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Research article

AI-assisted adaptive geometry e-Learning: Integrating ethno-realistic mathematics education to boost students' numeracy abilities

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Abstract: Culturally responsive approaches are increasingly recognized as vital, yet few researchers have explored how ethnomathematics can be effectively integrated with digital and AI-assisted learning to strengthen numeracy abilities. In this study, we investigated the integration of Ethno-Realistic Mathematics Education (Ethno-RME) with adaptive geometry e-learning and Artificial Intelligence (AI) to enhance students' numeracy abilities. Using a design research approach, the study involved 115 secondary students across four schools, embedding the Balinese cultural artifact *Sanggah Cucuk* into a Hypothetical Learning Trajectory (HLT). Data were collected through pre- and post-tests, student worksheets, AI-prompting tasks, and interviews. The results showed a marked improvement, with students achieving above the 80% threshold increasing from 51% (pre-test) to 91.3% (post-test). Qualitative findings revealed that AI-supported tasks promoted iterative reasoning, evaluation, and problem-solving, while cultural contexts enhanced engagement and identity-affirming learning. The study demonstrates the novelty of combining ethnomathematics, realistic problem-solving, and AI tools to bridge cultural practices with abstract mathematics.

Keywords: adaptive geometry e-learning, artificial intelligence (ai), design research, ethno-rme, numeracy abilities

1. Introduction

Globally, strengthening numeracy skills has become a central priority in 21st-century education systems, as mathematical literacy is increasingly linked to economic participation, technological competence, and informed citizenship. Despite substantial curriculum reforms and digital integration efforts, many countries continue to report persistent challenges in students' mathematical reasoning and problem-solving abilities [1]. Within this global context, Indonesian students present a serious challenge to educational quality. According to the 2022 PISA results, Indonesian students scored only 366 in mathematics, a decline of 13 points from the 2018 average of 379 [1,2]. A key difficulty lies in students' struggles with numeracy concepts, particularly geometry, which has numerous applications in real-world contexts [3,4]. Many learners fail to master geometric concepts because teaching methods are often disconnected from their lived experiences. This underscores the urgency of adopting more contextual, interactive, and culturally responsive teaching strategies to enhance students' participation and mathematical understanding [5].

Ethno-Realistic Mathematics Education (Ethno-RME) offers a promising approach by embedding local cultural elements and students' daily experiences within a realistic mathematics education framework [6]. By connecting numeracy content with cultural practices, students can recognize mathematical patterns in everyday life and gain a deeper appreciation of numerical concepts. Alongside cultural integration, advances in digital technology highlight the importance of combining technology-driven solutions with culturally relevant learning, making mathematics education more effective and engaging [7]. Adaptive e-learning systems represent one such innovation, as they personalize instruction by adjusting content and methods in real time according to students' levels of understanding [8]. Compared to conventional teaching approaches, adaptive e-learning provides flexibility, responsiveness, and more meaningful interaction.

Integrating Ethno-RME into adaptive e-learning creates opportunities for personalized, culturally grounded, and engaging learning experiences [9]. Artificial intelligence (AI), as part of modern digitalization, can further optimize efficiency by supporting guided problem-solving and delivering tailored content [10]. Combining AI-driven adaptive e-learning with cultural contexts not only enhances students' engagement but also deepens their numeracy understanding through interactive exploration. This study emphasizes the importance of advancing students' numeracy skills through innovative methods that merge culture and technology. We propose the design of an AI-supported adaptive geometry e-learning model based on Ethno-RME, addressing the limitations of previous studies that relied primarily on static modules and lacked full utilization of digital technologies [11]. These limitations have constrained personalization and limited student engagement, which we seek to overcome by providing adaptive, real-time feedback, and dynamic cultural content to enrich the learning process.

Research has demonstrated the richness of geometric concepts embedded in Indonesian culture, particularly in Bali and Nusa Tenggara, reflecting the nation's cultural diversity [12]. A descriptive analysis in 2021 highlighted the potential of integrating ethnomathematics into the mathematics curriculum [13]. A study conducted in 2022 revealed that students raised in the digital era showed strong interest in culturally rooted mathematics learning, especially with references to Balinese traditions [14]. More recent cross-cultural research in 2023 involving Indonesian and Thai participants reaffirmed the benefits of ethnomathematics for fostering mathematical understanding and engagement while emphasizing the role of technology in culturally based instruction [15].

Furthermore, integrating technology and culture through Ethno-RME-based e-modules significantly improved students' numeracy skills, though it also highlighted the need for broader cultural integration and more comprehensive use of digital tools. Building on these findings, we seek to advance prior work by moving beyond the limited use of static e-modules and toward the development of a fully adaptive e-learning design that is supported by AI and rooted in Ethno-RME principles.

Although researchers have explored ethnomathematics in classroom settings [12,13] and adaptive e-learning separately [10,16], these strands have largely developed in parallel. Studies integrating culture with digital tools often rely on static e-modules without adaptive feedback mechanisms [11], while AI-based learning systems rarely embed culturally grounded mathematical contexts. Consequently, a comprehensive integration of Ethno-RME with AI-driven adaptive environments remains underexplored. This research addresses that gap by offering a model that can personalize learning pathways, provide real-time feedback, and present cultural content in an engaging and contextually relevant manner. The novelty of this study lies in its dual contribution: First, we expand the application of Ethno-RME by embedding cultural elements from the eastern regions of Indonesia, such as Bali and Nusa Tenggara, thereby enriching the cultural diversity represented in mathematics education; and second, it leverages AI to maximize the adaptability, interactivity, and effectiveness of digital learning. By combining cultural depth with technological sophistication, we aim to produce an innovative framework for mathematics learning that is not only effective in improving numeracy but also inclusive and responsive to students' cultural and digital realities. We aspire to contribute to the creation of a more holistic and future-ready mathematics education system in Indonesia and beyond.

2. Literature review

2.1. Ethnomathematics

Ethnomathematics examines the relationship between mathematics and culture, highlighting how mathematical concepts are embedded in cultural traditions, artifacts, and practices. D'Ambrosio [17], who first articulated ethnomathematics as the study of mathematical practices embedded in cultural systems, argued that mathematics must be understood as a human activity shaped by social and historical contexts. By situating mathematical concepts within cultural contexts, ethnomathematics not only bridges abstract knowledge with real-life applications but also cultivates students' appreciation for their cultural heritage. This culturally grounded perspective provides opportunities to contextualize learning in ways that resonate with students' lived experiences and identities.

