Enhancing Prospective Mathematics Teachers' TPACK through Augmented Reality Based Ethnomathematics

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***Abstract*—** This study aims to develop innovative learning media that integrates Augmented Reality (AR) technology and Baduy ethnomathematics to improve the Technological Pedagogical Content Knowledge (TPACK) competencies of prospective mathematics teachers. The research was conducted at the Mathematics Education Study Program, Mathla'ul Anwar University, involving 40 students as research subjects. The method used was research and development (R&D) through the stages of needs analysis, product design, expert validation, limited testing, extensive testing, and effectiveness evaluation by using ADDIE development model. The results showed that the developed media had contextual and interactive characteristics, visualizing Baduy cultural elements such as traditional houses, leuit, aseupan, and weaving patterns in the form of 3D objects that could be scanned using digital devices. The developed media demonstrated high feasibility, as indicated by a score of 0.87. The effectiveness test showed a significant increase in the TPACK competence of prospective teachers, marked by an increase in the average score from 60.0 (pre-test) to 82.5 (post-test) with a gain score of 0.72 (high category). The challenges faced in implementing this media include limitations of AR devices, unstable internet networks, and the lack of initial skills among prospective teachers in using digital technology. The solutions offered include providing an offline version of the application, intensive training for teachers and prospective teachers, and developing learning modules that are in line with the Merdeka Curriculum. The results of this study show that culturally relevant AR-based media integrated Baduy highly effective in improving the competence of prospective mathematics teachers, also promoting the preservation of local culture and fostering innovative and contextual learning.

***Keywords*— Media, Augmented Reality, Ethnomathematics, TPACK, Prospective mathematics teachers.**

I. INTRODUCTION

The massive digital transformation that has taken place in the 21st century has driven a paradigm shift in education from conventional approaches to more interactive, collaborative, and contextual technology-based learning. This shift not only demands innovation in learning methods, but also the ability of educators to utilize technology as a means of improving the quality of education. In the context of mathematics education, the integration of technology is very important because of the abstract nature of this subject and its demand for high visualization skills [1].

One of the most prominent technologies in the last decade is Augmented Reality (AR). This technology allows users to combine the real world with virtual objects interactively and in real-time, creating an immersive and in-depth learning experience [2] (Azuma, 1997; Ibáñez & Delgado-Kloos, 2018). In mathematics learning, AR has great potential to facilitate conceptual understanding by presenting three-dimensional representations of geometric objects, patterns, or mathematical structures that are difficult to visualize using conventional media alone. Research findings suggest that the use of AR in mathematics instruction can improve students' motivation, active participation, and problem-solving skills [3].

However, the application of universal learning technologies often ignores the cultural dimensions and social contexts of learners. In fact, cultural contexts play an important role in shaping the way people think and interpret mathematical concepts. The ethnomathematics approach offers the perspective that mathematics is not a science that stands apart from culture, but rather an integral part of human activities that are reflected in social, economic, and local traditions [4] Through ethnomathematics, students can understand that mathematical ideas are naturally present in everyday life, such as in weaving patterns, architecture, traditional calculations, or traditional measurement systems. Ethnomathematics examines and integrates mathematical ideas, practices, and techniques that emerge from and are developed within specific sociocultural or community contexts [5]

In Indonesia, one cultural community that has a wealth of mathematical values is the Baduy tribe in Lebak Regency, Banten. This community lives with a philosophy of harmony with nature and upholds local wisdom. Various practices in Baduy society, such as weaving, building houses, organizing the traditional calendar system, and determining directions in ritual journeys, imply the application of mathematical concepts such as geometry, symmetry, comparison, and estimation [6]. Exploring Baduy ethnomathematics has the potential to provide an authentic and meaningful learning context, especially for students from similar social backgrounds.

Unfortunately, most ethnomathematics research conducted so far has focused on the exploratory and documentary stages without continuing on to the development of innovative learning media that utilize the results of these explorations [7]. Conversely, many studies related to AR in mathematics learning only emphasize the aspects of visualization and motivation without considering the relevance of local culture [8This shows a research gap between learning technology innovation and the integration of cultural values in mathematics education.

