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Embedding Cultural Heritage in Digital Learning: A Gamified Augmented Reality Ethnomathematics Comic for Improving Primary Students' Numeracy

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ABSTRACT

Strengthening numeracy skills in elementary schools requires contextual, engaging, and culturally-rooted learning innovations. The integration of ethnomathematics and digital technology is a strategic approach to connecting mathematical concepts with students' real-life experiences. This study aims to develop gamified ethnomathematics comics and Augmented Reality (AR) as interactive digital learning media to improve the numeracy skills of elementary school students. The research used the Borg and Gall development method, which includes the stages of needs analysis, design, expert validation, limited testing, revision, and extensive testing. Needs analysis was conducted in three regions—Gresik, Sidoarjo, and Surabaya involving teachers and students from six elementary schools to identify learning media needs that are appropriate to local cultural characteristics. The results of the analysis showed the need for media that is interactive, visual, and able to link the cultural context of the region with numeracy material. Based on these findings, an ethnomathematics comic was developed that combines local cultural narratives with AR technology to display three-dimensional objects and gamification elements to increase learning motivation. Trials were conducted in three schools (SD Hang Tuah X Juanda, SDN Ketintang 4, and UPT SDN 152 Gresik) involving fifth-grade students. Data were obtained through expert validation, implementation observation, response questionnaires, and numeracy tests, which were analyzed descriptively and quantitatively.
The results showed that the media had very high validity (average >85%), high practicality, and significant effectiveness in improving students' numeracy skills. The integration of culture, AR technology, and gamification proved to be able to build learning engagement, strengthen conceptual understanding, and foster students' intrinsic motivation. These findings confirm that the development of ethnomathematics-based learning media and digital technology has the potential to be an innovative solution to strengthen 21st-century numeracy literacy in Indonesian elementary schools.

Keywords: Ethnomathematics, Digital Comics, Augmented Reality, Gamification, Numeracy, Elementary School

INTRODUCTION

Background

Numeracy is one of the fundamental 21st-century skills that plays an important role in shaping logical, analytical, and rational thinking in students (Curdt et al., 2023; Gal et al., 2020; Persson et al., 2021; Yustitia et al., 2022; Zhu & Chiu, 2019). The OECD (2023) defines numeracy as the ability to apply mathematical concepts and procedures in real-life contexts (OECD, 2019). Numeracy is not merely the ability to calculate, but also the ability to reason quantitatively, interpret data, and solve problems contextually (Indraswara et al., 2023; Wulandari et al., 2024). Therefore, numeracy is an important indicator of students' readiness to face increasingly complex global challenges in the digital age.

However, various international and national assessment results show that Indonesian students' numeracy skills are still at an alarming level. The 2022 PISA results show that the average mathematical literacy score of Indonesian students is still below the OECD average, and most students are only able to solve problems with simple contexts. These findings indicate that many students are not yet able to apply mathematical concepts in new situations that require reasoning and data interpretation.

This condition is reinforced by the results of the Education Report Card (AKM Nasional) published by the Education Assessment Center (Pusmendik) of the Ministry of Education, Culture, Research, and Technology in 2023, which shows that the numeracy competency of elementary school students is still relatively low (Kementerian Pendidikan, Kebudayaan, Riset, 2023). AKM data shows that more than 50% of elementary school students are at the "Basic" and "Need Special Intervention" levels in numeracy. This means that most students are only capable of performing simple arithmetic operations without understanding their meaning in the context of everyday life. In addition, AKM data also indicates that students' ability to interpret data, understand patterns, and use mathematical reasoning is still limited. These results emphasize the need for more meaningful, contextual, and adaptive learning innovations tailored to student characteristics.

One approach that could be a solution is ethnomathematics, which is the study of the relationship between culture and human mathematical activities (Astuti et al., 2024; Mallqui & Chávez, 2021; Tampubolon et al., 2023). This approach teaches that mathematical concepts do not appear in a vacuum, but rather develop from cultural practices, architecture, art, and the social life of a community. D'Ambrosio (1985) explains that ethnomathematics enables students to understand mathematics through local cultural experiences and values. In the context of Indonesia, which is rich in cultural diversity, ethnomathematics has great potential to provide contextual, relevant, and meaningful mathematics learning (Ambrosio, 2006; Lidinillah et al., 2022; Mania & Alam, 2021). Through this approach, students can relate concepts of geometry, patterns, and measurement to cultural objects around them, such as batik, mosques, temples, and traditional buildings (Arthamevia et al., 2022; Faiziyah et al., 2021; Oktavia et al., 2025; Prahmana & D'Ambrosio, 2020; Suherman & Vidákovich, 2024).

However, despite its great potential, the implementation of ethnomathematics in schools still faces various obstacles. Most teachers do not yet have learning media that can combine cultural context with modern pedagogical approaches. The media used is still conventional, lacks interactivity, and is not suited to the characteristics of the current digital generation. Elementary school students need visually appealing and interactive learning experiences so that they can understand mathematical concepts in depth and apply them.

In this case, developments in educational technology provide a great opportunity to bridge the gap between traditional learning and 21st-century learning needs. One relevant innovation is the use of Augmented Reality (AR), which can display three-dimensional objects in a real environment. AR technology can help students visualize abstract mathematical concepts, such as shapes, symmetry patterns, and spatial concepts, in a realistic and engaging way (Mansour et al., 2024; Mirza et al., 2025; Rusillo-Magdaleno et al., 2023; S et al., 2021; Sánchez, 2022). Thus, AR plays an important role in strengthening exploration- and visualization-based learning experiences.

In addition to AR, the application of gamification in learning has also been proven effective in increasing student motivation and engagement. Gamification adapts game elements such as points, challenges, levels, and rewards to create a fun and competitive learning atmosphere (Krath et al., 2021; Ortiz-Rojas et al., 2025; Saleem et al., 2022; Yu et al., 2024). Research by Li et al., (2024) shows that gamification increases students' intrinsic motivation, curiosity, and perseverance in learning. In the context of mathematics, gamification can change negative perceptions of this subject into a positive and motivating experience.

The integration of ethnomathematics, AR, and gamification provides a holistic learning approach: culture-based (contextual), technology-based (interactive), and motivation-based (participatory). The medium that can effectively combine these three aspects is interactive digital comics. Comics have narrative power that can engage students' emotions and imagination through light-hearted storylines and attractive visuals (Canbulut & Kılıç, 2022; Kusmaharti et al., 2023; Suprapto et al., 2024). When enriched with elements of Augmented Reality (AR) and gamification, comics become not only a means of educational entertainment, but also a fun, challenging, and meaningful medium for numeracy learning.

