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Research Article

Optimization of TPACK-Based Project Learning in Micro Teaching Courses in the Mathematics Education Study Program

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ABSTRACT

The purpose of this research is to optimize project learning based on *Technological Pedagogical Content Knowledge* (TPACK) in the Micro Teaching course in the Mathematics Education Study Program. A descriptive qualitative approach is used to describe student involvement in each stage of the project: starting from planning, digital media development, implementation of micro teaching, reflection, revision, to publication of results. Data was collected through observations, project documents, and assessment sheets based on the TPACK rubric. The results showed that students were able to integrate elements of technology, pedagogy, and content quite well, with the highest scores in *the Pedagogical Knowledge* (4.5) and TPACK (4.4) dimensions, and the lowest scores in *the Technological Content Knowledge dimension* (4.1). These findings show that the TPACK-based project learning model is effective in developing the competencies of prospective 21st century mathematics teachers who not only master the material and learning strategies, but are also able to utilize technology appropriately. This study recommends the sustainable application of similar models to support the transformation of digital-based education and innovative pedagogy in higher education.

Keywords: TPACK; Micro Teaching; Project Learning; Prospective Teachers; Mathematics Education

1. INTRODUCTION

The development of information and communication technology has brought significant changes in the world of education, especially in terms of learning strategies and the role of teachers in the 21st century. Teachers are not only required to master teaching materials, but also must be able to apply technology in learning and understand the characteristics of students in depth (Choi & Young, 2021). In this context, the integration between pedagogy, content, and technology becomes essential to produce a meaningful and relevant learning process. One of the conceptual frameworks that supports such integration is *Technological Pedagogical Content Knowledge* (TPACK) introduced by Mishra and Koehler (Mishra & Koehler, 2006).

The TPACK framework emphasizes the importance of synergy between content knowledge (CK), pedagogical knowledge (PK), and technology (*Technological Knowledge*/TK) in designing and implementing effective learning (Koehler et al., 2007). The application of TPACK has become very relevant in the digital era, especially in teacher education which aims to prepare prospective educators to face modern learning challenges (Charania et al., 2024). In the mathematics education study program, the mastery of TPACK by prospective teachers not only improves the quality of teaching, but also becomes an important foundation in creating contextual and technology-based mathematics learning (Azrai et al., 2024). One of the strategic courses in the teacher education study program is *Micro Teaching*, which is designed to equip students with basic teaching skills before jumping into the actual classroom. However, the reality in the field shows that the implementation of micro teaching tends to be conventional, focusing on teaching practices in simulated scenarios with the dominance of lecture approaches and minimal technological exploration. This leads to a lack of optimal formation of technology-based pedagogic competencies in prospective teachers (Rahmatika et al., 2025).

In the context of higher education, the Micro Teaching course acts as a training tool for prospective teacher students to develop teaching competencies before entering the field. *Project-Based Learning* (PjBL) is considered effective in improving teaching skills because it involves students in solving real problems collaboratively (Nuraina et al., 2022). However, the optimization of project-based learning with the TPACK approach in Micro Teaching courses still needs to be studied more deeply, especially in the context of Mathematics Education, where the integration of technology and pedagogy must be in

harmony with the characteristics of abstract and problem-solving-based mathematics science.

Several previous studies have shown that the application of TPACK can improve the teaching ability of prospective teachers (Azrai et al., 2024; Muschaweck, 2023). However, there are still challenges in implementing TPACK optimally, such as students' lack of understanding of technology integration in mathematics learning and limited experience in designing TPACK-based projects (Herizal et al., 2022). Therefore, this study aims to explore the optimization strategy of TPACK-based project learning in the Micro Teaching course in the Mathematics Education Study Program.