To bridge this gap, an approach that holistically integrates technology, pedagogy, and content is needed. The Technological Pedagogical Content Knowledge (TPACK) framework developed by Mishra and Koehler (2006) provides a strong theoretical foundation for teachers to design effective and contextual learning. Through TPACK, teachers are not only expected to understand mathematical content and teaching strategies, but also to be able to select and manage appropriate technology to achieve learning objectives [9] (Koehler, Mishra, Akcaoglu, & Rosenberg, 2013). The integration of these three aspects enables learning that is adaptive to the needs of the 21st century, where technology is a means, not an end, in the educational process.

In the context of mathematics teacher education, mastery of the TPACK framework is a key competency that must be developed in higher education. Prospective teachers not only need to understand learning theory but also be able to translate it into practice by utilizing relevant technology. The development of AR-based learning media with Baduy ethnomathematics content is one way to foster prospective teachers' reflective abilities in designing learning that is oriented towards technological fluency, cultural awareness, and pedagogical creativity. Thus, this media serves a dual purpose: as a means of learning mathematics and as a training tool for prospective teachers to master the application of TPACK in real situations [10] (Thy, Im, & Iwayama, 2023).

In addition, the convergence between AR and Baduy ethnomathematics is also in line with the direction of national education policy, which emphasizes the importance of developing digital literacy and cultural literacy in 21st-century learning. This convergence presents a great opportunity to develop mathematics learning that is not only innovative but also rooted in local values. By presenting Baduy symbols, artifacts, and cultural activities in AR media, students and prospective teachers can internalize mathematical concepts contextually while fostering an appreciation for the nation's culture.

This study attempts to respond to these needs through the development of a convergence model of Augmented Reality learning media and Baduy ethnomathematics within the TPACK framework. Specifically, this study is aimed at: (1) designing AR-based learning media that contains authentic and pedagogical Baduy ethnomathematics content; (2) testing the effectiveness of these media in improving the TPACK competence of prospective mathematics teachers; and (3) exploring user experience (usability) in the context of technology-culture-based learning. This research is expected to contribute significantly to the development of mathematics education theory and practice that integrates modern technology with Indonesian local wisdom.

This research also contributes to the vision of higher education in producing prospective teachers who are competent, cultured, and adaptive to technological changes. By implementing the TPACK framework through the convergence of AR and ethnomathematics, prospective teachers are expected to be able to design learning that is not only innovative and effective, but also relevant to the socio-cultural context of Indonesian society.

II. LITERATUR REVIEW

The rapid digital transformation in the 21st century has significantly reshaped mathematics education, requiring innovative technological integration to enhance conceptual understanding and learner engagement. Mathematics, characterized by abstract structures and symbolic representations, demands strong visualization support to facilitate deeper cognitive processing. Empirical evidence indicates that technology-enhanced environments improve students' spatial reasoning and conceptual representations when pedagogically aligned [11]. Among emerging technologies, Augmented Reality (AR) has demonstrated considerable potential in mathematics education due to its ability to integrate virtual 3D objects into real-world contexts in real time. A systematic review by Ibáñez and Delgado-Kloos reported that AR significantly improves motivation, engagement, and academic achievement in STEM learning environments [12]. Furthermore, a meta-analysis by Garzón and Acevedo confirmed moderate-to-high effect sizes of AR applications in educational settings, particularly in geometry learning [13]. Akçayır and Akçayır emphasized that AR effectiveness depends heavily on instructional design quality, reinforcing the need for pedagogically grounded integration rather than technological novelty [14].

Parallel to technological innovation, ethnomathematics has gained recognition in global mathematics education discourse as a culturally responsive framework. D'Ambrosio conceptualized mathematics as a socio-cultural construct embedded in community practices, challenging the perception of mathematics as a culturally neutral discipline. Rosa and Orey highlighted that ethnomathematics strengthens epistemological equity by validating local knowledge systems within formal mathematics instruction [15]. Powell further argued that culturally grounded mathematics fosters identity development and meaningful engagement, particularly among marginalized learners [16]. Additionally, Nasir et al. demonstrated that integrating cultural practices into mathematics classrooms bridges the boundary between community knowledge and formal domain knowledge, thereby enhancing student engagement and participation [17]. However, despite its theoretical richness, ethnomathematics research often remains exploratory and lacks integration with immersive digital technologies.