Previous studies have proven the effectiveness of ethnomathematics in strengthening conceptual understanding, as well as the success of using AR and gamification in increasing learning motivation (Darmayanti et al., 2022). However, research that comprehensively integrates these three components—ethnomathematics, gamification, and AR—into a single learning medium for improving the numeracy of elementary school students is still very limited.

Therefore, this study aims to develop and test the effectiveness of gamification-based ethnomathematics comics and Augmented Reality (AR) as innovative learning media to improve the numeracy skills of elementary school students. A needs analysis was conducted in three regions, namely Gresik, Sidoarjo, and Surabaya, to ensure the suitability of the product with the cultural characteristics and learning context of the students. Product trials

were conducted in three schools, namely SD Hang Tuah X Juanda, SDN Ketintang 4 Surabaya, and UPT SDN 152 Gresik, to measure the validity, practicality, and effectiveness of the media in improving students' numeracy.

This study is expected to contribute theoretically to the development of learning models that integrate culture, technology, and learning motivation. In practical terms, the results of this study can be used as a reference for teachers and educational media developers to design mathematics learning that is interesting, contextual, and relevant to the challenges of 21st-century learning. Thus, this innovation of gamification and AR-based ethnomathematics comics is expected to be a concrete solution in improving the numeracy outcomes of Indonesian students, which are still unsatisfactory based on the results of the AKM and PISA reports.

RESEARCH METHOD

This study uses a Research and Development (R&D) approach by adapting Borg and Gall's development model, which has been simplified into six main stages, namely: (1) needs analysis, (2) product design, (3) initial product development, (4) expert validation, (5) limited testing, and (6) extensive testing. This model was chosen because it is suitable for developing technology-based learning products that emphasize validity, practicality, and effectiveness.

The research was conducted in three areas in East Java, namely Gresik Regency, Sidoarjo Regency, and Surabaya City, which were purposively selected to represent diverse cultural contexts and student characteristics. The research subjects involved fifth-grade students and elementary school teachers. The needs analysis stage involved six elementary schools in the three regions to identify difficulties in numeracy learning, the need for interactive media, and the potential for integrating local culture into mathematics learning. Based on the results of the needs analysis, learning media in the form of gamified ethnomathematics comics and Augmented Reality (AR) technology were developed. The stories in the comics were taken from the cultural context of East Java, such as the architecture of the Al Akbar Mosque, the Red Bridge, and traditional batik ornaments.

The product development stage was carried out through a visual design process, the creation of educational narratives, and the integration of gamification elements (challenges, points, quizzes, and rewards) as well as AR-based visualization to display three-dimensional mathematical objects interactively. The initial product was then validated by six experts consisting of two mathematics subject matter experts, two learning media experts, and two educational technology experts. The validation covered aspects of content, appearance, interactivity, language, and suitability for numeracy learning objectives.

A limited trial was conducted at Hang Tuah X Juanda Elementary School in Sidoarjo, involving 30 students to assess the practicality and comprehensibility of the media. After revision, a large-scale trial was conducted in three schools, namely SDN Ketintang 4 Surabaya, SD Hang Tuah X Juanda, and UPT SDN 152 Gresik, with a total of 90 fifth-grade students participating. The effectiveness test design used a one-group pretest–posttest design to determine the improvement in students' numeracy skills after using AR-based comics and gamification media.

Research data was obtained through several instruments, namely: (1) expert validation sheets to assess the feasibility of the media, (2) student and teacher response questionnaires to assess the practicality and attractiveness of the media, (3) learning implementation observation sheets, and (4) numeracy tests to measure learning outcome improvement. Expert validation and response questionnaires were analyzed descriptively and quantitatively, while test result data were analyzed using a paired sample t-test and N-Gain Score calculations to determine the effectiveness of the media in improving students' numeracy skills.

Qualitative analysis was conducted on teacher interview data and classroom observations to reinforce quantitative findings. A product is considered valid if the average expert validation score is $\geq 85\%$, practical if the average student and teacher response score is $\geq 80\%$, and effective if there is a significant improvement in numeracy results ($p < 0.05$) with a minimum improvement category of moderate based on N-Gain.

With this design, this study produced innovative learning media in the form of gamified and AR-based ethnomathematics comics that were empirically and pedagogically validated to improve the numeracy skills of elementary school students.

Needs Analysis

Needs analysis was conducted as the initial stage of developing gamification-based ethnomathematics comics and Augmented Reality (AR). This activity aims to identify numeracy learning problems faced by elementary school students and teachers' needs for contextual, interesting, and digital technology-based learning media. The analysis was conducted in six elementary schools in three regions, namely Gresik Regency, Sidoarjo Regency, and Surabaya City, which have different learning environments and cultural backgrounds.

Data was collected through in-depth interviews with 12 mathematics teachers and 6 school principals, as well as through questionnaires distributed to 180 fifth-grade students. In addition, mathematics learning processes were

observed for two weeks to obtain a realistic picture of numeracy teaching strategies in the classroom. The data obtained was then analyzed descriptively, qualitatively, and quantitatively to explore the needs, interests, and challenges of numeracy learning in elementary schools.

Numeracy Learning Conditions in Elementary Schools

Observations show that mathematics learning in the three regions is still dominated by conventional approaches. Most teachers use lecture methods and exercises from textbooks without relating mathematical concepts to the real-life contexts of students. As many as 82% of teachers admitted that numeracy learning has not fully developed students' critical thinking and problem-solving skills, because learning activities tend to focus on the final calculation results rather than the reasoning process.

Meanwhile, interviews with teachers revealed that students often feel bored and have difficulty understanding abstract concepts such as fractions, units of measurement, and relationships between flat shapes. Teachers also complained about the lack of interesting learning media that suits the visual characteristics of elementary school students. Some teachers stated that efforts to use digital media are often hampered by time constraints, technological skills, and access to interactive devices.

This condition is reinforced by data from the National Education Report Card (AKM 2023), which shows that more than 50% of elementary school students are in the "Needs Special Intervention" and "Basic" categories in numeracy skills. The AKM results also confirm that most students are not yet able to interpret data and apply mathematical concepts in everyday contexts. This fact highlights the urgent need for learning media that can transform the mathematics learning experience from merely memorizing procedures to meaningful and contextual activities.