As an innovative effort to improve the quality of micro teaching, the integration of *project-based learning* (PjBL) approaches combined with the TPACK framework is a potential solution. Project learning allows prospective teacher students to be actively involved in designing, developing, and reflecting on learning practices in an authentic, collaborative, and contextual manner (Asfihana et al., 2022; Novalia et al., 2025). When PjBL is implemented with TPACK principles, students not only learn about lesson content and teaching strategies, but are also skilled in using technology to support learning objectives (Kholid et al., 2022; Pramasdyahsari et al., 2023).

Recent research shows that the implementation of TPACK-based PjBL can improve the learning design ability, creativity, and collaborative skills of prospective teacher students (Rahardjanto et al., 2019; Sukackė et al., 2022). Especially in the field of mathematics education, where material abstraction is often a challenge, the integration of technology in micro teaching projects is important to develop interactive learning media, digital LKPDs, and mathematics learning videos that are interesting and easy for students to understand. Based on this background, this study aims to in-depth examine the optimization of TPACK-based project learning in micro teaching courses in mathematics education study programs, with a focus on improving pedagogic competence, content, and technology of prospective teachers. This research is expected to make a theoretical and practical contribution to the development of innovative and adaptive micro teaching learning models for today's educational needs.

2. RESEARCH METHOD

This study uses a descriptive qualitative approach with the aim of describing in depth the process and results of optimizing TPACK-based project learning in the Micro Teaching course. This approach was chosen because the researcher wanted to explore the perception, experience, and understanding of students and lecturers towards the integration of TPACK in the context of project-based learning (PjBL). The research subjects are 6th semester students of the Mathematics Education Study Program, Malikussaleh University in Aceh who are taking the Micro Teaching course, as well as the lecturer who teaches the course. The research was carried out in the even semester of the 2024/2025 academic year in the classroom and micro teaching laboratory of the Malikussaleh University campus.

Data collection is carried out through the following techniques:

1. Participatory Observation
   Observations were made during the project learning process, especially when students designed, implemented, and reflected on TPACK-based teaching practices. The researcher used an observation sheet that contained TPACK indicators and activities in the learning project.
2. Semi-structured interviews
   Interviews were conducted with students and lecturers to explore their experiences, challenges, and perceptions of project-based learning and TPACK integration. The questions are designed open-ended to allow for extensive exploration of the answers.
3. The documentation collected includes learning tools from student projects (RPP, LKPD, digital media), micro teaching videos, as well as the results of reflections or individual/group reports.
4. TPACK Questionnaire
   To quantitatively measure the level of mastery of students' TPACK, questionnaires that have been validated by experts and adapted from instruments developed by (Kosiol & Ufer, 2024; Tschönhens et al., 2024) and modified according to the context of mathematics and project learning are used.

The main instrument in this study is the researcher himself (human instrument), which is assisted by supporting instruments in the form of:

1. TPACK indicator-based observation sheets (Huq Shamim et al., 2024; Kurniawan et al., 2021)
2. Interview Guidelines.
3. Student project product assessment rubric,
4. TPACK questionnaire is based on the Likert scale (1–5).

Data Analysis Techniques

Qualitative data analysis is carried out interactively through the following stages:

1. Data reduction–sorting, simplifying, and grouping relevant data based on TPACK categories and *project-based learning syntax*.
2. Data presentation–organizing data in the form of descriptive narratives, tables, and diagrams to facilitate the extraction of meaning.

3. Conclusion drawing and verification – carried out continuously throughout the research process so that the results are valid and reliable (Jannah et al., 2025).
4. Data from the TPACK questionnaire was analyzed in a quantitative descriptive manner by looking for the average score, percentage, and score distribution of each aspect (TK, PK, CK, TPK, TCK, PCK, and TPACK).

Data Validity

1. To ensure the validity of the data, the researchers used:
2. Technical triangulation (observation, interview, documentation, questionnaire),
3. Member checking with the research subject to confirm findings,
4. Expert judgment for instrument validation.