Effectively integrating technology and cultural elements into instructional practice requires a comprehensive pedagogical framework. The Technological Pedagogical Content Knowledge (TPACK) framework, proposed by Mishra and Koehler, defines teacher knowledge as the intersection of content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK) [18]. Further research has shown that the development of teachers' TPACK plays a crucial role in determining the success of technology integration in mathematics classrooms [19]. Voogt et al. emphasized that professional development grounded in TPACK improves instructional coherence and digital readiness [20]. Harris and Hofer further proposed activity-type taxonomies to operationalize TPACK in instructional planning, ensuring that technology selection aligns with pedagogical objectives [21]. Nevertheless, limited research has explored the convergence of immersive AR technology with culturally contextualized content under the TPACK framework, particularly in mathematics teacher education contexts.

Based on international scholarship, three significant gaps emerge: (1) AR research emphasizes visualization and engagement without embedding local cultural knowledge; (2) ethnomathematics research remains largely descriptive without digital innovation; and (3) TPACK studies rarely examine immersive and culture-based technological integration simultaneously. Therefore, integrating AR technology with Baduy ethnomathematics within the TPACK framework constitutes a theoretically grounded and innovative contribution to mathematics teacher education, aligning technological advancement with culturally responsive pedagogy.

III. MATERIALS AND METHODS

This study uses a research and development (R&D) approach that aims to produce Augmented Reality (AR)-based mathematics learning media integrated with Baduy Ethnomathematics within the Technological Pedagogical Content Knowledge (TPACK) framework. The R&D method was chosen based on the research objectives, which were not only oriented towards testing theories but also towards developing products that are feasible, valid, and effective for use in learning. In the development process, this study used the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation [22] (Branch, 2009).

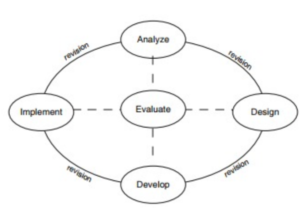

Figure 1. Model ADDIE

Tabel 1. Research stages, instruments, and data analysis based on ADDIE model

Stage	Main Activities	Instruments	Data Analysis
Analysis	Curriculum analysis. Student characteristics analysis. Identification of learning problems. Analysis of ethnomathematics (Baduy culture). Technology needs analysis (AR media).	Curriculum documents. Interviews. Observations. Literature review.	Qualitative descriptive analysis (needs analysis, contextual learning needs, technology readiness).
Design	Designing learning objectives. Designing AR-based learning media. Developing storyboards and UI/UX design. Integrating TPACK framework. Preparing assessment instruments.	Design documents. Storyboards. Lesson plans (RPP). Validation sheets.	Descriptive analysis of design feasibility and alignment with TPACK.
Development	Developing AR media. Creating AR marker cards. Integrating ethnomathematics content. Expert validation (media and material). Revision based on feedback.	Expert validation sheets. Media testing instruments. Documentation.	Qualitative and quantitative descriptive analysis (validity using Aiken's V).
Implementation	Trial of AR media in classroom (SMP IX). Small group and large group trials. Learning activities using AR.	Observation sheets. Student questionnaires. Pretest-posttest instruments.	Descriptive analysis (student responses, practicality). Statistical analysis (pretest-posttest results).
Evaluation	Evaluating	Test results.	Effectiveness

	learning outcomes. Measuring effectiveness of AR media. Analyzing improvement in students' understanding. Final revision of media.	Questionnaires. Observation sheets.	analysis (N-Gain). Inferential statistics (paired sample t-test). Descriptive analysis of learning outcomes.

As summarized in Table 1, each stage of the ADDIE model—consisting of analysis, design, development, implementation, and evaluation—involves specific activities, instruments, and data analysis techniques. Each stage is systematically designed to ensure that the developed Augmented Reality (AR)-based learning media meets the criteria of validity, practicality, and effectiveness.