A growing body of research demonstrates the potential of ethnomathematics to connect formal mathematics with students' everyday practices. For example, incorporating cultural artifacts such as batik motifs, woven textiles, and traditional architectural designs into classroom instruction has been shown to improve engagement and conceptual understanding. Prahmana & D'Ambrosio [12] illustrated how the study of symmetrical patterns in Yogyakarta batik designs can enrich students' grasp of geometric concepts, while Suherman and Vidákovich [18] emphasized that Lampung's traditional Tapis fabric not only promotes Indonesian cultural wisdom globally but also serves as a contextual medium for mathematics education in diverse school settings. Despite these promising findings, the use of ethnomathematics in formal classrooms remains limited due to challenges such as teachers' lack of expertise in embedding cultural contexts, the scarcity of culturally based teaching resources, and the minimal integration of digital tools to support its application. Addressing these issues, we seek to design and implement digital instructional materials that incorporate ethnomathematics, making its application more practical, scalable, and accessible across educational contexts.

2.2. Realistic mathematics education (RME)

Realistic Mathematics Education (RME) is a pedagogical approach that emphasizes the use of real-world situations as the foundation for teaching mathematical concepts. Originating in the Netherlands, this method has been shown to significantly strengthen students' mathematical reasoning and problem-solving abilities by encouraging them to actively construct knowledge through guided exploration in meaningful contexts [19]. Hans Freudenthal [20] emphasized that mathematics should be experienced as a human activity grounded in reality rather than transmitted as finished knowledge. Rather than focusing solely on abstract procedures, RME situates learning in realistic experiences, enabling students to develop deeper conceptual understanding while applying mathematics to practical scenarios.

Extensive research has confirmed the effectiveness of RME in enhancing student learning outcomes. In Indonesia, Prahmana [6] found that RME-based geometry instruction improved students' skills in analyzing and solving problems tied to authentic contexts, such as determining the dimensions of traditional houses or examining the shapes and areas of rice fields. Similarly, Altıner et al. [21] demonstrated that the approach increased engagement and conceptual comprehension by linking abstract mathematical ideas with everyday life experiences. Despite these benefits, challenges remain in its classroom application, particularly the lack of teacher preparation and limited instructional resources in developing countries. Furthermore, although RME has shown strong potential, its integration with ethnomathematics and digital technologies has not been fully explored. To address this gap, we propose the development of digital instructional designs that merge RME with ethnomathematics, offering a scalable and culturally responsive solution for advancing geometry education in resource-constrained environments.

2.3. Adaptive e-learning & AI

Adaptive e-learning has emerged as a significant innovation in digital education, offering personalized learning experiences tailored to individual students' needs. Unlike traditional learning systems, adaptive e-learning utilizes algorithms to adjust the pace, difficulty, and type of instructional content based on learners' performance and engagement in real time [16]. Studies highlight that this adaptability enhances students' motivation, improves retention, and promotes deeper understanding of mathematical concepts compared to static instructional designs. Moreover, adaptive e-learning supports differentiated instruction, enabling students with varying levels of ability to progress along customized learning trajectories [22]. This flexibility is especially valuable in mathematics education, where students often struggle with abstract concepts, as adaptive platforms can scaffold understanding and present content in more accessible and contextualized ways.

AI has become an essential driver of adaptive e-learning, strengthening its ability to deliver responsive and interactive learning environments. AI technologies such as machine learning, intelligent tutoring systems, and natural language processing facilitate real-time analysis of student performance and provide immediate, personalized feedback [23]. Research shows that AI-assisted adaptive systems not only increase efficiency in content delivery but also improve learner engagement by simulating one-on-one tutoring experiences [24]. In mathematics learning, AI-supported adaptive systems have been shown to help students identify misconceptions, receive guided problem-solving support, and develop higher-order thinking skills through interactive exploration. Thus, the integration of AI into adaptive e-learning represents a transformative shift from static digital learning tools to intelligent, student-centered platforms capable of fostering conceptual understanding and active participation.

Despite its transformative potential, AI integration in education presents several risks. Generative systems may produce mathematically inaccurate outputs or "hallucinations," which require careful human oversight [25]. Additionally, algorithmic bias may inadvertently privilege dominant cultural representations, potentially distorting nuanced local artifacts. Maintaining cultural authenticity within automated systems therefore requires critical teacher mediation and iterative validation. A balanced understanding of AI's affordances and limitations is essential for responsible implementation.

3. Method

3.1. Research design

By addressing the identified gaps in the literature, namely the limited integration of Ethno-RME, literacy, and numeracy within adaptive e-learning systems supported by AI, weaim to design a comprehensive Local Instructional Theory (LIT) that combines cultural relevance with technological innovation [26]. The LIT emphasizes the use of culturally grounded contexts alongside adaptive digital tools to improve student engagement, personalize learning experiences, and strengthen numeracy skills across learners. In doing so, we not only respond to the need for more inclusive and contextually meaningful mathematics education but also advance the discourse on how AI-driven adaptive e-learning can be effectively combined with culturally responsive pedagogy. The findings are expected to contribute significantly to the broader field of mathematics education by offering an innovative approach that bridges traditional cultural practices with modern technological advancements, ensuring academic relevance and cultural authenticity.

3.2. Guiding principles and criteria for integration

The integration of adaptive e-learning and AI into this study was informed by three guiding principles: contextual relevance, cognitive load, and engagement through interactivity. Contextual relevance ensures that the learning design integrates Realistic Mathematics Education (RME) principles with local ethnomathematical contexts, enabling students to meaningfully connect abstract mathematical concepts to their cultural and real-world experiences [12]. Cognitive load remains central to the instructional design, as materials must be carefully sequenced and scaffolded to balance intrinsic, extraneous, and germane loads in line with Cognitive Load Theory, ensuring students can progressively build higher levels of mathematical reasoning [27]. The use of AI in adaptive e-learning strengthens this process by dynamically adjusting content difficulty and providing personalized pathways for learners, thereby optimizing cognitive efficiency. Finally, engagement and interactivity are enhanced through multimedia resources, gamified assessments, and adaptive feedback, which significantly increase student motivation and participation [28]. By aligning Ethno-RME principles with AI-driven adaptive e-learning, we ensure that the instructional design is not only pedagogically robust but also culturally meaningful and technologically innovative.

3.3. Research location, participants, and time

The study was conducted during the 2025/2026 academic year in four middle schools, comprising public and private institutions, with two schools in Bali and two in Nusa Tenggara. One class of 8th-grade students from each school participated in the research. The selection of these schools was informed by other studies that emphasized the richness of ethnomathematical exploration within Balinese and Nusa Tenggara cultural contexts. Including two schools from each region enabled for comparative analysis, thereby strengthening the validity of the findings. The participating schools were chosen based on established collaboration agreements with the research institution, which facilitated coordination and ensured the availability of necessary support such as teachers, students, classrooms, and research equipment. In total, four schools took part in the study, with 30 students from School 1, 25 from School 2, 30 from School 3, and 30 from School 4.