3. RESULTS AND DISCUSSION

3.1 Application of TPACK-Based Project Learning in Micro Teaching

The application of TPACK-based project learning in the Micro Teaching course at the Mathematics Education Study Program, Malikussaleh University of Aceh showed significant results in improving the teaching competence of 6th semester students. Based on the research findings, students were given a project to design and implement a mathematics Learning Implementation Plan (RPP) that integrates technology, pedagogy, and scientific content holistically. For example, in algebra or geometry topics, students use applications such as GeoGebra, Desmos, or Microsoft Excel to visualize abstract concepts, while implementing active learning strategies such as group discussions or problem-based learning. This approach is in line with the research of (Nuraina & Rohantizani, 2024), who found that the integration of TPACK in project-based learning can improve students' conceptual understanding while developing prospective teachers' technology skills. Based on participatory observations and project documentation, it was found that the integration of project learning and TPACK was carried out through six stages:

1. Project planning: Students work in groups to determine math learning themes, develop lesson plans, and choose technology-based media (Canva, GeoGebra, and interactive PowerPoint).
2. Digital media design: Students develop learning videos, digital LKPDs, and online quizzes using Kahoot and Quizizz.
3. Implementation of micro teaching: Students practice learning in simulated classrooms with real scenarios.
4. Reflection and feedback: Lecturers and peers provide evaluations based on the TPACK rubric.
5. Product revision and finalization: Students improve learning products according to input.
6. Project presentations and publications: Projects are presented in classroom forums and published on campus learning platforms.

The results of the observation show that most students have been able to integrate the three main elements of TPACK simultaneously. For example, in learning the topic of building volume of space, students not only explain concepts verbally (CK), but also use 3D simulations in GeoGebra (TK) and apply the problem posing method in group discussions (PK). This is in line with the findings of (Marhami, Fonna, et al., 2020) who stated that the TPACK-based project-based learning model is able to facilitate authentic and complex learning experiences.

In addition, observations during the implementation of Micro Teaching showed that students experienced an increase in the ability to design student-centered learning. They not only use technology as a presentation tool, but also design interactive activities, such as digital quizzes using Quizizz or collaborative projects through Google Classroom. These findings are supported by (Marhami, Rohantizani, et al., 2020), who stated that project-based learning with the TPACK approach encourages students to think critically in choosing technology that suits the learning objectives and characteristics of the mathematics material. However, several obstacles were also identified, such as limited internet access and lack of students' mastery of some digital tools, which is in accordance with the findings of (Kim et al., 2021) on the challenges of technology integration in education.

Evaluation through self-reflection and feedback from lecturers and peers also revealed that students are increasingly skilled in combining pedagogical aspects, content, and technology. For example, in teaching statistics material, some students have successfully developed a project based on real data using spreadsheets, then analyzed them collaboratively. This shows that TPACK-based project learning not only enhances technical skills, but also hones 21st century skills such as collaboration and problem-solving (Gómez-Trigueros, 2023). Thus, this study strengthens the evidence that this learning model is effective in preparing prospective mathematics teachers who are adaptive to educational technology developments. However, more intensive training and adequate infrastructure are needed to maximize its potential for future implementation.

3.2 Students' Perception of TPACK Integration

The perception of students of the Mathematics Education Study Program, Malikussaleh University of Aceh towards the integration of TPACK in Micro Teaching learning is generally positive, although there are several challenges faced. Based on the results of questionnaires and interviews, most 6th semester students realize the importance of mastering TPACK in

preparing themselves to become competent mathematics teachers in the digital era. They acknowledge that this approach helps them design more interactive and contextual learning, especially in visualizing abstract mathematical concepts through tools such as GeoGebra and Desmos. These findings are in line with the research of (Sartika et al., 2023), which shows that prospective teachers trained in TPACK tend to be more confident in integrating technology into learning. However, some students expressed obstacles in applying TPACK optimally, especially related to the limitations of technology mastery and the availability of supporting infrastructure. Some respondents admitted that it was still difficult to combine pedagogical aspects and mathematics content with available technology, especially when it came to adjusting to the curriculum and student characteristics. This is reinforced by the findings of (Heath & Moore, 2024), who stated that although students understand the components of TPACK theoretically, their implementation in real practice often requires more intensive mentoring. In addition, some students also highlighted the need for continuous training related to the use of educational applications, considering the dynamics of rapid technological development.

