries and determine the most effective form of TPACK development of prospective mathematics teacher students.

Results and Discussion

In the results and discussion, there are two questions discussed which are the core of the research conducted with the Systematic Literature Review approach. The questions are related to the development of TPACK of prospective mathematics teacher students and the most effective form of TPACK development of prospective mathematics teacher students. The following is an explanation related to the results of these questions.

Based on the results of Export PRISMA data, it was found that there were 7 articles that matched the keywords of this study. However, after a thorough review, it was found that there were 4 articles that contributed to the questions of this study. As shown in table 6 below.

Tabel 6. Findings related to the Development of TPACK of Prospective Mathematics Teacher Students

Article Title	Author	Year	Findings related to the development of TPACK of prospective mathematics teacher students
The Evaluation of a Pre-Service Mathematics Teacher's TPACK: A	İpek Saralar Mine Işıksal-Bostan Didem Akyüz	2018	This study focuses on how participants teach multiple views of three-dimensional objects in a private secondary school. In this case study, the main objective was to investigate how a preservice

Article Title	Author	Year	Findings related to the development of TPACK of prospective mathematics teacher students
Case of 3D Shapes with GeoGebra			teacher utilized her TPACK in a real classroom setting and to see if the classroom experience during the course influenced her TPACK. The findings of the study revealed that there was observable development in the participant's skills in teaching with technology during the school experience course that helped improve her TPACK. It is proposed that the school experience helped her develop her knowledge of teaching in a dynamic geometry integrated mathematics classroom.
Development of TPACK with Web 2.0 tools: Design-based study	Tugba Uygun Ali Sendur Rahime Dere Bilal Ozcakir	2023	This study aimed to examine the development of preservice teachers, conducted as a design-based study. During a 14-week instructional series, preservice teachers were given training based on a designed hypothetical learning trajectory. The findings of the study indicated that there was an increase in preservice mathematics teachers' technological pedagogical content knowledge with the training provided for the use of Web 2.0 tools in mathematics education.
Pre-Service Mathematics Teachers' Use of Multiple Representations in Technology-Rich Environments	Mehmet Fatih Özmantar Hatice Akkoç Erhan Bingölbali Servet Demir Berna Ergene	2010	In this study, prospective mathematics teachers' use of multiple representations (MRs) in a technology-rich environment after they took a course designed for technology integration into their teaching was examined. The use of multiple representations (MRs) is important because it has the potential to create conditions for effective learning and lead to deeper levels of understanding of the subject. The researchers examined the development of prospective mathematics teachers' use of multiple representations (MRs) while teaching in a technology-rich environment. The prospective teachers took a preparation program aimed at integrating technology into mathematics instruction. The findings of the study suggest that any effort to prepare prospective teachers for the effective use of technology in mathematics

Article Title	Author	Year	Findings related to the development of TPACK of prospective mathematics teacher students
			instruction needs to explicitly focus on the functions of multiple representations (MRs) in conjunction with the mathematical content being considered. The study also discusses the educational implications of the study for designing and implementing preparation programs related to the successful integration of technology into mathematics instruction.
Time-travelling in philosophy of mathematics courses: From classroom to newsroom	Mehmet Kasım Koyuncu	2024	This article presents a new teaching method that uses media production as a principle in education, which aims to convey the philosophy of mathematics effectively. The effects of this method on participants' technological pedagogical content knowledge were investigated using a mixed methodology approach with a sample of forty prospective mathematics teachers. The findings of the study revealed that creating newspapers not only fosters the development of technological pedagogy inherent in the teaching profession, but also contributes to the development of the expected roles of individuals in educational environments in the technological era. Therefore, this method can be a source of inspiration for teacher educators, especially those who teach courses in related contexts.

The data in table 6 shows that various methods or ways of developing TPACK of prospective mathematics teacher students were found. Research by İpek Saralar, et al. (2018) revealed that school experience helps prospective mathematics teachers develop their knowledge of teaching in dynamic geometry integrated mathematics classes (Saralar et al., 2018). In the research of Tugba Uygun, et al. (2023) it was explained that prospective mathematics teachers were given training based on a hypothetical learning trajectory designed for 14 weeks of instructional series, from the study it was revealed that there was an increase in the knowledge of the content of technological pedagogy of prospective mathematics teachers with training given for the use of Web 2.0 devices in mathematics education (Uygun et al., 2023). In the research of Mehmet Fatih Özmantar, et al. (2010), it was explained about the use of multiple representations (MRs) by prospective mathematics teachers in a technology-rich environment after they took a course designed for the integration of technology into teaching. Prospective mathematics teachers follow a preparation program aimed at integrating technology into mathematics teaching. The research findings indicate that any effort to prepare prospective teachers for the effective use of technology in mathematics teaching

needs to explicitly focus on the function of multiple representations (MRs) in conjunction with the mathematical content being considered. The study also discusses the educational implications of the study in designing and implementing preparation programs related to the successful integration of technology in mathematics teaching (Özmantar et al., 2010). Mehmet Kasım Koyuncu's (2024) study presents a new teaching method that uses media production as a principle in education, which aims to convey the philosophy of mathematics effectively. The effects of this method on participants' technological pedagogical content knowledge were investigated using a mixed methodology approach with a sample of forty prospective mathematics teachers. The findings of the study revealed that creating a newspaper not only fosters the development of technological pedagogy inherent in the teaching profession but also contributes to the development of the expected roles of individuals in the educational environment in the technological era (Koyuncu, 2024).