3.4. Data collection techniques

The primary data for this research comprised qualitative descriptive and quantitative data. Qualitative data were gathered through the design and implementation of the learning process using Focus Group Discussions (FGD), classroom observations, field notes, analysis of student worksheets, video recordings of the learning process, and interviews, with unstructured observations and open-ended interviews applied to capture richer insights [29]. The qualitative instruments, including interview guides and FGD prompts, underwent face and content validity review by two experts in mathematics education and qualitative research methodology. Feedback focused on clarity, cultural sensitivity, and alignment with research objectives. Revisions were made accordingly prior to implementation. In addition, although classroom observations were unstructured, a standardized observation protocol was used to record categories such as student engagement, AI interaction patterns, and collaborative dialogue, thereby minimizing researcher bias.

Quantitative data on students' numeracy skills were collected using pre-test and post-test assessments, administered in the form of essay-based questions. The mathematical content selected for this study was plane geometry, as it plays a crucial role in the middle school curriculum by providing the foundation for more advanced geometric concepts. Moreover, plane geometry was well-suited for the integration of cultural contexts through Ethno-RME and could be effectively supported by adaptive E-Learning and AI-enhanced interactive modules, enabling students to visualize and explore concepts in dynamic and engaging ways. This integration ensured the content remained culturally meaningful while leveraging digital innovations to foster deeper understanding and numeracy development.

All qualitative data sources were analyzed using a triangulation approach to ensure consistency and validity of findings across data types. Each data source contributed to understanding students' engagement, reasoning processes, and interactions with AI-supported tasks.

3.5. Validation of HLT

The Hypothetical Learning Trajectory (HLT) was validated by two experts: One in mathematics education content and the other in digital learning design. A validation tool was applied with criteria including content accuracy, cultural relevance, alignment with Ethno-RME principles, and the effectiveness of adaptive e-learning and AI integration. The mathematics education expert recommended embedding more culturally meaningful and interactive tasks to strengthen alignment with ethnomathematical principles, while the digital learning expert suggested leveraging AI to transform the actual practice of creating Sanggah Cucuk. Instead of manually constructing the artifact, students were encouraged to use AI prompts to generate Sanggah Cucuk designs by analyzing their mathematical and cultural characteristics, thereby fostering critical thinking and creative reasoning. In addition, the expert advised incorporating AI-driven visualization to enhance exploration of geometric concepts and replacing static materials with adaptive, interactive modules. Based on these suggestions, the HLT was revised to integrate AI-based cultural simulations and interactive assessments, ensuring a more dynamic, engaging, and contextually meaningful learning experience. These revisions were then revalidated by the experts to confirm their effectiveness in supporting our objectives.

3.6. Research procedure

This research was conducted in three major stages: preliminary design, design experiment, and retrospective analysis over four months, with the aim of producing a Hypothetical Learning Trajectory (HLT) in the early stage and a Local Instructional Theory (LIT) in the final stage. Prior to this study, several preliminary investigations on Ethno-RME, adaptive e-learning, and AI-based tools were carried out. The activities in each stage are summarized in Table 1.

Table 1. Research stages.

No	Stage	Activities
1	Preliminary design	This stage focused on identifying challenges in mathematics education, particularly in geometry and numeracy. Activities included observing classroom practices, interviewing teachers, analyzing curriculum demands, and reviewing prior studies. Based on this, the initial HLT and learning tools such as AI-assisted adaptive e-learning using Google Site and ChatGPT, digital media, and evaluation instruments were developed. Instrument validation used the content validity index, validity scale, and reliability testing. A pre-test was also conducted to measure students' initial numeracy levels.
2	Design experiment	The HLT was implemented in four schools (25–35 students per class), two in Bali and two in Nusa Tenggara. Implementation involved observations, field notes, AI-assisted documentation of the learning process, and multi-modal data collection. Cross-school comparisons were carried out to generate more valid and comprehensive findings.
3	Retrospective analysis	Data from the design experiment were analyzed qualitatively using constant comparison steps: (1) reviewing lesson recordings, (2) creating general transcripts, (3) coding critical segments, (4) elaborating these segments, (5) confirming or

	challenging findings with other data, and (6) validating interpretations through peer discussion. Quantitative data from pre- and post-tests were analyzed using mean difference tests to evaluate improvements in numeracy skills. Video recordings and FGD transcripts were transcribed verbatim and analyzed using open coding, followed by axial categorization to identify themes related to geometric reasoning, AI interaction strategies, and cultural contextualization. Codes were cross-validated through peer debriefing to enhance reliability.

The retrospective analysis presented in Table 1 provided insights into students' learning progression, supported by their scores, worksheets, and reflections. These findings were used to refine the HLT and contribute to the development of a scalable LIT that integrates Ethno-RME, adaptive e-learning, and AI.

3.7. Pre-test and post-test content

The pre-test and post-test instruments targeted plane geometry, covering concepts such as properties of shapes, perimeter, area, and geometric reasoning in real-world settings. Ethnomathematical and cultural elements were embedded in some items. The comparison of results against the minimum mastery criteria served as the basis for measuring the effectiveness of the intervention.

4. Results and discussion

4.1. Results

4.1.1. Preliminary design

In the preliminary phase of the study on "Designing Adaptive E-Learning Geometry with Ethno-Realistic Mathematics Education and AI Support: A Research-Based Approach to Enhancing Numeracy Skills", several essential activities were undertaken, including an in-depth literature review, interviews with mathematics teachers, and the initial development of the Hypothetical Learning Trajectory (HLT) under supervisor guidance. The literature review concentrated on the integration of cultural contexts, realistic problem-solving approaches, and the application of adaptive e-learning and AI to strengthen geometry learning. Interviews with three mathematics teachers highlighted that students often relied heavily on memorization and procedural problem-solving, with limited conceptual understanding, particularly when tasks involved irregular or culturally rooted shapes. To overcome these challenges, the HLT was designed over two months, embedding ethnomathematical contexts and supported by AI-driven interactive learning tools to encourage deeper reasoning and engagement. The HLT was subsequently validated by experts in ethnomathematics, RME, and digital learning technologies, ensuring a well-rounded framework that aligns cultural, pedagogical, and technological dimensions in geometry instruction. In the following section, we present the summary of the HLT design, including the structured learning activities and key findings across each stage.

Table 2. Hypothetical learning trajectory (HLT).

No.	Learning Objective	Main Activity	Key Outcome
1	**Knowing the Sanggah Cucuk** Students recognize the shape and function of Sanggah Cucuk.	• Watch videos and analyze images of Sanggah Cucuk. • Identify geometric shapes and materials needed.	• Identify Sanggah Cucuk as a triangular prism. • Determine the geometric components (e.g., Klakat shapes).
2	**Understanding the Design of Sanggah Cucuk** Students understand the design for Sanggah Cucuk.	• Understanding the design of Sanggah Cucuk using 3D model. • Counting the amount and length of bamboo required to make a Sanggah Cucuk.	• Answer the question with accurate quantities (e.g., 3 square Klakats, 1 triangular Klakat).
3	**Generating Sanggah Cucuk Using AI** Students construct Sanggah Cucuk.	• Construct the model image using AI (ChatGPT). • Compare with other groups and reflect on challenges.	• Able to generate the model of Sanggah Cucuk using AI prompt. • Reflect on design and material challenges.
4	**Applying Mathematical Concepts** Students calculate and compare surface area and materials.	• Calculate the surface area and total bamboo needed. • Compare with a standard triangular prism.	• Accurately calculate the surface area and material needed. • Understand the connection between math concepts and the design.