To provide greater transparency regarding the instruments used, Table 2 presents the development and validation procedures, including expert validation sheets, teacher and student response questionnaires, as well as pretest–posttest instruments used to measure students' improvement in understanding ethnomathematics-based solid geometry concepts.

Table 2. Development and Validation Procedures of Research Instruments

Instrument	**Purpose**	**Assessed Aspects**	**Development Procedure**
Expert Validation Sheet	To assess the feasibility of AR media and learning materials	Content validity, language, media design, alignment with TPACK, and ethnomathematics integration	Developing indicators → constructing the instrument → validation by material and media experts → revision
Teacher Questionnaire	To determine the practicality and usability of the media	Ease of use, suitability for teaching, usefulness of the media	Developing blueprint → constructing questionnaire → limited trial → revision
Student Questionnaire	To identify students' responses to the AR media	Interest, ease of use, understanding of material, interactivity	Developing indicators → constructing questionnaire → trial → revision
Pretest–Posttest	To measure improvement in students' understanding of solid geometry concepts	Conceptual understanding, mathematical reasoning, problem-solving skills	Developing test blueprint → constructing items → expert validation → trial → revision
Observation Sheet	To observe the implementation of AR-based learning	Student activities, engagement, interaction with media	Developing observation format → trial → revision

IV. Result and Discussion

4.1. Result

4.1.1 Analysis

The analysis stage is the initial phase in the ADDIE model, which aims to identify the needs for developing an Augmented Reality (AR)-based learning media integrated with ethnomathematics. This stage involves a comprehensive analysis covering curriculum analysis, student characteristics, learning problems, the potential of local culture (Baduy ethnomathematics), and technology needs relevant to mathematics learning.

The curriculum analysis was conducted through a review of the Merdeka Curriculum documents to identify learning outcomes, learning objectives, and relevant topics suitable for AR-based media development. The results indicate that geometry, particularly solid geometry, involves a high level of abstraction, requiring learning media that can visualize concepts concretely. Furthermore, the curriculum emphasizes contextual learning, where mathematical concepts should be connected to real-life situations.

The analysis of student characteristics was carried out through observations and interviews to explore students' prior knowledge, learning styles, and learning needs. The findings reveal that students tend to understand concepts more effectively through visualization and interactive learning experiences. However, the current learning process is still dominated by conventional teaching methods, which are less engaging and have not optimally facilitated student participation.

The analysis of learning problems shows that students experience difficulties in understanding abstract mathematical concepts, especially in solid geometry. In addition, the use of technology in learning is still limited and not optimally integrated. Therefore, there is a need for innovative learning media that combines technology with a contextual approach to enhance students' understanding.

The ethnomathematics analysis was conducted by identifying elements of Baduy culture that are relevant to geometric concepts, such as traditional objects including leuit, lesung, nyiru, and aseupan. These cultural artifacts represent forms of three-dimensional shapes that can be used as meaningful contexts in mathematics learning. The integration of ethnomathematics is expected to make learning more relevant and meaningful for students.

Furthermore, the technology needs analysis was conducted to determine appropriate media to support the learning process. The results indicate that Augmented Reality (AR) technology has strong potential to provide interactive visualization of mathematical objects. AR enables students to observe three-dimensional objects in real-time, thereby enhancing conceptual understanding more effectively.

Overall, the data obtained in this stage were analyzed using qualitative descriptive analysis. This approach aims to describe learning needs, technology readiness, and the relevance of integrating ethnomathematics into mathematics learning. The findings from this analysis stage serve as the foundation for designing and developing AR-based ethnomathematics learning media that are aligned with students' needs and curriculum demands.

4.1.2 Design

The design stage focuses on planning and structuring the development of Augmented Reality (AR)-based learning media integrated with ethnomathematics and aligned with the TPACK framework. This stage involves designing learning objectives, media features, instructional strategies, and assessment instruments to ensure that the developed product meets pedagogical, technological, and content requirements.