Teachers' Need for Interactive and Contextual Learning Media

Teachers involved in the needs assessment study emphasized that students greatly need visual, interactive, and narrative learning media to help them better understand abstract mathematical concepts. A total of 87% of teachers stated that a local culture-based approach (ethnomathematics) could be an important bridge to connect mathematics with students' daily experiences. They gave examples of many cultural elements around students that contain mathematical concepts, such as symmetry patterns in batik, geometric shapes in the architecture of the Al Akbar Mosque in Surabaya, and traditional measurement systems in markets.

However, 90% of teachers admitted that they did not yet have media that could integrate cultural contexts with modern digital technology. Teachers felt that the learning media currently available were not able to optimally attract students' interest, especially for the digital generation who are more interested in interactive visualizations and game elements. This emphasizes the need to develop learning media that not only contain cultural values but are also able to utilize technologies such as Augmented Reality (AR) and gamification to increase student engagement.

Teachers also highlighted the importance of media that is easy to use, does not require a continuous internet connection, and can be operated with simple devices such as smartphones or tablets. The majority of teachers stated that they are willing to use innovative media if it is proven to be practical and effective in improving students' numeracy.

Student Preferences and Expectations for Learning Media

Student survey data shows that 91% of students are more interested in learning mathematics through digital media that presents moving images, animations, or interactive games than through conventional learning. Most students mentioned that they like learning with stories and characters that have an adventure plot, because it makes mathematics feel more alive and closer to everyday life.

In addition, 84% of students stated that they wanted mathematics learning to be related to their surroundings, such as historical buildings, batik motifs, or traditional trading activities. This shows that students have a high interest in ethnomathematics-based learning, especially if it is packaged in an interesting and interactive way.

When asked about the use of technology, 95% of students expressed interest in the Augmented Reality (AR) feature, which allows them to see three-dimensional images directly through their device's camera. Meanwhile, 88% of students liked the concept of gamification, such as points, quizzes, and challenges with prizes in learning. This data indicates that the combination of cultural stories (ethnomathematics), AR, and gamification is highly suited to the needs and preferences of today's elementary school students.

Implications of Needs Analysis Results

Based on the results of the needs analysis, numeracy learning in elementary schools still faces a number of fundamental challenges that hinder the optimization of student learning outcomes. One of the main obstacles lies in the limited interactive learning media that can link mathematical concepts to real-life situations. Most learning

activities are still abstract and procedural, making it difficult for students to understand the meaning of numeracy in everyday contexts. In addition, the integration of local cultural elements in mathematics learning has not received adequate attention, even though Indonesia has a wealth of ethnomathematics that has great potential to be used as a source of contextual and inspirational learning. Another challenge that is no less important is the low interest and motivation of students to learn due to monotonous, teacher-centered teaching methods that do not provide space for exploration or meaningful learning experiences.

These findings emphasize the importance of developing innovative, contextual learning media that are in line with the characteristics of the current digital generation. Based on these analysis results, an ethnomathematics comic based on gamification and Augmented Reality (AR) technology was developed, combining the richness of local culture with interactive three-dimensional visualizations and educational game elements (Atalay & Ömer, 2022; Dewi & Kuswanto, 2023; Hidayat & Wardat, 2024; Tobar et al., 2023). Through a cultural context as the story background, AR technology to enhance the visual experience, and gamification as a motivator and healthy competition, this media is designed to help students understand numeracy concepts more meaningfully while increasing their engagement in the mathematics learning process .

In addition, the analysis results also show that both teachers and students demonstrate high readiness and enthusiasm for the use of new technology in learning. This condition reinforces the belief that learning innovations based on ethnomathematics, AR, and gamification are no longer optional, but a real necessity in addressing the problem of low numeracy skills among Indonesian students, as illustrated in the results of the National AKM Report Card. These innovations are believed to be capable of providing a more contextual, interesting, and relevant learning experience in line with the demands of 21st-century education.

Product Design

The product design stage was carried out based on the results of a needs analysis that showed the need for more interactive, contextual, and elementary school student-friendly numeracy learning media. The product developed was an ethnomathematics comic based on gamification and Augmented Reality (AR) technology, designed to integrate the local cultural context of East Java with numeracy learning. The design objective is to produce learning media that is not only visually appealing but also capable of providing a meaningful learning experience through a combination of cultural stories, mathematical challenges, and AR-based digital interactions.

The design process began with developing the concept and story structure adapted from the local cultural context, such as the Al Akbar Mosque in Surabaya, the Red Bridge in Surabaya, and the Heroes Monument. This cultural background was chosen because it has strong historical and architectural value and contains mathematical concepts that can be integrated into numeracy learning, such as symmetry patterns, geometric shapes, and spatial measurement. The comic's storyline is structured as an educational adventure that invites the main character—an elementary school student—to solve numeracy problems in everyday situations rooted in local cultural life. Each episode begins with an introduction to the contextual situation, followed by an exploration of mathematical concepts, then interaction using AR, and ends with a gamified challenge in the form of a quiz or puzzle that assesses the student's understanding.