The HLT design presented in Table 2 offers a structured overview of the planned learning activities, summarizing the key observations and insights from each stage. This HLT is adapted into e-learning that can be access through this link: https://sites.google.com/mahadewa.ac.id/geometri/home?authuser=0.

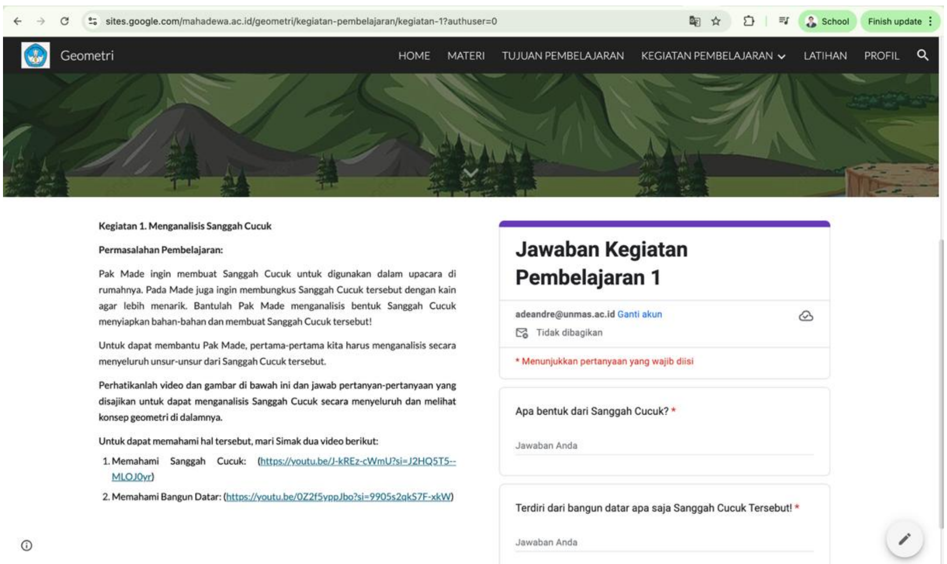

Figure 1. HLT display in e-learning form.

Figure 1 illustrates the HLT that has been adapted into an E-Learning format using Google Sites. As shown, each activity is organized into two distinct spaces: The right-hand space provides the learning materials and instructions, while the left-hand space is designated for inputting questions and answers through Google Forms. This design ensures that students can easily access guidance and content while simultaneously engaging in interactive tasks, thereby creating a structured yet flexible online learning environment.

4.1.2. Design experiment and retrospective analysis

The data collected from the four participating schools, consisting of students' worksheet responses for each activity, were systematically compiled, refined, and categorized according to the key findings of the learning activities. To encourage collaborative learning, students were organized into groups of 4–7 members in each class, enabling them to complete the worksheets through discussion and teamwork. The data were then analyzed to evaluate students' numeracy skills and their comprehension of each component of the lesson. For this analysis, we focused on identifying recurring patterns and trends in students' work, thereby assessing their progress in mastering geometric concepts and applying numeracy skills across instructional stages.

4.1.3. Integration of multiple qualitative data sources

To ensure the trustworthiness and depth of the findings, data from multiple qualitative sources, including classroom observations, field notes, Focus Group Discussions (FGDs), student worksheets, and video recordings, were systematically triangulated throughout the analysis. Classroom observations and field notes were used to capture patterns of student engagement, interaction, and responses during AI-supported learning activities. These data indicated that students were actively involved in collaborative discussions, particularly during tasks involving AI-generated outputs.

FGD data provided deeper insights into students' collective reasoning processes. Students frequently discussed the accuracy of AI-generated images and debated whether the structures appropriately represented the Sanggah Cucuk geometrically and culturally. These discussions revealed that students were not only engaging with mathematical concepts but also critically evaluating cultural representations.

Student worksheets and video recordings were analyzed to trace the development of students' geometric reasoning across learning activities. The worksheet results presented in Table 3, Table 4, Table 5, Figure 3, and Figure 4 provided concrete evidence of students' ability to identify geometric components, perform calculations, and connect cultural artifacts with mathematical concepts. Moreover, video recordings enabled detailed observation of students' iterative prompt refinement and error correction processes when interacting with AI tools.

These multiple data sources complemented the interview findings and strengthened the validity of the results through methodological triangulation.

Learning Activity 1

As shown in Table 2, the first activity required students to analyze the structure of the *Sanggah Cucuk*, a traditional Balinese shrine, through an instructional video embedded in the e-learning module. The online redesign enabled students to independently explore the material, revisit the video as needed, and refine their observations. This process guided them to recognize the geometric form of the shrine and to decompose it into its fundamental shapes. Students identified the *Sanggah Cucuk* as a triangular prism composed of three rectangular faces and one equilateral triangular face. This demonstrated not only their growing ability to connect geometry with a culturally significant object but also their improved capacity to break down complex structures into simpler components.

Table 3. Example of student's response in learning activity 1.

Question	Student Response	Interpretation of Student Thinking
What is the shape of the Sanggah Cucuk?	Triangular prism	Student accurately recognized the overall structure, showing clear spatial reasoning and ability to identify 3D forms.
Which plane figures make up the Sanggah Cucuk?	Three rectangles and one equilateral triangle	Student correctly decomposed the prism into its constituent shapes, reflecting precise geometric analysis.
What materials are needed to construct a Sanggah Cucuk?	Bamboo, *Canang*, banana leaves, and bamboo rope	Student realistically linked geometry with cultural context. While bamboo and rope are correct, the inclusion of *Canang* shows cultural reasoning shaped by ritual practices.

This example, presented in Table 3, illustrates that students could effectively analyze the *Sanggah Cucuk*'s geometry, demonstrating accurate recognition of its 3D form and its 2D components. Their responses reflect strong geometric reasoning paired with realistic thinking, as they related mathematical concepts to cultural practices they observe in daily life. The mention of *Canang*, a ritual offering not actually part of the construction, highlights how deeply cultural context influenced their reasoning. This shows that embedding cultural artifacts in mathematics not only improved comprehension of geometric concepts but also encouraged students to merge mathematical reasoning with their lived cultural experiences, resulting in more meaningful engagement and authentic learning outcomes [30].