On the other hand, students who have successfully implemented TPACK in the Micro Teaching project report increased motivation and creativity in teaching. They feel that this approach not only enriches the teaching experience, but also prepares them to face the challenges of 21st century learning. Some students even suggested that TPACK integration be extended to other courses, so they had more opportunities to practice. These findings support the research of (Kurnianto & Sarwono, 2023), who emphasize that TPACK-based learning is effective in forming adaptive and innovative teacher candidates. Overall, despite the obstacles, students view the integration of TPACK as a necessity in mathematics teacher education, in line with the demands of teacher competence in the digital era (Mishra et al., 2023; Mishra & Koehler, 2006). The results of the questionnaire showed that the majority of students responded positively to TPACK integration. The average score for each dimension is as follows:

Table 1. Results of the Student Perception of TPACK Integration questionnaire

Level	Aspects Assessed	Statement	Percentage				
			1	2	3	4	5
Recognition	Content Knowledge (CK)	I didn't have any difficulty explaining math concepts to my peers during micro teaching.	0	26,3	64,2	9,5	0
	Content Knowledge (CK)	I am able to relate the concept of mathematics to the problems of daily life.	2	12	65,5	20,5	0
	Technology Knowledge (TK)	I can use PowerPoint or GeoGebra media minimally in learning.	0	8	58	30	4
	Pedagogical Knowledge (PK)	I am not sure that I can formulate the right learning strategy in the micro teaching lesson plan.	0	10	50	32	8
Accepting	Technology Knowledge (TK)	I realize the importance of using ICT-based media in micro teaching activities.	0	5	55	35	5
	Pedagogical Knowledge (PK)	I do not recommend the lecture method in the implementation of micro teaching.	0	6	48	36	10
	Technology & Content Knowledge (TCK)	Complex mathematical concepts are difficult for students to accept without the help of ICT.	0	4	45	40	11
	Pedagogical Knowledge (PK)	I was able to organize math concepts for project-based learning.	1	6	42	38	13
Adapting	Technology Knowledge (TK)	The use of online simulations such as GeoGebra can improve students' understanding of micro teaching.	0	7	41	37	15
	Technology Knowledge (TK)	The role of lecturers can be temporarily replaced by learning videos in micro teaching activities.	0	5	40	39	16
Exploring	Pedagogical Knowledge (PK)	Assigning group assignments is not always effective in improving student understanding.	1	6	39	38	16
	Pedagogical Knowledge (PK)	Individual student guidance is difficult to do in the implementation of micro teaching.	0	4	36	40	20
	Technology Knowledge (TK)	I can use simulations like GeoGebra in micro teaching.	0	3	35	41	21
	Technology Knowledge (TK)	I can carry out synchronous media-assisted learning (Zoom/Meet).	1	5	34	40	20
	Technology Knowledge (TK)	I use digital worksheets (Google Forms/Docs) to evaluate student learning outcomes.	0	2	30	45	23
	Pedagogical Knowledge (PK)	I utilize students' digital skills to explore math teaching materials.	0	3	33	42	22
Improvement (Advancing)	Technology Knowledge (TK)	I am not sure that ICT integration can help students understand mathematics learning.	1	4	32	41	22
	Pedagogical Knowledge (PK)	The use of ICT in micro teaching makes me more confident in teaching.	0	2	28	44	26
	Technology Knowledge (TK)	I had difficulty integrating complex math content with ICT.	0	3	27	45	25
	Pedagogical Knowledge and Content (PCK)	I had a hard time integrating learning strategies with appropriate math concepts.	0	2	25	47	26