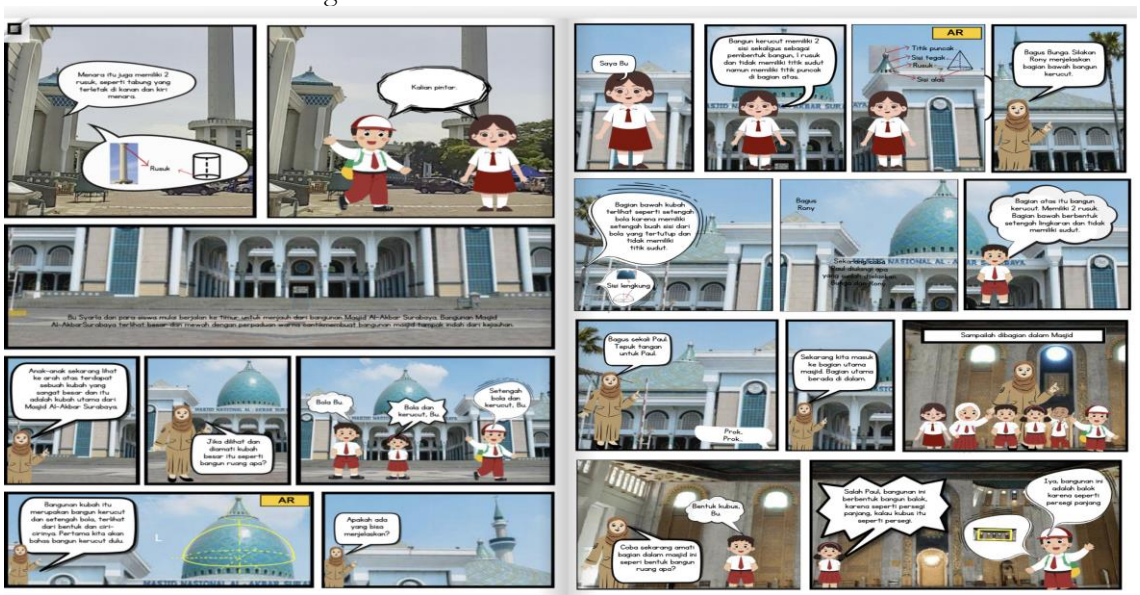


Figure 1 shows the conceptual flow of AR-based ethnomathematics comics and gamification that illustrates the relationship between cultural elements, mathematics learning, and interactive digital elements. The comic narrative is developed in a simple, communicative style that is appropriate for the cognitive level of fifth-grade elementary school students. The story is structured to stimulate curiosity, character values, and national spirit through reflection on regional culture.

Visually, the comic is designed using a semi-realistic illustration style with bright colors and an attractive layout. The main character and supporting characters are designed to represent Indonesia's cultural diversity. The main character is depicted as an intelligent, critical, and adventurous elementary school student, while supporting characters such as teachers and cultural figures provide guidance and motivation in the process of solving numeracy problems. The page layout is dynamic, taking into account the balance between text, illustrations, and interactive space. This design follows the principles of child-centered learning design, which emphasizes visual clarity and ease of navigation for elementary school students.

Figure 2 shows examples of the main characters and cultural backgrounds used in digital comics, such as views of the Al Akbar Mosque, the Red Bridge, and typical Surabaya and Gresik ornaments. Visual elements not only serve as the backdrop for the story, but also as a realistic context for learning mathematics, where students can relate shapes, sizes, and patterns to their real lives.

The integration of gamification is an important element in this design stage. Gamification is used to foster learning motivation and increase student engagement. Game elements such as points, levels, missions, and rewards are applied in each episode of the comic. Students earn points each time they successfully answer a quiz or complete a numeracy challenge, and can advance to the next level when they reach a certain score. Each success is also accompanied by achievement badges to foster a sense of accomplishment and healthy competition. This gamification system is designed to foster self-regulated learning, where students are motivated to learn not because of obligation, but because of curiosity and the challenges in the game (Krath et al., 2021; Rodrigues et al., 2022).

In addition to gamification, Augmented Reality (AR) technology is used to enrich the student learning experience. The AR feature allows students to scan codes or markers on the comic pages using their device's camera, which then displays three-dimensional objects relevant to the numeracy material. For example, when students point their camera at an image of the dome of the Al Akbar Mosque, a 3D hemisphere visualization appears, complete with information about its volume and surface area. In another episode, an image of the Red Bridge brings up a 3D model of beams and triangles to explain the concepts of geometric shapes and structural strength. This interaction makes learning more immersive and concrete, as students can manipulate the viewing angle of objects, observe shapes in more detail, and understand the connection between mathematics and the real world.

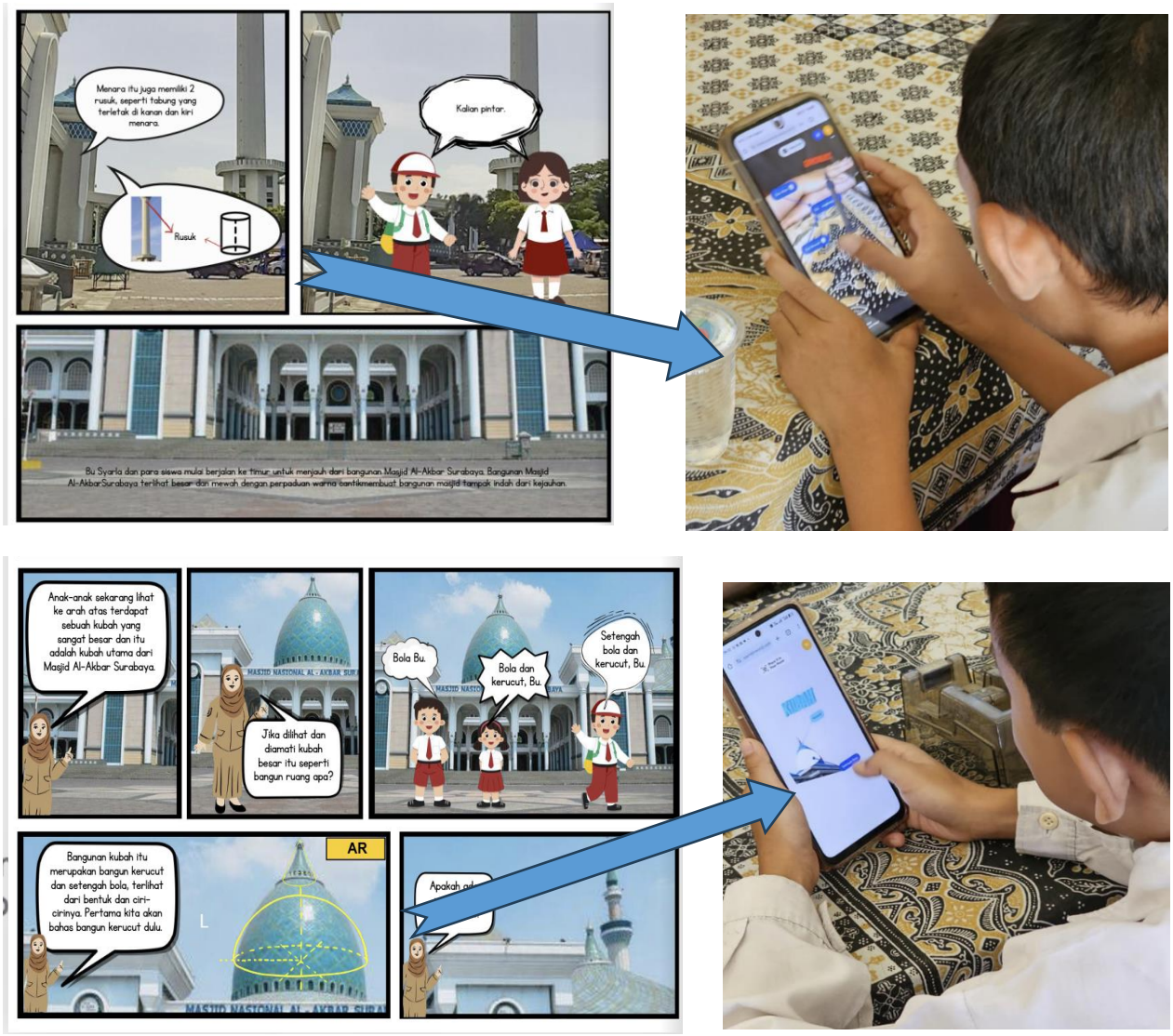


Figure 3 shows an example of Augmented Reality in digital comics, where 3D objects appear from the comic pages through the students' devices. The integration of AR in these comics not only enriches the visual aspect but also helps students build mental images of previously abstract numeracy concepts. Thus, AR serves as a bridge between symbolic representations and students' real experiences.