Learning Activity 2

In the second learning activity, students were tasked with designing their version of a Sanggah Cucuk. Before this, they had watched a 3D design demonstration in the E-Module. Building on this visual guidance, students analyzed the design and then proceeded to create their sketches. The hands-on nature of this task, combined with the interactive 3D model, sparked enthusiasm among the students, as they engaged actively in manipulating the 3D design. This approach not only enabled students to exercise their creativity but also deepened their spatial reasoning and geometric understanding. The following example showcases a student's original design, reflecting their engagement with the cultural context and their grasp of geometric principles.

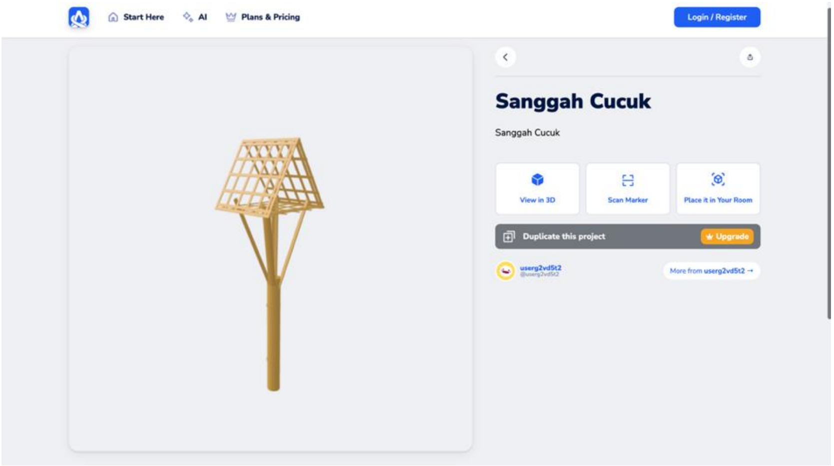

Figure 2. The 3D design of Sanggah Cucuk.

Learning Activity 2 involved students manipulating the 3D design of the *Sanggah Cucuk*, as presented in Figure 2, through the E-Learning platform. The 3D visualizations presented in Figure 2 were developed using Assemblr Studio for structural modeling. The adaptive e-learning environment was implemented via Google Sites integrated with Google Forms for response collection, while generative AI interactions were conducted using ChatGPT (OpenAI, GPT-4 architecture). Adaptivity was operationalized through differentiated task pathways and AI-guided feedback prompts rather than automated algorithmic sequencing. This activity encouraged students to carefully analyze the structure and apply their mathematical understanding to determine the number of panels (*Klakat*), the amount of bamboo required, and the measurement of each bamboo component. The results show that students were able to engage in meaningful reasoning, connecting abstract geometry with practical construction needs [31]. Their responses demonstrated the ability to decompose the design into essential components and translate these into measurable quantities. Although some of their answers were concise, they reflect strong analytical skills and a realistic approach to problem solving, as they linked the geometry of the *Sanggah Cucuk* with the materials needed in real-world practice.

Table 4. Example of students' responses in learning activity 2.

Question	**Student Response**	**Interpretation of Student Thinking**
How many *Klakat* are needed to construct a *Sanggah Cucuk*?	3 square *Klakat* and 1 triangular *Klakat*	Student shows correct decomposition of the structure into geometric panels, applying visual reasoning.
How many pieces of bamboo are required to build the *Sanggah Cucuk*?	52 bamboo sticks	Student provides a specific number, indicating careful estimation, though explanation is brief.
What is the size of each bamboo piece?	30 cm	Student demonstrates awareness of measurement, though the response could benefit from more detail.

This activity (Table 4) highlights that students demonstrated solid reasoning abilities by breaking down the 3D design into clear and realistic components. Their concise yet accurate answers show not only an understanding of geometric composition but also an attempt to connect mathematical reasoning with cultural and practical knowledge. Interestingly, the brevity of their responses may reflect a tendency to focus on the most essential aspects of construction, consistent with their everyday observations of how such cultural artifacts are built. By grounding their reasoning in lived experiences, students were able to move beyond abstract calculation and toward authentic, applied problem solving, demonstrating how cultural context can sharpen their ability to analyze, estimate, and reason mathematically.

Learning Activity 3

The third activity emerged as the most motivating stage for students, as it integrated AI into the learning process. In this activity, students were tasked with generating images of the Sanggah Cucuk using AI prompts based on their prior analyses from Activities 1 and 2. This design enabled them to apply their geometric understanding and cultural knowledge in a creative and interactive way. Students expressed high levels of enjoyment and engagement, as the task resembled both problem-solving and exploration, transforming mathematics into a playful yet rigorous process.

Students employed various strategies in constructing prompts, often starting with detailing the number and type of Klakats (components of the Sanggah Cucuk) without specifying their geometric arrangement. As a result, the AI generated images that included the correct number of Klakats but failed to assemble them into a triangular prism structure, which is essential for accurately representing the Sanggah Cucuk. Recognizing this discrepancy, students revised their prompts to explicitly instruct the AI to form the Klakats into the correct prism configuration and to include additional cultural and structural details such as bamboo material, rope binding, and proportional dimensions. This revision process highlights students' iterative critical thinking, as they evaluated the initial AI output, identified structural errors, and adapted their reasoning to guide the AI toward a culturally and geometrically accurate representation. An example of AI-generated outputs in Learning Activity 3 is shown in Figure 3.

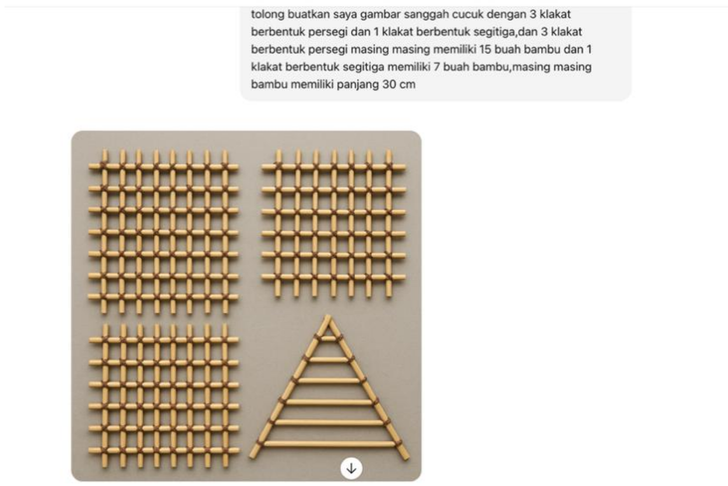

Figure 3. Initial example of a student's AI generated image.

In Figure 3, the initial AI-generated image based on a students' first prompt is shown. Although the AI included the correct number of Klakats, it did not assemble them into the triangular prism structure, reflecting that students' initial prompt lacked precise geometric instructions. This output demonstrates partial understanding, students accurately accounted for the components but had not yet fully translated their geometric and cultural analysis into the AI prompt.

Figure 4. Revision of a student's AI generated image.