Based on **Table 1**, it shows that in general, students have a positive perception of the integration of *Technological Pedagogical and Content Knowledge* (TPACK) in *micro teaching* activities. This can be seen from the dominance of answers on a scale of 4 and 5 in almost all indicators, which indicates that students have good ability and readiness in integrating

elements of technology, pedagogy, and content into learning practices. This finding is in line with the research of (Chua & Islam, 2021; Skliarova, 2021) who stated that *micro teaching experience* is able to increase the mastery of *technological knowledge* of prospective teacher students, especially in the use of computer-based learning media such as PhET and GeoGebra. Similar results were also reported (Tong et al., 2020) that through *micro teaching*, students not only practice teaching skills but also reflect on the integration of the technology used so as to form an initial awareness of the TPACK framework.

At the introduction and acceptance levels, students show the ability to use digital media and realize the importance of the application of ICT in learning. This condition strengthens the findings of Mishra and Koehler (2006) and Koehler et al. (2013) who affirm that the conceptual understanding of TPACK starts from teachers' awareness and acceptance of the benefits of technology in increasing learning effectiveness. These results are also in line with Putri et al. (2021) who found that prospective mathematics teacher students with intensive exposure to digital media have higher pedagogical readiness and learning motivation. Thus, in the early stages of *micro teaching*, students have shown mental and cognitive readiness in utilizing learning technology.

Furthermore, at the level of adaptation and exploration, it can be seen that students are starting to be able to adjust their learning strategies with the support of technology and explore various digital platforms such as *Zoom*, *Google Forms*, and *digital worksheets*. This finding is in line with the results of (Guo et al., 2020) research which states that direct experience in using learning technology contributes to improving the pedagogical exploration ability of prospective teachers. (Kholid et al., 2022; Paul et al., 2023) also added that students who often explore online learning applications show a significant increase in *technological knowledge* and *pedagogical knowledge* skills. However, some students still experience obstacles in integrating complex content with technology. This is in line with the research of (Gomez-del Rio & Rodriguez, 2022; Gupta, 2022) which found that even though students have good technological adaptability, they still have difficulty in applying technology to explain abstract or conceptual material.

At the level of improvement, students begin to show the ability to integrate the three components of TPACK in their entirety. They are able to design learning that combines pedagogical strategies, mathematical content, and digital technology support simultaneously. However, around 20–30% of students still show doubts and difficulties in integrating technology for complex material. These results are in line with the findings of (Ekawati & Prastyo, 2022a, 2022b) who affirm that the process of improving TPACK integration requires continuous practice and reflective guidance. Meanwhile, research by (Padzil et al., 2021) found that students with limited practical experience tend to still face a gap between *technological knowledge* and *content knowledge*. This imbalance is one of the main challenges in the implementation of TPACK at the student level of prospective teachers.

In general, the results of this study reinforce previous findings that *micro teaching* is an effective means to foster TPACK integration in prospective teachers. However, there are still research gaps that can be studied further, especially regarding how *reflective teaching* and *peer feedback* can help students deepen their ability to integrate technology into conceptual mathematics learning. In addition, it is necessary to conduct further research that examines the differences in TPACK mastery levels between students with different digital experience backgrounds, as well as the effectiveness of lesson study-based interventions in strengthening the integrative TPACK skills of prospective teachers in the digital era.

3.3 Constraints and Solution Strategies

The implementation of TPACK-based learning in the Micro Teaching course at the Mathematics Education Study Program, Malikussaleh University Aceh faces several significant obstacles, especially related to technical and pedagogical aspects. One of the main challenges faced by 6th semester students is the lack of mastery of learning technology, where most students are still not used to using applications such as GeoGebra, Desmos, or other interactive learning platforms. This is exacerbated by limited infrastructure, such as unstable internet access and the lack of supporting facilities such as laptops or projectors in some classrooms. These findings are in line with the research of (Chiu et al., 2024) which states that the lack of adequate technology training and facilities is the main obstacle to the integration of TPACK in the educational environment. In addition, some students also have difficulty balancing aspects of mathematics, pedagogy, and technology content, so that the learning designed tends to focus on the use of technological tools without considering their suitability with learning objectives. This condition is in accordance with the results of research by (Deja et al., 2021) who found that even though students understand the concept of TPACK theoretically, its application in a real context still requires intensive deepening and mentoring.