The first step in this stage is designing the learning objectives based on the Merdeka Curriculum. The objectives are formulated to ensure that students are able to understand and apply concepts of solid geometry through contextual and meaningful learning experiences. These objectives also emphasize the development of higher-order thinking skills, particularly reasoning and problem-solving abilities.

Next, the design of AR-based learning media is carried out by determining the structure, features, and content of the application. The media is designed to include interactive elements such as 3D object visualization, AR scanning using markers (AR cards), and contextual explanations based on Baduy culture. This design aims to provide an engaging and immersive learning experience that connects abstract mathematical concepts with real-world cultural contexts.

The development of storyboards and UI/UX design is also an essential component of this stage. Storyboards are created to illustrate the flow of the application, including navigation between menus such as the main page, instructions, materials, and AR camera features. Meanwhile, the UI/UX design focuses on creating a user-friendly, intuitive, and visually appealing interface to enhance user interaction and learning engagement.

Furthermore, the integration of the TPACK framework is systematically embedded in the design process. The content knowledge (CK) is represented through solid geometry materials, pedagogical knowledge (PK) is reflected in the use of contextual and interactive learning approaches, and technological knowledge (TK) is incorporated through the use of AR technology. The intersection of these components ensures that the learning media supports effective and meaningful teaching and learning processes.

In addition, assessment instruments are prepared to measure the effectiveness of the developed media. These instruments include validation sheets for experts, questionnaires for teachers and students, and pretest–posttest items to assess students' conceptual understanding. The preparation of these instruments is aligned with the learning objectives and research goals.

All design outputs, including design documents, storyboards, lesson plans (RPP), and validation sheets, are then analyzed using descriptive analysis to evaluate their feasibility and alignment with the TPACK framework. This analysis ensures that the designed media is appropriate, systematic, and ready to be developed in the next stage.

4.1.3 Development

The development stage focuses on producing and refining the Augmented Reality (AR)-based learning media integrated with ethnomathematics. At this stage, the initial design is transformed into a functional product through a systematic development process, followed by expert validation and revisions to ensure the quality of the media.

The first step involves developing the AR learning media, including the creation of three-dimensional (3D) objects representing solid geometry concepts such as cubes, prisms, and pyramids. These objects are designed to be interactive and accessible through AR technology, allowing users to visualize mathematical concepts more concretely. In addition, AR marker cards are created as triggers for displaying the 3D objects when scanned using the application.

Furthermore, ethnomathematics content is integrated into the media by incorporating elements of Baduy culture, such as traditional objects like *leuit*, *lesung*, *nyiru*, and *aseupan*. These cultural elements are used to contextualize mathematical concepts, making learning more meaningful and relevant to students' real-life experiences.

After the media is developed, expert validation is conducted to assess its quality in terms of content and media aspects. The validation process involves material experts and media experts who evaluate the appropriateness, accuracy, design, and usability of the product using validation sheets. The results of this validation provide important feedback for improving the media.

Based on the feedback obtained from the experts, revisions are carried out to enhance the quality of the AR learning media. These revisions may include improvements in visual design, clarity of content, navigation features, and the accuracy of mathematical representations.

The instruments used in this stage include expert validation sheets, media testing instruments, and documentation of the development process. The collected data are analyzed using both qualitative and quantitative descriptive analysis. Qualitative analysis is used to interpret suggestions and feedback from experts, while quantitative analysis is conducted to measure the validity of the media using Aiken's V formula.

Overall, this stage ensures that the developed AR-based ethnomathematics learning media meets the criteria of validity and is suitable for implementation in the next stage.