Figure 4 presents a refined AI-generated image after students revised their prompt. *Explanation:* After instructing the AI to assemble the Klakats into a triangular prism and including additional details such as material and proportions, the AI produced an image closely resembling the intended Sanggah Cucuk. This demonstrates students' ability to merge geometric accuracy with cultural context, showing persistence, evaluation, and problem-solving skills.

This activity illustrates how AI integration in mathematics education can facilitate engagement and higher-order thinking skills. Students not only deepened their understanding of geometric concepts but also developed critical thinking by evaluating AI outputs, identifying errors, and reasoning through iterative corrections [32]. The integration of AI as a digital tool demonstrated significant potential for fostering effective, culturally relevant, and enjoyable learning experiences. Although common AI errors included incorrect prism assembly, misaligned triangular faces, and disproportionate scaling of bamboo components, the students corrected these errors by explicitly specifying geometric constraints such as "three rectangular lateral faces forming a triangular prism," "equilateral triangular bases," and "equal edge lengths." These revisions required precise mathematical vocabulary and demonstrated the development of structural reasoning through iterative prompt refinement.

Learning Activity 4

Learning Activity 4 challenged students to move from visual and structural analysis toward more abstract mathematical modeling of the Sanggah Cucuk. They were asked to calculate the surface area and the total length of bamboo required and to relate these results to the properties of a triangular prism. In addition, students were required to formulate equations for surface area and edge length and then apply these models to determine the total cloth needed to cover the structure. Finally, they reflected on whether such mathematical models would be useful for constructing the Sanggah Cucuk in the future.

The responses varied in completeness: Some students provided only numerical results, while others connected formulas with cultural context. The most comprehensive response integrated the calculation of surface area and edge length with correct formulas, offered a practical model linking bamboo and cloth requirements, and explained the usefulness of the mathematical model. This indicates higher-order thinking, where the student not only applied formulas but also recognized the value of mathematics in solving real-world, culturally embedded problems.

Table 5. Example of a student's response in learning activity 4.

Question	Student Response (Translated)	Interpretation of Student Thinking
What is the surface area and total length of bamboo in the Sanggah Cucuk?	"Surface area = 5,400 cm²; the total length of the triangular prism's edges is the sum of 3 base edges, 3 vertical edges, and 3 top edges."	Student demonstrates accurate use of formulas for a triangular prism, correctly identifying structural elements (base edges, vertical edges, top edges) and relating them to the shrine's construction.
How does surface area relate to the total length of edges in a triangular prism?	"The total length of edges in a triangular prism is the sum of all edges; the surface area is calculated from (2 × base area) + (base perimeter × prism height)."	Student shows strong conceptual understanding by connecting edges with surfaces, demonstrating awareness of geometric relationships.
What are the formulas for surface area and total edge length?	"Formula for surface area: (2 × base area) + (base perimeter × prism height); formula for total edge length: (3 × base side length) + (3 × prism height)."	Student provides complete and precise formulas, showing ability to generalize geometric reasoning into mathematical models.
How much total cloth would Pak Made need to wrap the Sanggah Cucuk?	"3,150 cm² of cloth is required."	Student connects geometric results with practical application, recognizing the role of mathematics in resource planning.
How does mathematical modeling relate to bamboo length and total cloth needed?	"The mathematical model for constructing a Sanggah Cucuk can be approached with simple equations that connect the length and number of bamboo sticks with the total cloth area."	Student successfully integrates cultural context with mathematical abstraction, showing the usefulness of modelling beyond calculation.
Is the model useful for constructing a Sanggah Cucuk in the future?	"Yes, because it helps us determine the triangular prism dimensions in the Sanggah Cucuk."	Student reflects on the practical significance of mathematics, reinforcing the value of applying geometric models to real-life cultural artifacts.

The selected student's response presented in Table 5 illustrates a comprehensive progression of mathematical thinking that moves from procedural accuracy to applied reasoning. By first identifying the Sanggah Cucuk as a triangular prism, the student demonstrated an ability to connect a cultural artifact with a standard geometric form, enabling the use of established formulas for calculating surface area and total edge length. This step shows not only procedural fluency in recalling and applying the formulas correctly but also the ability to decompose a complex cultural structure into essential mathematical components [33]. The student's explanation of the relationship between edges and surfaces reveals deeper conceptual reasoning, emphasizing that edges form boundaries which, in turn, create measurable surfaces. Such reasoning indicates that the student does not treat geometry as a set of disconnected formulas but as an interconnected system where each element contributes to the integrity of the whole structure.

What makes this response particularly strong is the student's integration of mathematical abstraction with practical application. Instead of stopping at theoretical calculations, the student extended the results to determine the total cloth needed to wrap the Sanggah Cucuk and formulated a simple mathematical model that links bamboo length, number of pieces, and cloth requirements. This step reflects higher-order skills in generalization, abstraction, and modeling, as the student recognized the utility of equations beyond the classroom context. Finally, by affirming the usefulness of the model for future construction, the student engaged in reflective thinking, recognizing mathematics as a valuable tool for cultural preservation and problem-solving [34]. This layered reasoning demonstrates a complete cycle of mathematical engagement; procedural fluency, conceptual understanding, applied modeling, and reflective awareness, showing how culturally contextualized learning activities can effectively foster higher-order thinking and meaningful connections between mathematics and real-world practices.

4.1.4. Students' test and interview results

4.1.4.1. Pre-test and post-test result

Before implementing the digital and AI-assisted learning design, the researcher conducted a pre-test on students' numeracy skills to determine their initial abilities. After the implementation, a post-test was administered to evaluate the effectiveness of the approach. The comparison of pre-test and post-test results is presented in Table 6.

Table 6. Comparison of a students' pre-test and post-test scores in each school.

School	**Number of Students**	**Pre-Test: % Passing (>80)**	**Pre-Test: Number Passing**	**Post-Test: % Passing (>80)**	**Post-Test: Number Passing**
School 1	30	47%	14	90%	27
School 2	25	52%	13	92%	23
School 3	30	55%	16	93%	28
School 4	30	50%	15	90%	27
Total	**115**	**51%**	**58**	**91.3%**	**105**

The pre-test results in Table 6 indicate that students' numeracy skills were limited before the introduction of full digital and AI-based learning. Only 51% of the total 115 students achieved scores above the 80 threshold. School 1 had the lowest pass rate, with just 47% (14 of 30 students) meeting the standard. School 4 showed a slightly better result at 50% passing, while School 2 performed moderately at 52%. School 3 had the best initial performance, but only 55% of students surpassed the threshold. These figures suggest that more than half of the students across all schools faced challenges in achieving satisfactory numeracy proficiency, demonstrating the need for stronger instructional approaches.

After implementing the full digital and AI-based instructional design, students' performance improved substantially across all schools. The overall pass rate rose sharply to 91.3%, with 105 of 115 students achieving scores above 80. School 3 demonstrated the highest improvement, with 93% of students passing, while Schools 1 and 4 reached 90%. School 2 also showed remarkable progress with a 92% pass rate. This consistent improvement across schools highlights the strong effectiveness of digital and AI-supported learning strategies. The results suggest that the integration of AI tools not only helped students grasp complex numeracy concepts more effectively but also motivated them to achieve higher outcomes [35]. The comparison shows that digital and AI-based learning significantly narrowed the learning gaps and enhanced overall numeracy proficiency among students.