Regarding the most effective form of TPACK development for prospective mathematics teacher students, the data in table 6 shows that TPACK development for prospective mathematics teacher students can be done in various ways or methods. Each method certainly has its own advantages and disadvantages. However, from these data, the author sees that by combining several of these methods, the development of TPACK for prospective mathematics teachers will be more effective, namely in the form of training or learning that involves technology in it (Özmantar et al., 2010; Uygun et al., 2023) with the target of producing products (Koyuncu, 2024) so that prospective mathematics teachers have a rich learning experience with technology (Saralar et al., 2018) to be applied in their classes later.

The development of TPACK for prospective mathematics teacher students is a crucial aspect in preparing educators who are able to integrate technology effectively in the learning process. Good teaching with technology requires the integration of content, pedagogy, and technology (Mishra & Koehler, 2008). Teachers must have sufficient skills to manage and use technology in learning, and be able to improve the quality of learning through technology (Saputra et al., 2023). To be able to integrate information and communication technology in mathematics learning, mathematics teachers need to understand and have Technological Pedagogical Content Knowledge (TPACK) skills in themselves (Rosyid, 2016). TPACK combines knowledge of content (Content Knowledge), pedagogy (Pedagogical Knowledge), and technology (Technological Knowledge) to create a comprehensive learning experience for students. The idea of TPACK emerged formally in an education journal in 2003 and began to be widely discussed in 2005, which was initially abbreviated as TPCK but changed to TPACK to make it easier to pronounce (Chai et al., 2013). TPACK is a development of Shulman's (1986) Pedagogical Content Knowledge (PCK) (Shulman, 1986). TPACK is a framework for integrating technology in teaching (Koehler et al., 2013).

In the context of TPACK development, prospective mathematics teacher students are expected to be able to develop pedagogical skills that integrate technology into learning content. Pre-service teachers' digital literacy significantly predicts their technology use skills (Nurzhanova et al., 2024). TPACK development should be an important goal in teacher education and teacher professional development (Mishra & Koehler, 2006). This aims to improve the effectiveness of learning and facilitate students' understanding of mathematical concepts. Overall, TPACK development for prospective mathematics teachers requires a comprehensive approach, including

improving content knowledge, pedagogy, and technology. The integration of these three components is expected to produce teachers who are competent in utilizing technology to improve the quality of mathematics learning. TPACK development for prospective mathematics teacher students can be done in various ways or methods. Professional development programs are effective in improving the knowledge and skills of prospective teachers in integrating technology into science and mathematics teaching through activities such as microteaching, training, learning design, and reflection (Kafyulilo et al., 2015). Teacher professional development courses support increased technology integration in the classroom (Guzmán González & Vesga Bravo, 2024). TPACK development for prospective mathematics teacher students can be through training or learning that involves technology in it. The learning process that includes more technology integration has a positive impact on the development of TPACK for prospective teachers (Durdu & Dag, 2017). The training or learning will also provide a rich learning experience with technology for prospective mathematics teachers that they can later apply to their classes. Technology Pedagogy Knowledge (TPK) has a stronger influence on the implementation of TPACK by prospective teachers than other elements (Santos & Castro, 2021).

Conclusions and Suggestions

This study reviews articles on the development of TPACK of prospective mathematics teacher students published in Scopus-indexed journals during the period 2010 to 2024. The results of the study indicate that the development of TPACK of prospective mathematics teacher students can be done using various methods or ways. In the context of TPACK development, prospective mathematics teacher students are expected to be able to develop pedagogical skills that integrate technology into learning content so that they are able to integrate technology effectively in the mathematics learning process. Each method or method of developing TPACK of prospective mathematics teacher students certainly has its own advantages and disadvantages. By combining several of these methods, the development of TPACK of prospective mathematics teachers will be more effective, namely in the form of training or learning that involves technology in it with the target of producing products so that prospective mathematics teachers have a rich learning experience with technology to be applied to their classes later.

Given the increasingly rapid development of ICT, it is time for the development of TPACK of prospective mathematics teacher students to receive serious attention so that prospective mathematics teachers are able to integrate technology effectively in the mathematics learning process. Furthermore, with all the limitations of this study, further research is highly recommended to be carried out in the future.

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