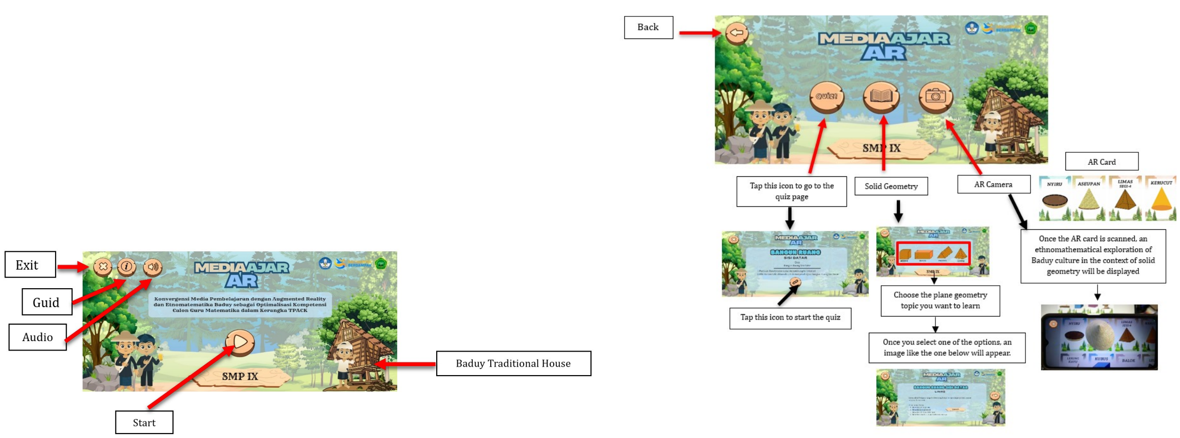

Figure 2. User Interface of the AR Application

4.1.4 Implementation

The implementation stage involves applying the developed Augmented Reality (AR)-based learning media in a real learning environment. This stage aims to examine the practicality and effectiveness of the media when used by students and prospective mathematics teachers in the learning process.

The implementation is carried out in a classroom setting where students interact directly with the AR application. They use AR marker cards to scan and explore three-dimensional (3D) objects representing solid geometry concepts integrated with ethnomathematics, particularly Baduy cultural elements. The learning process is designed to be interactive, allowing students to observe, explore, and discuss mathematical concepts in a contextualized manner.

During this stage, the teacher acts as a facilitator who guides students in using the AR application and encourages active participation. Students are engaged in various learning activities, including exploring AR visualizations, discussing concepts in groups, and solving contextual problems related to everyday life and cultural contexts.

To evaluate the practicality of the media, questionnaires are distributed to both teachers and students. These questionnaires aim to gather responses regarding the usability, attractiveness, and effectiveness of the AR-based learning media. In addition, observations are conducted to monitor student engagement and interaction during the learning process.

The data collected in this stage are analyzed using descriptive analysis to determine the level of practicality and user acceptance. The results of the implementation stage provide insights into how well the media functions in real classroom situations and whether it supports meaningful learning experiences.

4.1.5 Evaluation

The evaluation stage aims to assess the effectiveness of the developed AR-based learning media in improving students' understanding of mathematical concepts and enhancing TPACK competencies. This stage involves both formative and summative evaluation processes.

Formative evaluation is conducted throughout the development and implementation stages, including expert validation and revisions based on feedback. This ensures that the media is continuously improved before being fully implemented.

Summative evaluation is carried out after the implementation stage by analyzing students' learning outcomes using pretest and posttest instruments. These tests are designed to measure students' conceptual understanding of solid geometry before and after using the AR-based learning media. The improvement in learning outcomes is analyzed using gain scores (N-Gain) to determine the effectiveness of the media.

In addition to cognitive outcomes, the evaluation also considers students' engagement and responses, as well as the extent to which the media supports the integration of technology, pedagogy, and content knowledge (TPACK). The results indicate whether the developed media successfully facilitates meaningful and technology-enhanced learning.

The data obtained in this stage are analyzed using quantitative descriptive analysis for test results and qualitative descriptive analysis for questionnaire responses and observations. The findings of the evaluation stage determine whether the AR-based ethnomathematics learning media meets the criteria of effectiveness and can be recommended for broader implementation.

4.2. Discussion

4.2.1 Effectiveness and Practicality Results

The effectiveness of the Augmented Reality (AR)-based ethnomathematics learning media was measured through the comparison of pretest and posttest scores. The data were analyzed using the normalized gain (N-Gain) formula to determine the improvement in students' conceptual understanding.