4.1.4.2. Observation result

Classroom observations revealed that students demonstrated high levels of engagement and collaborative interaction throughout the AI-supported learning activities. During Learning Activity 3, students actively discussed the structure of the Sanggah Cucuk while evaluating AI-generated outputs. Observation notes indicated that students frequently pointed to specific geometric features, such as triangular faces and rectangular panels, and negotiated how these components should be represented in the AI prompts. Many groups revised their prompts multiple times after comparing the generated images with their conceptual understanding, suggesting that the AI environment encouraged iterative reasoning and collective problem-solving. This pattern of interaction reflects how students externalized their thinking through dialogue and used peer feedback to refine their mathematical and cultural interpretations.

Field observations also showed that students were able to connect cultural knowledge with formal geometric reasoning in meaningful ways. When analyzing the Sanggah Cucuk, students often referred to their prior experiences with cultural practices, which supported their identification of geometric structures and materials. In several instances, students debated whether certain AI-generated designs were culturally appropriate, indicating an awareness of authenticity beyond mathematical correctness. The observation data further revealed that students became more precise in using mathematical language over time, particularly when revising prompts to correct structural errors such as misaligned faces or incorrect proportions. This progression suggests that the integration of Ethno-RME and AI not only enhanced engagement but also supported the development of conceptual understanding and culturally grounded reasoning through observable learning behaviors.

4.1.4.3. Interview result

In addition to the test, the researcher conducted interviews with two representative students from each school to gain deeper insights into their experiences and perceptions of the full digital and AI-based learning model. The selection of students was based on their active participation during lessons and the diversity of their academic performance, ensuring the inclusion of high-achieving and average students. This approach provided a balanced perspective on how different types of learners perceived the effectiveness of the instructional design. The interviews aimed to explore how the integration of AI tools and digital learning environments influenced students' motivation, problem-solving strategies, and overall engagement in mathematics.

The findings from these interviews revealed that students felt highly motivated and engaged throughout the learning process. They particularly appreciated the interactive and exploratory nature of AI-supported tasks, such as generating and refining images of the Sanggah Cucuk, which encouraged them to apply mathematical reasoning and cultural understanding in a creative way. Many students reported that the digital and AI-based approach transformed mathematics from a rigid subject into an enjoyable and meaningful experience, as it enabled them to experiment, evaluate outputs critically, and make iterative improvements. Moreover, the inclusion of cultural elements within the AI activities was perceived as enriching, as students not only strengthened their numeracy and problem-solving skills but also deepened their appreciation of local traditions. This combination of digital innovation and cultural relevance made the learning activities more relatable, memorable, and impactful, aligning with findings that AI-enhanced, contextually grounded instruction can significantly boost learning outcomes and student motivation [36].

These interview findings are consistent with evidence from classroom observations, FGDs, and video recordings, which similarly indicated high levels of engagement, collaborative reasoning, and iterative problem-solving. The convergence of multiple data sources reinforces the credibility of the findings and demonstrates that students' responses were not only self-reported but also observable in their learning behaviors.

4.2. Discussion

The integration of Ethno-Realistic Mathematics Education (Ethno-RME) with a fully digital and AI-assisted learning design provides significant insights into how such approaches can enhance students' numeracy skills, engagement, and culturally grounded understanding. By embedding cultural artifacts like the Sanggah Cucuk into adaptive e-learning activities, students were able to link abstract geometric concepts to tangible cultural practices, making mathematics meaningful and motivating. Moreover, studies indicate that AI-enhanced learning environments can be deliberately designed to support culturally responsive instruction, helping learners connect local knowledge with formal mathematics when pedagogical intent and cultural content are explicitly aligned [37]. Through this integration, students not only engaged with mathematical procedures but also connected them to the cultural contexts that surrounded them, fostering a more holistic and personally relevant learning experience.

Beyond increasing engagement, the adaptive and iterative nature of AI played a cognitive scaffolding role within the Ethno-RME framework. The prompt–response cycle functioned as an externalized thinking space in which students translated concrete cultural representations into increasingly formalized geometric descriptions. When initial AI outputs failed to assemble the Sanggah Cucuk into a triangular prism, students were required to diagnose structural inconsistencies and articulate geometric constraints explicitly (e.g., specifying prism configuration, edge relationships, and proportional alignment). This process aligns with Vygotskian notions of mediated learning, where tools support the internalization of higher-order reasoning. The AI environment acted as a semiotic mediator, enabling students to iteratively refine language, structure, and mathematical abstraction. In this way, AI did not merely enhance engagement but facilitated the cognitive transition from culturally grounded representation to formal geometric modelling.

Students demonstrated significant gains in procedural fluency, such as calculating surface areas, estimating material quantities, and applying geometric formulas, as well as increased motivation when working on AI-supported, project-based tasks. However, consistent with reviews on technology use in mathematics education, students required scaffolded guidance to transition from concrete representations, such as visual models and AI-generated images, to formal algebraic and symbolic modeling [25]. Digital tools alone were insufficient for conceptual transfer without structured pedagogical support. This suggests that while AI and digital platforms serve as powerful enablers for engagement and creativity, they must be paired with instructional scaffolds that promote deeper abstraction and reasoning. Carefully designed prompts, step-by-step guidance, and reflective questioning were crucial in helping students move from observation and manipulation of cultural models to formalized mathematical reasoning.

The iterative AI-prompting activity (Activity 3) provided an authentic and motivating context for developing higher-order thinking skills. Students had to critically evaluate outputs, detect structural inconsistencies, such as Klakats not correctly assembled into a triangular prism, and refine their instructions, mirroring authentic mathematical reasoning and model refinement. Emerging literature on AI in mathematics education highlights similar affordances, showing that generative AI can facilitate critique, revision, and reflective dialogue when learners treat AI outputs as provisional models rather than definitive answers [38]. This dynamic interplay between human judgment and AI-generated responses enabled students to practice evaluation, justification, and iterative improvement; core competencies in mathematical practice. The combination of AI with culturally situated tasks also encouraged identity-affirming engagement, as learners found relevance and meaning in connecting mathematics with local cultural artifacts.