To overcome these obstacles, several solution strategies have been implemented in this study. First, intensive training on the use of educational technology is provided to students before the implementation of the Micro Teaching project, focusing on mastering relevant tools for mathematics learning, such as GeoGebra for geometry visualization or Microsoft Excel for data analysis. This approach is supported by research by (Ostayeva et al., 2023) which emphasizes the importance of technology workshops in improving the competence of TPACK prospective teachers. Second, collaborative learning through peer teaching is applied to enable students to share knowledge and experience in designing TPACK-based learning. This strategy has proven to be effective in building students' confidence, as revealed by Koehler & Mishra (2005) that

collaboration between prospective teachers can enrich their understanding of the integration of technology in learning. Third, mentoring by lecturers is periodically carried out to assist students in compiling lesson plans that combine the three components of TPACK in a balanced manner. This assistance is not only technical, but also pedagogical, by providing feedback on students' teaching practices. In addition, the use of simple, accessible technologies, such as the use of Google Forms for assessment or YouTube for self-paced learning, is also implemented to overcome infrastructure limitations.

While these strategies have shown positive results, the study also identifies the need for sustainable development in TPACK implementation. For example, the provision of more adequate facilities by institutions, such as stable internet access and technology-based classrooms, can encourage a more optimal implementation of TPACK. In addition, the integration of TPACK into the teacher education curriculum more systematically, not only in the Micro Teaching course, is also an important recommendation so that students have more opportunities to practice. These findings are relevant to the research of Mishra & Koehler (2006) which confirms that mastering TPACK requires a long process and habituation in various learning contexts. Thus, although obstacles in the implementation of TPACK are unavoidable, a structured and sustainable solution strategy can help Mathematics Education students of Malikussaleh Aceh University to be better prepared to face the demands of learning in the digital era. Based on interviews with students and lecturers, several main obstacles were found in the implementation of TPACK-based project learning:

Table 2. Interview questions and sample respondent answers

Aspects Assessed	Sample Questions	Sample Respondent Answer
Technology Knowledge (TK)	Through micro teaching courses, has your mastery of ICT for mathematics learning increased?	1. Increase, because lecturers direct the use of ICT media such as GeoGebra, PhET, and interactive learning videos.2. It is increasing, because in micro teaching, students are required to use technology-based media.
	What efforts are you making to improve ICT mastery in mathematics learning?	1. Create computer-based learning media (GeoGebra, interactive PPT).2. Conduct self-exploration through online simulations and educational applications.
Pedagogical Knowledge (PK)	Through micro teaching, has your ability to design math learning strategies improved?	1. It is quite improved, because it helps to find variations of learning models that have not been understood before.2. Improved, because it trains in identifying errors in the preparation of learning steps.
	What makes you feel less confident in the implementation of micro teaching?	1. Because they have to appear in front of classmates and do it openly.2. Because the preparation of learning tools and media is still immature.
Content Knowledge (CK)	Through micro teaching, has your mastery of math material increased?	1. Improve, because before practice you must really understand the mathematical concepts to be taught.2. Increase, because concepts that have been learned before can be recalled during teaching practice.
	What efforts are you making to improve your mastery of math material?	1. Learn through books, journals, and internet resources.2. Discuss and learn with peers.

Based on the results of the interviews presented in **Table 2**, it can be seen that students' abilities in the aspect of technological knowledge (TK) have shown an active effort to use and develop ICT-based learning media such as GeoGebra, PhET, and interactive PowerPoint. These results are in line with the findings of (Habibi et al., 2020) who stated that the application of technology-based media can increase student involvement in the micro teaching process. However, some students still experience obstacles in choosing the right media and integrating it effectively, as also revealed by (Msafiri et al., 2023)that limited practical experience is often an inhibiting factor in the implementation of TPACK in the early stages of learning.