The digital comic interface is designed to be easy for students to operate without direct assistance from teachers (Darmayanti et al., 2022; Fitria & Halili, 2023; Kumar & Dhar, 2024) . Navigation between pages uses simple icon buttons with next, back, and home functions. The AR scan feature is placed in the lower corner of each page to make it easy for students to access additional content, while the quiz menu can be accessed after students have read a full episode. This interface design follows the principles of usability design for elementary school children, namely simplicity, consistency, and clarity.

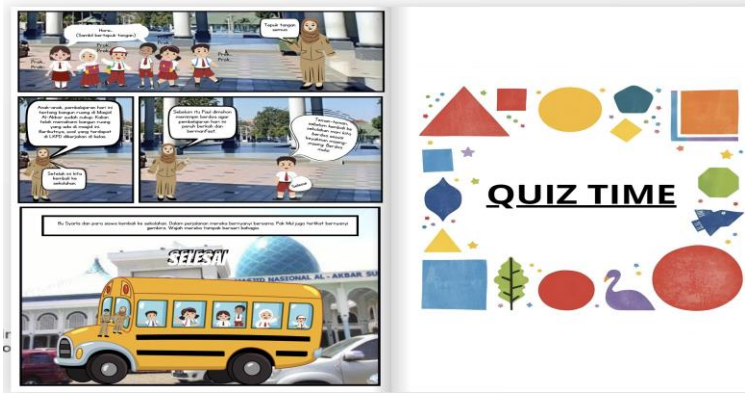


Figure 4 shows the main interface of the interactive digital comic, which features navigation buttons, AR scanning icons, and a numeracy challenge menu.

The final stage of the design process involved initial design validation by six experts, consisting of two mathematics experts, two learning media experts, and two educational technology experts. The validators assessed the content, language, visual appearance, interactivity, and pedagogical suitability. The validation results showed that the developed comic had an average feasibility score of 89.7%, which is considered highly valid. The experts provided several suggestions, including the need to adjust the level of difficulty of the numeracy questions to the abilities of fifth-grade students, the addition of technical instructions for using AR on the first page, and the simplification of several narrative sentences to make them more communicative. After revisions were made according to the experts' suggestions, the digital comic product was declared suitable for testing in a real learning context in elementary schools.

Overall, the results of this product design show that the integration of local culture (ethnomathematics), Augmented Reality technology, and gamification elements can produce attractive, interactive, and meaningful learning media. The combination of these three elements makes numeracy learning not only focus on mastering mathematical concepts, but also on developing students' curiosity, creativity, and critical thinking skills. This product also has the potential to be a learning tool that supports the implementation of the Merdeka Curriculum, which emphasizes contextual, exploratory, and student-centered learning.

Expert Validation Results

The expert validation stage was conducted to assess the suitability of the content, appearance, and interactivity of the gamified and Augmented Reality (AR)-based ethnomathematics comics that were developed. This validation involved six experts, consisting of two mathematics experts, two learning media experts, and two educational technology experts. The purpose of the validation was to ensure that the resulting media met pedagogical standards, content appropriateness, visual clarity, and technological functionality before being field tested. The validation process was carried out by filling out an assessment sheet that included aspects of content feasibility, language, visual appearance, interactivity, and suitability for elementary school numeracy learning objectives.

In general, the validation results showed that this gamification and AR-based ethnomathematics comic received an overall average score of 89.7%, which is classified as highly valid. This means that the developed product has met the eligibility criteria in terms of both content and technical aspects. In terms of content feasibility and concept accuracy, subject matter experts gave an average score of 90.5%, noting that the numeracy material presented was in line with the basic competencies of fifth-grade elementary school students. The experts also assessed that the integration of local cultural contexts, such as the architecture of the Al Akbar Mosque, Surabaya batik patterns, and the shape of the Red Bridge, was an innovative approach that was able to bridge abstract mathematical concepts with students' real experiences. However, the experts suggested that some mathematical terms be simplified without reducing their accuracy so that they would be easier for elementary school students to understand.

In terms of visual appearance and media design, the comic received an average score of 88.7%. Media experts assessed that the illustrations and layout of the comic were attractive, communicative, and appropriate for elementary school children. The use of bright colors and a semi-realistic drawing style is considered to enhance visual appeal without detracting from the seriousness of the learning. Media experts also highlighted the choice of easy-to-read typography and the arrangement of comic panels that make it easy for students to follow the storyline. However, it is recommended that the space between panels be widened on some pages to avoid a crowded impression and provide visual comfort when read on a device screen.

In terms of language and narrative, the comic received a score of 87.5%. Learning experts assessed that the language used was communicative, simple, and appropriate for the cognitive level of the students. The dialogue between the characters helped to build the context of the numeracy problems well. However, some of the narrative sentences at the beginning of the story were still considered too long and needed to be simplified to be more effective. Improvements were also made to mathematical terms such as "measuring the circumference of a curved area," which was changed to "measuring the curved part of a building" to make it more natural for students.

The interactivity and functionality aspects of AR technology received the highest score, namely 92.3%. Educational technology experts assessed that the Augmented Reality features embedded in comics are capable of providing an immersive and concrete learning experience. The 3D objects that appear from comic markers, such as spheres, cubes, and prisms, are considered to help students understand the relationship between geometric concepts and real shapes in their cultural environment. The AR system's response to marker scanning works well, the 3D display is stable, and no internet connection is required for use. Experts suggest that technical instructions for using AR be added to the first page of the comic so that teachers and students can access the feature more easily.