While AI enhanced iterative reasoning, occasional inaccuracies in generated images required careful student verification. This highlights the need of positioning AI as a provisional collaborator rather than an authoritative source. Cultural nuances also required explicit human clarification to ensure the faithful representation of the Sanggah Cucuk structure. Culturally embedded digital and AI-supported tasks enhanced motivation and contextualized reasoning. Learners reported that relating mathematics to familiar cultural objects made problem-solving more relevant and enjoyable. Systematic studies on culturally responsive curriculum materials and digital ethnomathematics support the claim that culturally anchored resources, such as e-worksheets, interactive modules, and AR/VR experiences, can enhance student engagement and facilitate deeper understanding, particularly when teachers explicitly guide connections between the cultural context and mathematical concepts [39]. Consequently, Ethno-RME combined with carefully designed digital and AI tools can promote mathematical learning and cultural appreciation, provided that teachers actively orchestrate cognitive and social scaffolds to help students bridge concrete cultural experiences with abstract mathematical reasoning.

This study provides several important implications for mathematics education in the context of digital and AI-assisted learning. First, it highlights the value of deliberately designing AI-supported activities as iterative model-building exercises. When students are encouraged to propose an initial hypothesis, generate an AI output, evaluate its accuracy, and refine their instructions, they engage in cycles of reasoning that mirror authentic mathematical practices [40]. This iterative approach not only fosters higher-order thinking but also positions AI as a tool for critical reflection rather than a source of final answers. Educators should structure tasks that guide students from concrete cultural representations to abstract mathematical formulations, ensuring that digital tools are paired with scaffolding that supports conceptual transfer. For example, students working with the Sanggah Cucuk could begin by identifying shapes and components in AI-generated images, then progress to calculating surface area and edge lengths, and finally express these findings in symbolic or algebraic forms. Interactive digital resources, such as e-worksheets, virtual manipulatives, or AR/VR simulations, can further reinforce this progression by enabling learners to visualize and manipulate cultural artifacts in ways that connect directly to mathematical reasoning [41]. In essence, the integration of culturally grounded digital tools can transform mathematics from an abstract subject into a meaningful, contextually relevant, and engaging learning experience.

Another key implication concerns teacher preparation and curriculum design. For AI-assisted, culturally responsive learning to be effective, teachers must be equipped to design tasks that align cultural content with mathematical objectives, scaffold reasoning, and critically evaluate AI outputs for accuracy and cultural fidelity [36]. Structured guidance should include step-by-step prompts, modeling of problem-solving strategies, and opportunities for reflection that explicitly connect students' cultural knowledge with formal mathematics. Additionally, curriculum developers should consider embedding culturally relevant digital materials throughout learning sequences, enabling students to repeatedly engage with local practices in ways that enhance numeracy and cultural understanding [42]. This dual focus, strengthening mathematical skills while affirming cultural identity, can improve motivation, deepen engagement, and foster meaningful learning outcomes. Beyond academic achievement, such approaches also cultivate digital literacy, critical thinking, and an appreciation of students' cultural heritage. By attending to these interrelated dimensions, educators and curriculum designers can leverage AI and digital tools to create a holistic learning environment that develops mathematical competence and culturally grounded, reflective learners.

While we focus primarily on student outcomes, successful scaling of AI-assisted Ethno-RME requires careful attention to instructor readiness and technological acceptance. Emerging research suggests that educators may experience anxiety, uncertainty, or cognitive overload when integrating advanced digital tools into classroom practice [43]. Instructors must not only understand mathematical content and cultural context but also critically evaluate AI-generated outputs for accuracy and cultural authenticity. Therefore, professional development programs should emphasize AI literacy, prompt design strategies, and critical oversight of generative outputs. Without structured support, the integration of AI may risk superficial adoption rather than meaningful pedagogical transformation.

5. Conclusions

Our findings of this research demonstrate the significant positive impact of integrating Ethno-Realistic Mathematics Education (Ethno-RME) with full digital and AI-assisted learning designs on enhancing students' numeracy skills, conceptual understanding, and engagement. The learning activities, which incorporated culturally relevant contexts, such as the Sanggah Cucuk, enabled students to connect abstract geometric concepts with concrete cultural practices, resulting in high levels of numeracy and spatial reasoning. Students showed strong procedural fluency, including calculating surface areas, estimating materials, and applying geometric formulas, while demonstrating creativity and critical thinking during AI-supported, project-based tasks. The iterative AI-prompting activity further strengthened higher-order thinking by requiring students to evaluate outputs, identify structural inconsistencies, and refine instructions, mirroring authentic mathematical reasoning and model refinement. Collaborative group work and culturally grounded tasks reinforced problem-solving skills, teamwork, and reflective learning, illustrating how Ethno-RME combined with digital and AI tools provides a meaningful, culturally responsive, and educationally impactful learning experience.

Despite these positive outcomes, it is important to acknowledge the limitations of this study. The research was conducted in four schools within a cultural context, which may limit the generalizability of the findings to other regions or more diverse student populations. Additionally, the culturally homogeneous sample restricted the exploration of other ethnomathematical practices beyond the Sanggah Cucuk, which may differ in structure, symbolism, or local significance. In future studies, researchers should aim to include a broader range of cultural contexts and larger sample sizes, enabling a more comprehensive understanding of how cultural perspectives can be integrated with digital and AI-assisted mathematics learning. This approach would contribute to the development of more inclusive, adaptable, and contextually responsive instructional strategies across educational settings. In addition, we employed a one-group pre-test–post-test design without a control group receiving traditional instruction. While the significant improvement suggests effectiveness, causal claims comparing this model with conventional teaching remain limited. Researchers should incorporate quasi-experimental or randomized comparative designs to strengthen causal inference.

Based on these conclusions, it is recommended that educators and curriculum developers intentionally incorporate culturally relevant content into mathematics instruction. By aligning mathematical tasks with students' cultural backgrounds and real-world experiences, teachers can create more engaging, meaningful, and relatable learning environments that support cognitive and affective development. Structured prompts, scaffolded guidance, and iterative AI-based activities, as highlighted in this study, are essential for helping students transition from concrete, visual representations to abstract, formal mathematical reasoning. Incorporating these approaches not only enhances comprehension and problem-solving abilities but also fosters a culturally responsive, student-centered mathematics education framework that integrates technology, AI, and local knowledge to enrich learning outcomes.

Author contributions

I Putu Ade Andre Payadnya: Conceptualisation, investigation, methodology, formal analysis and writing the initial draft. Kadek Rahayu Puspadewi: Methodology, formal analysis, writing original draft, writing review and editing. Luh Putu Risma Noviana: Methodology, formal analysis, writing original draft, writing review and editing.

Use of Generative-AI tools declaration

The authors declare that they used Artificial Intelligence (AI) tools (Grammarly and Consensus) to improve the language and conduct reference search.

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Conflict of interest

The authors declare there is no conflict of interest in this article.

Ethics declaration

The human-participant component of this study received ethical approval from the Cooperation Forum of the Faculty of Teacher Training and Education, Universitas Mahasaraswati Denpasar, under approval numbers K.565/J.14.01/FKIP-Unmas/VII/2025 and K.566/J.14.01/FKIP-Unmas/VII/2025. The research was carried out in line with applicable local regulations and institutional policies. All participants provided written informed consent prior to taking part in the study.

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