The results indicate a significant improvement between pretest and posttest scores. The average pretest score was 56.20, while the average posttest score increased to 82.45. The calculated N-Gain value was 0.60, which falls into the moderate category. This finding shows that the developed learning media is effective in improving students' understanding of solid geometry concepts. The summary of the N-Gain results is presented in Table 3

Table 3. N-Gain Results

Statistics	**Pretest**	**Posttest**	**N-Gain**
N	30	30	30
Mean	56.20	82.45	0.60
Std. Deviation	8.45	7.30	0.12

Minimum	40.00	70.00	0.35
Maximum	70.00	95.00	0.80

In addition, the usability of the learning media was evaluated through questionnaires given to students and teachers after the media had been implemented. The questionnaire covered aspects such as ease of use, attractiveness, clarity of content, and usefulness in learning.

The results indicate that students provided an average response of 87%, while teachers gave 90%, both falling into the very practical category. These findings suggest that the developed AR-based learning media is user-friendly, engaging, and supports the learning process effectively. The detailed questionnaire results are presented in Table 4.

Table 4. Questionnaire Results

Respondents	**N**	**Mean (%)**	**Category**
Students	30	87.00	Very Practical
Teachers	2	90.00	Very Practical

4.2.2 Relationship with TPACK

The results of this study indicate that the developed AR-based ethnomathematics learning media effectively facilitates the integration of Technological Pedagogical Content Knowledge (TPACK).

From the Technological Knowledge (TK) perspective, the use of AR technology enables interactive visualization of three-dimensional objects, enhancing students' engagement and understanding. From the Pedagogical Knowledge (PK) aspect, the learning process applies a contextual and student-centered approach through ethnomathematics, encouraging active participation and meaningful learning. Meanwhile, from the Content Knowledge (CK) perspective, solid geometry concepts are presented systematically and connected to real-life cultural contexts, making them easier to understand.

The integration of these three components forms a comprehensive TPACK framework. This is supported by the N-Gain results, which indicate improved conceptual understanding, and the questionnaire results, which reflect high practicality. Therefore, the developed AR-based ethnomathematics learning media is not only effective and practical but also contributes to enhancing prospective mathematics teachers' TPACK competencies.

V. CONCLUSION

Based on the results of the research and development conducted, it can be concluded that the Augmented Reality (AR)-based ethnomathematics learning media for solid geometry developed using the ADDIE model is valid, practical, and effective for mathematics learning.

The expert validation results indicate that the developed learning media fulfills the feasibility criteria in terms of both content and media quality. In addition, the practicality assessment demonstrates that the media received highly positive responses from students and teachers, categorized as very practical, suggesting it is user-friendly and engaging in the learning process. Regarding effectiveness, the N-Gain analysis reveals a moderate improvement in students' conceptual understanding, which is further supported by the Paired Sample t-test results showing a significant difference between pretest and posttest scores (Sig. < 0.05). These findings confirm that the developed learning media significantly enhances students' learning outcomes. Furthermore, the integration of ethnomathematics provides more contextual and meaningful mathematical concepts, while AR technology improves the visualization of abstract concepts into more concrete forms. Overall, this development contributes to strengthening prospective mathematics teachers' Technological Pedagogical Content Knowledge (TPACK), particularly in effectively combining technology, pedagogy, and content in the learning process.

CONFLICT OF INTEREST

The authors hereby declare that there are no conflicts of interest associated with this study.

AUTHOR CONTRIBUTIONS

Each author played a distinct role in this study. Nenden Suciyati Sartika designed the research framework, oversaw the overall execution of the study, supervised data collection, and drafted the initial manuscript as the corresponding author. She also ensured the incorporation of relevant theoretical perspectives and maintained methodological rigor throughout the study. Agung Sugiarto and Abdul Fatah contributed to designing the research approach, developing research instruments, and supporting the fieldwork implementation. Aan Subhan Pamungkas and Dayat Hidayat strengthened the theoretical foundation, conducted conceptual analyses, and refined the discussion section to deepen the scholarly quality of the manuscript. Peni Permatasari handled technical coordination, managed data collection and processing, and drafted the results section. Rizki Amsyarul Firdaus performed the statistical analyses, assisted in interpreting the findings, and prepared the tables and visualizations included in the manuscript. All authors have reviewed and approved the final version of the manuscript.

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