In terms of pedagogical suitability and relevance to numeracy skills, the media scored 89.6%. The experts assessed that each section of the comic was designed in line with the numeracy learning objectives, namely to understand, apply, and reason mathematical concepts in real-life contexts. Gamification elements such as quizzes, rewards, and badges were considered effective in encouraging student motivation and active participation. Teachers can use this comic not only as a learning support medium but also as a formative assessment tool that helps assess student understanding in a fun way.

The overall assessment results show that the gamification- and AR-based ethnomathematics comic media developed meet the criteria of being highly valid and suitable for use in numeracy learning. All experts stated that this innovation combines the strengths of culture and technology in an attractive, relevant learning ecosystem that meets the demands of 21st-century learning.

In addition to providing assessment scores, the experts also provided a number of highly constructive qualitative inputs for product improvement. These inputs included: (1) clarifying the instructions for using AR on the first page of the comic, (2) adding a variety of numeracy questions that require higher order thinking skills, (3) strengthening the cultural reflection aspect by adding dialogues that touch on the values of mutual cooperation or creativity in the context of local culture, and (4) adding language options to the digital version to expand accessibility. All of this feedback was used as the basis for revising the product before proceeding to the field trial stage.

Conceptually, the results of this expert validation confirm that the interactive technology-based ethnomathematics approach is a learning strategy that is relevant to the characteristics of elementary school students in the digital age. The ethnomathematics comics developed not only meet the criteria for technically and pedagogically sound learning media, but also have the potential to serve as a bridging learning medium—connecting formal mathematical concepts with real experiences in the context of local culture. The main advantage of this product lies in the combination of cultural stories, concrete AR visualizations, and motivating gamification elements, which together create a more enjoyable and meaningful learning experience.

With these high validation results, gamification and AR-based ethnomathematics comics are declared ready for testing in the next stage, namely limited trials and extensive trials in three elementary schools (Aini et al., 2025; Anawati et al., 2024; Oktavia et al., 2025; Pratama & Yelken, 2024; Skovsmose, 2022; Tampubolon et al., 2023). Expert validation provides an empirical basis that this media has strong potential to improve students' numeracy skills while strengthening their appreciation of Indonesian cultural values through a technology and culture-based learning approach.

Limited Trial Results

Limited trial was conducted at SD Hang Tuah X Juanda, Sidoarjo, to evaluate the practicality and initial appeal of gamification-based ethnomathematics comics with Augmented Reality (AR) before broader implementation. The participants were 30 fifth-grade students and one mathematics teacher over two sessions per week.

Students used two comic episodes—"Measuring the Beauty of the Al Akbar Mosque Dome" and "The Secrets of Geometry in the Red Bridge"—that integrated local cultural contexts with numeracy concepts. Observations showed that over 90% of students were highly enthusiastic, actively using AR features to view 3D objects and discuss geometric shapes. The AR interaction promoted visual-spatial thinking and helped students connect abstract mathematical ideas with familiar cultural artifacts.

The gamification elements (quizzes, points, badges) significantly boosted motivation and engagement. Students expressed enjoyment and intrinsic motivation to learn mathematics through challenges and rewards. Teachers confirmed increased focus, collaboration, and classroom energy.

Questionnaire results revealed 92% of students found the media helpful for understanding mathematical concepts, and 88% felt more motivated due to the mix of stories and games. Teachers rated the media's practicality at 91% (very practical), noting its ease of use, offline accessibility, and effectiveness in linking math concepts with everyday cultural contexts.

Minor technical issues, such as poor lighting affecting AR recognition, were easily resolved through added visual guides and voice prompts. Students suggested more quizzes, challenges, and animations for greater immersion.MTeachers observed improved engagement, confidence, and self-efficacy, particularly among low-achieving students who felt a sense of accomplishment from completing challenges.

Overall, the trial demonstrated that AR-based ethnomathematics comics with gamification are engaging, feasible, and highly practical. They enhance motivation, conceptual understanding, and align with 21st-century learning principles—contextual, interactive, collaborative, and technology-driven. These promising results form a solid foundation for large-scale trials in Surabaya, Sidoarjo, and Gresik to evaluate the media's broader effectiveness and adaptability.

Enhanced Interactivity.

Large-Scale Trial Phase

The large-scale trial phase was conducted after the gamification-based ethnomathematics comic book and Augmented Reality (AR) technology were revised based on the results of the limited trial. This trial aimed to comprehensively assess the effectiveness of the media in improving the numeracy skills of elementary school students from various regions and school characteristics. The activities were carried out in three elementary schools, namely SDN Ketintang 4 Surabaya, SD Hang Tuah X Juanda Sidoarjo, and UPT SDN 152 Gresik.

These three schools were chosen because they represent three different educational contexts: a densely populated urban area (Surabaya), a semi-military suburban area (Sidoarjo), and a semi-rural area (Gresik). The trial involved 90 fifth-grade students, 30 from each school, and three mathematics teachers as assistants. The research design used was a one-group pretest–posttest design, in which students were given numeracy tests before and after using digital comics. In addition, observations, interviews, and student and teacher response questionnaires were used to reinforce the quantitative results.

Descriptive and Statistical Analysis Results

Before using the media, a numeracy pretest was conducted to determine the students' initial abilities. The average pretest scores at the three schools were relatively similar, namely SDN Ketintang 4 (64.3), SD Hang Tuah X Juanda (62.8), and UPT SDN 152 Gresik (63.0). After three meetings using AR-based ethnomathematics comics and gamification, the posttest scores increased significantly in all three schools: SDN Ketintang 4 (84.2), SD Hang Tuah X Juanda (80.5), and UPT SDN 152 Gresik (81.7).

Table 1 below shows a comparison of the average pretest and posttest scores and the N-Gain values, which indicate the level of improvement in students' numeracy skills.