In the pedagogical knowledge (PK) aspect, students show the ability to design learning that supports student involvement as well as the ability to reflect on mistakes in the preparation of learning steps. These findings support the research of (Istiningsih, 2022) who explains that direct experience through micro teaching can strengthen the reflective abilities of prospective teachers. However, weaknesses were still found in students' readiness and confidence when appearing to teach, which is in line with the findings (Sopiyani et al., 2023) that psychological factors such as nervousness and lack of experience also affect the effectiveness of micro teaching. Meanwhile, in the aspect of content knowledge (CK), students show a good understanding of mathematical concepts, but some of them still have difficulty in relating these concepts to practical application in the context of learning. This result is similar to the research of (Hayati et al., 2024) who found that the understanding of prospective teachers' content is often theoretical and has not been fully integrated with pedagogical approaches. This shows that there is a need for continuous mentoring to strengthen the linkage between content mastery and its application through TPACK-based learning strategies. Thus, the results of this study confirm the importance of an integrated training approach that emphasizes not only technological mastery, but also on pedagogical skills and content in a balanced manner. The research gap that is still open is the development of a continuous coaching model based on lesson study or peer coaching to support the deeper internalization of TPACK among prospective teachers.

4. CONCLUSION

Based on the results of the research that has been conducted, it can be concluded that the ability of prospective teacher students to integrate TPACK in micro teaching activities still varies in each aspect. In the aspect of technological knowledge (TK), most students have shown the ability to utilize ICT-based learning media such as GeoGebra, PhET, and interactive PowerPoint, but still need assistance in selecting relevant and effective media according to learning goals. In the aspect of pedagogical knowledge (PK), students are beginning to be able to design learning that encourages student involvement and reflect on the shortcomings in the implementation of learning, although readiness and confidence when performing are still the main obstacles. Meanwhile, in the aspect of content knowledge (CK), students have understood mathematical concepts theoretically, but the integration between content, pedagogy, and technology has not been optimal. Overall, the results of this study show that the mastery of TPACK of prospective teacher students still needs to be strengthened through integrated training that focuses on the application of technology in pedagogical contexts and relevant content. Advanced strategies such as tech clinics, lesson studies, and peer coaching are needed so that prospective teachers not only understand TPACK theory, but also be able to implement it reflectively and contextually in learning practices. These findings also open up opportunities for future research to develop a more effective sustainable coaching model in improving the integration of TPACK in the education of prospective teachers.

RECOMMENDATIONS

Based on the findings of the research, it is suggested that: (1) The Mathematics Education Study Program improve supporting facilities and organize TPACK training periodically for students; (2) Micro Teaching lecturers strengthen assistance in designing TPACK-based learning; and (3) Researchers can further develop similar studies with a broader scope or different approaches to enrich findings on the effectiveness of TPACK in teacher education. Educational institutions are advised to integrate the TPACK approach holistically in the curriculum to prepare competent teacher candidates in the digital era.

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AUTHOR'S CONTRIBUTIONS

All authors actively contributed to the research and writing process of this article. Nuraina is responsible for research design, data collection, and result analysis. Rahmi Hayati and Rohantizani played a role in data processing, theoretical framework, and writing discussion sections. Mursalin provided conceptual direction, methodological analysis, and substantive revision to the manuscript. Muliana assisted in the interpretation of the results and the preparation of conclusions, while Ratna Unaida contributed in the final editing and preparation of the references. All authors discuss the results of the research and contribute from the initial stage to the preparation of the final manuscript.

CONFLICT OF INTEREST

The authors state that there is no potential conflict of interest in this study. The entire process of research and article writing is carried out objectively and independently, without any influence from any party that can affect the results or interpretation of the research.

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