Table 1. Hasil Pretest, Posttest, dan N-Gain di Tiga Sekolah

School	Pretest Average	Posttest Average	Improvement	N-Gain	Category
SDN Ketintang 4 Surabaya	64.3	84.2	19.9	0.68	Moderate-High
SD Hang Tuah X Juanda	62.8	80.5	17.7	0.56	Moderate
UPT SDN 152 Gresik	63.0	81.7	18.7	0.59	Moderate-High
Rata-rata	63.4	82.1	18.7	0.61	Moderate-High

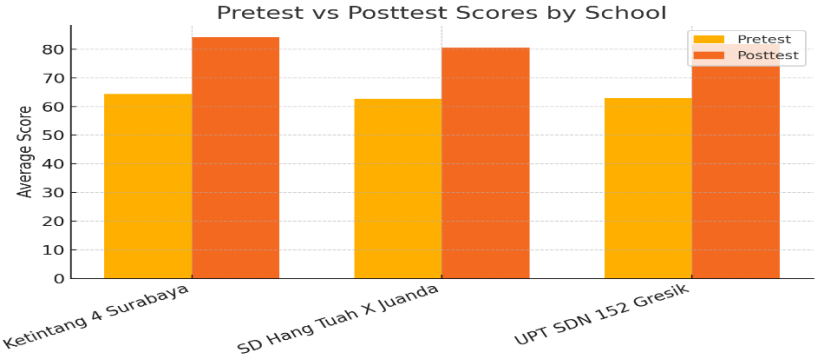
The paired sample t-test statistical test shows that all schools experienced a significant increase between the pretest and posttest scores with a p-value of $0.000 < 0.05$, indicating that AR-based ethnomathematics comics and gamification are effective in improving students' numeracy skills.

In general, the highest increase occurred in mathematical reasoning indicators, with an average increase of 21%, followed by problem-solving at 18%, and data interpretation at 15%. This shows that media not only improves basic arithmetic skills, but also strengthens students' higher-order thinking skills through visual and narrative experiences.

Visualization of Field Test Results

Figure 1 below presents a comparison of the average pretest and posttest scores for numeracy skills in three elementary schools.

Figure 1. Comparison of Average Pretest and Posttest Scores for Student Numeracy Skills in Three Schools



(The image caption you will insert later can be a two-color bar chart: blue for the pretest, orange for the posttest. Each bar represents one school: Surabaya, Sidoarjo, Gresik.)

The chart shows an increase in the average numeracy scores of students at all trial locations. The highest increase was seen at SDN Ketintang 4 Surabaya, which has a learning environment with more complete digital facilities. However, interestingly, the increase at UPT SDN 152 Gresik was also high even though it was conducted in a semi-rural environment. This indicates that AR-based comic media can adapt across contexts, both in schools with high and limited facilities, because the media is designed to be used offline.

Qualitative Analysis: User Activities and Responses

In addition to quantitative data, the results of the extensive pilot test also showed significant changes in student learning behavior and teacher perceptions of mathematics learning. Based on the results of observations, more than 93% of students appeared active during the learning process. They read comics enthusiastically, discussed with each other to answer numeracy quizzes, and competed healthily in the point acquisition system.

Teachers from all three schools stated that the gamification element successfully increased learning motivation. Students appeared excited when they saw their scores appear on the screen and tried to correct their mistakes to earn the next badge. Teachers also assessed that the instant feedback system in the numeracy quizzes helped students understand their mistakes immediately and improve their thinking strategies.

From the response questionnaire results, students gave very positive assessments of the media. As many as 94% of students said the comics were interesting and fun, 91% of students felt it was easier to understand numeracy concepts, and 89% of students said learning was not boring. One student from Gresik Elementary School said, "Math feels like an adventure. I can learn about bridges and mosque domes while playing." This statement shows the success of the media in fostering joyful learning and strengthening the contextual meaning of mathematics.

Teachers also shared similar impressions. According to a teacher at SDN Ketintang 4 Surabaya, this media is very effective for explaining geometry and measurement concepts because students can "see" the shapes directly through AR, rather than just imagining them. Meanwhile, a teacher at SD Hang Tuah X Juanda emphasized that the cultural context made students feel proud of their local heritage and more interested in learning.

Pedagogical Interpretation

Extensive testing results show that the use of AR-based ethnomathematics comics and gamification not only has a significant impact on improving numeracy scores, but also has a broader pedagogical impact on students' learning experiences.

First, learning becomes more contextual. The cultural narratives in the comics serve as a bridge between formal mathematical knowledge and students' life experiences. Contexts such as mosque architecture, bridge shapes, and batik motifs reinforce mathematical meanings that were originally abstract, making them concrete.

Second, the use of AR fosters multimodal learning. Students not only read and calculate, but also see, rotate, and interact directly with three-dimensional objects. This activity supports the Dual Coding theory (Paivio, 1990), which explains that information presented in both visual and verbal forms will increase retention and understanding of concepts.

Third, gamification elements encourage students' intrinsic motivation. Challenges, points, and badges make students feel valued for their learning process. These simple game elements create a flow learning condition, where students are immersed in learning activities without feeling pressured.

Fourth, social interaction and collaboration increase. In each session, students work in pairs or small groups to discuss quiz answers and scan AR objects. Teachers observed that students who were usually passive became more courageous in expressing their opinions.

These findings show that AR-based ethnomathematics comics and gamification not only function as a medium for conveying information, but also as a digital learning ecosystem that supports the principles of active, collaborative, and culture-based learning.

N-Gain Visualization per School

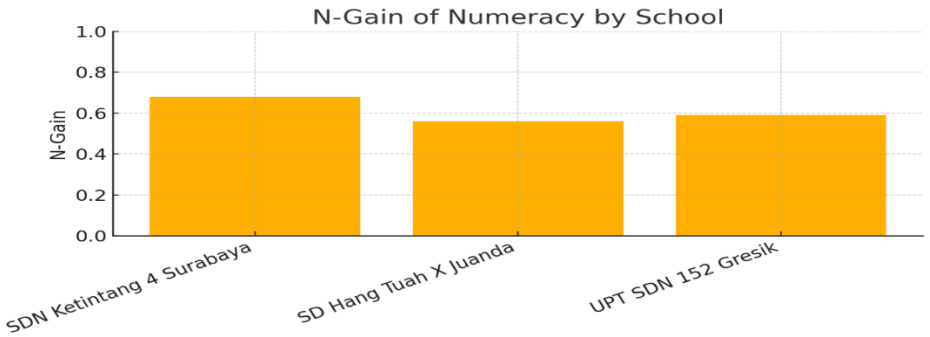


Figure 2. Comparison of N-Gain Numeracy Scores in Three Schools

(This figure can be a bar graph showing N-Gain for three schools: Surabaya = 0.68, Gresik = 0.59, Sidoarjo = 0.56. Label the category "Moderate–High.")

This graph shows that the greatest improvement in numeracy skills was achieved by students at SDN Ketintang 4 Surabaya. However, the distribution of improvement across all locations was relatively even, which means that the media has stable effectiveness in various learning contexts.

This study proves that gamified ethnomathematics comics and Augmented Reality (AR) are effective, valid, and practical for improving the numeracy skills of elementary school students. Through the Borg and Gall development stages, this media was designed by integrating the local cultural context of East Java—such as the Al Akbar Mosque, the Red Bridge, and historic buildings in Gresik—into interactive technology-based mathematics learning.

Expert validation results showed a very high feasibility level (89.7%), while limited and extensive trials in three schools (Surabaya, Sidoarjo, and Gresik) showed a significant increase in students' numeracy skills, with an N-Gain value of 0.61 (medium-high category) and significance $p < 0.05$. Students and teachers responded positively to the media, which they found interesting, easy to use, and capable of bridging abstract mathematical concepts with real life.

Pedagogically, these comics not only strengthen numeracy learning outcomes but also foster motivation, curiosity, and pride in local culture. This innovation has the potential to become a culture- and technology-based numeracy learning strategy that is relevant for the implementation of the Merdeka Curriculum in Indonesian elementary schools.

DISCUSSION

The results of this study indicate that the development of gamification- and Augmented Reality (AR)-based ethnomathematics comics has a significant positive impact on improving the numeracy skills of elementary school students. The effectiveness of this media can be seen from the increase in numeracy scores in a large-scale trial in three elementary schools with an average N-Gain value of 0.61 (medium-high category) and t-test results showing a significant difference between the pretest and posttest results ($p < 0.05$). These findings are in line with the views of the OECD (2023) and Pusmendik (2023) that improving numeracy requires learning strategies that are able to creatively and sustainably link mathematical concepts to real-life contexts.

The integration of ethnomathematics, gamification, and AR has proven to be effective because the three complement each other in creating contextual, interactive, and motivating learning experiences. From a pedagogical perspective, ethnomathematics serves as a bridge between formal mathematics and students' cultural experiences. Cultural contexts such as the architecture of the Al Akbar Mosque, the Red Bridge, and local batik motifs present relevant and meaningful learning situations, in line with the principles of Realistic Mathematics Education (RME) by Freudenthal. Learning that connects mathematics with the real world helps students build a deeper conceptual understanding and improves their knowledge transfer skills.

Meanwhile, the application of Augmented Reality (AR) technology strengthens students' visual and cognitive aspects in understanding abstract numeracy concepts. These findings support Paivio's Dual Coding theory, which states that learning is more effective when information is presented in both verbal and visual forms simultaneously. Three-dimensional visualizations of cultural objects—such as a hemispherical mosque dome or a block-shaped bridge structure—help students manipulate, observe, and interpret geometric concepts concretely. Thus, AR not only serves as a visual aid but also as a means of forming mental imagery that deepens students' conceptual understanding of numeracy.

Gamification elements also contribute significantly to increasing student motivation and engagement in learning. Elements such as points, badges, and challenge levels can create a healthy competitive atmosphere and foster intrinsic motivation. These findings are in line with the results of studies by (Ciuchita et al., 2023) and (Ortiz-Rojas et al., 2025), which state that increases students' sense of achievement, perseverance, and active participation in the learning process. In the context of this study, students who were initially passive in mathematics learning became more enthusiastic and dared to participate because they felt appreciated for their efforts and achievements.

In addition to cognitive and affective aspects, this study also confirms that AR-based ethnomathematics comics and gamification have a positive influence on the social and emotional aspects of learning. The comic-based learning process encourages collaborative discussion, social interaction, and communication of mathematical ideas among students. Teachers reported that students helped each other when using the AR feature or answering numeracy quizzes, reflecting an increase in social engagement and teamwork. This shows that interactive digital media-based learning can support the development of soft skills such as collaboration and communication, which are among the key competencies in the Merdeka Curriculum and 21st Century Learning Framework.

From an educational technology perspective, the success of this media also lies in its interactive design, which is adaptive to the characteristics of the digital generation. Trial results in three school contexts—urban (Surabaya),

semi-urban (Sidoarjo), and semi-rural (Gresik)—showed consistent effectiveness despite differences in facilities and access to technology. This proves that the offline-capable AR design makes this media inclusive and suitable for the diverse educational context in Indonesia. In other words, this innovation is able to bridge the digital divide between urban and non-urban schools.

Theoretically, the results of this study reinforce the idea that meaningful mathematics learning cannot be separated from the socio-cultural context and visual experiences. The combination of ethnomathematics, gamification, and AR supports the Constructivist Learning Theory and Situated Learning frameworks, which emphasize that knowledge is constructed through interaction with the environment and real contexts. Students do not just memorize formulas, but also construct mathematical meaning through experiences, stories, and digital exploration.

These findings also have significant practical implications. First, teachers can use AR-based ethnomathematics comics as an alternative medium in numeracy learning to create a more engaging and participatory learning environment. Second, this medium can serve as a formative assessment tool because gamified quizzes allow teachers to monitor student understanding in real time. Third, for educational media developers, these research results open up opportunities to expand the application of similar concepts to other materials, such as geometry, measurement, or context-based statistics based on regional culture.

In general, these research results are consistent with previous research by , which found that the integration of Skovsmose (2022) in digital media improves students' critical thinking and numeracy skills. However, the contribution of this study lies in its integrative innovation—namely, combining the three main components (ethnomathematics, gamification, and AR) into a single, culturally-based learning medium. This approach is not only relevant to the local Indonesian context but can also serve as a global model for culture-based mathematics learning in the digital age.

Thus, the results of this discussion confirm that gamification and AR-based ethnomathematics comics are innovative learning media capable of overcoming the challenge of low numeracy scores among Indonesian students, as reflected in the National AKM Report Card and PISA. This medium is not only cognitively effective in improving numeracy understanding but also affectively and socially meaningful as it fosters curiosity, cultural pride, and a spirit of collaboration among students. This innovation demonstrates that when culture, technology, and pedagogy synergize, mathematics learning can become an enjoyable, relevant, and transformative experience for elementary school students.

CONCLUSION

This study proves that gamification-based ethnomathematics comics and Augmented Reality (AR) are effective, valid, and practical for improving the numeracy skills of elementary school students. Through the Borg and Gall development stages, this media was designed by integrating the local cultural context of East Java—such as the Al Akbar Mosque, the Red Bridge, and the historic buildings of Gresik—into interactive technology-based mathematics learning.

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Pedagogically, these comics not only strengthen numeracy learning outcomes but also foster motivation, curiosity, and pride in local culture. This innovation has the potential to become a culture- and technology-based numeracy learning strategy relevant for the implementation of the Merdeka Curriculum in Indonesian elementary schools.

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