



## Development of a technology-integrated ethnomathematics digital comic using hadroh music context: effects on students' numeracy and self-regulated learning

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### Abstract

**Background:** Mathematics plays a vital role in fostering logical, analytical, and systematic thinking in the 21st century, with numeracy and self-regulated learning recognized as essential competencies in the Merdeka Curriculum. However, students' numeracy skills and learning independence remain relatively low, particularly among Grade VIII students at SMP Negeri 1 Pekuncen.

**Aims:** This study aims to develop a technology-integrated ethnomathematics digital comic using a hadroh music context and to evaluate its validity, practicality, and effectiveness in improving students' numeracy skills and self-regulated learning.

**Method:** This research employed a Research and Development (R&D) approach based on the 4D model (Define, Design, Develop, Disseminate). The study involved Grade VIII students in the 2025/2026 academic year. Data were collected through expert validation sheets, questionnaires, and numeracy tests, and analyzed using both descriptive and inferential statistical techniques.

**Results:** The developed digital comic was categorized as valid, with material expert validation of 77.7% and media expert validation of 84%. It was also considered practical based on positive responses from teachers and students. Descriptive findings indicate improved numeracy scores and self-regulated learning in the experimental group. Inferential analysis shows that self-regulated learning improved significantly, while numeracy improvement demonstrated a positive but not statistically significant trend.

**Conclusion:** The ethnomathematics-based digital comic integrating hadroh music is valid, practical, and has strong potential to enhance students' learning autonomy and contextual mathematical understanding.

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## INTRODUCTION

Mathematics is a fundamental subject that plays a crucial role in developing logical, analytical, and systematic thinking skills required in the 21st century. These competencies are essential for students to navigate complex problems and make informed decisions in both academic and real-life contexts. One of the key competencies emphasized in contemporary education is numeracy, which involves the ability to interpret, analyze, and apply mathematical concepts in everyday situations (Díez-Palomar et al., 2023; Geiger & Schmid, 2024; Hoogland, 2023). Numeracy is not limited to performing calculations but also includes reasoning, problem-solving, and critical thinking skills (Ogunsola & Adigun, 2025; Reyna & Brainerd, 2023; Torres-Peña et al., 2025; Yustitia et al., 2025). In the context of modern education, numeracy has become a priority as it supports students' readiness to face global challenges (Grotlüschen et al., 2020). However, despite its importance, students' numeracy skills remain relatively low in many educational settings. This condition reflects persistent

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difficulties in understanding and applying mathematical concepts, particularly in solving contextual problems. Students often struggle to connect abstract mathematical ideas with real-world situations, which limits their ability to use mathematics meaningfully (Montesdeoca, 2023; Sevinc, 2023; Sevinc & Lesh, 2022; Wisenöcker et al., 2024). Such challenges indicate that current instructional practices may not fully support the development of higher-order thinking skills. Therefore, there is a need for more effective and meaningful approaches to enhance students' numeracy competencies.

One of the mathematical topics that significantly contributes to the development of numeracy skills is number patterns. This topic serves as a foundation for understanding algebraic thinking and recognizing relationships between mathematical concepts. Through number patterns, students learn to identify regularities, generalize rules, and interpret mathematical relationships (Mulligan et al., 2020; Schifter & Russell, 2022; Sterner, 2025; Zippert et al., 2021). However, in practice, this topic is often perceived as difficult due to its abstract nature and the dominance of symbolic representation. Many students experience challenges in identifying and generalizing patterns because learning activities are frequently presented in a procedural manner (Ellis et al., 2022; Huang & Lajoie, 2021; Hunter & Miller, 2022; Kama et al., 2023; Sutarto et al., 2022). As a result, students tend to memorize formulas without fully understanding the underlying concepts. This situation reduces their ability to apply knowledge in different contexts. To overcome this issue, learning approaches that connect mathematical concepts with students' real-life experiences are needed. Contextual and meaningful learning can help students better understand abstract ideas by linking them to familiar situations. In this regard, integrating cultural elements into mathematics learning can provide a relevant and engaging context. Therefore, innovative approaches that bridge abstract mathematical concepts and concrete experiences are essential for improving students' understanding.

The integration of cultural context and digital technology offers a promising direction for improving mathematics learning. Ethnomathematics is an approach that connects mathematical concepts with cultural practices, allowing students to learn mathematics through familiar and meaningful contexts (Sari et al., 2023). This approach not only enhances conceptual understanding but also strengthens students' cultural awareness and identity. One example of cultural context that can be utilized in mathematics learning is music, which contains structured and repetitive patterns (Azaryahu et al., 2023; Budiawan & Ananda, 2023; Kabuye Batiibwe, 2024). Hadroh music, in particular, presents rhythmic patterns that can be interpreted mathematically as number sequences. This characteristic makes it suitable as a contextual medium for learning number patterns. In addition to cultural integration, the use of digital learning media has become increasingly important in modern education. Digital comics are one form of interactive media that combines visual, narrative, and multimedia elements (Chen et al., 2026; Fernández, 2023). This type of media can present abstract mathematical concepts in a more concrete and engaging way. Digital comics also support independent learning by allowing students to explore content at their own pace. Furthermore, such media can enhance students' motivation and engagement during the learning process. Therefore, combining ethnomathematics with digital comic media has the potential to create an effective and meaningful learning experience.

Previous studies have widely explored numeracy skills as predictors of mathematical competence and their development through various instructional approaches, including early interventions, game-based learning, and contextual pedagogies (Lopez-Pedersen et al., 2023; Seitz & Weinert, 2022; Singh et al., 2021). At the same time, ethnomathematics has been extensively investigated as a culturally responsive approach that enhances students' conceptual understanding by connecting mathematics with local cultural practices (Lidinillah et al., 2022; Prahmana & D'Ambrosio, 2020; Sari et al., 2023). In addition, digital comics have been recognized as effective technology-based learning media that improve students' engagement and literacy across different domains (Fitria et al., 2023; Linardatos & Apostolou, 2023). However, these research streams largely

remain isolated, with most studies focusing on only one or two aspects without integrating them into a comprehensive learning framework. Specifically, limited studies have combined ethnomathematics and digital comic media within a single instructional design, particularly in mathematics learning contexts. Furthermore, although cultural integration has been explored, the use of music-based cultural representations such as hadroh as a medium for modeling mathematical concepts remains underexplored. Moreover, research that simultaneously addresses both numeracy skills and self-regulated learning within a technology-integrated and culturally grounded approach is still scarce. Therefore, there is a significant research gap in developing and evaluating an integrated learning medium that combines ethnomathematics, digital comics, and culturally relevant contexts to holistically enhance students' numeracy skills and learning autonomy.

Based on the background and identified research gap, this study aims to develop a technology-integrated ethnomathematics digital comic using a hadroh music context in mathematics learning. This study focuses on creating an innovative learning medium that integrates cultural relevance and digital technology to support meaningful learning experiences. The developed digital comic is designed to present number pattern concepts in a contextual and engaging manner. In addition, this study aims to evaluate the quality of the developed product in terms of its validity, practicality, and effectiveness. The validity aspect is assessed to ensure that the content and design of the media are appropriate and aligned with learning objectives. The practicality aspect is evaluated based on students' and teachers' responses to the usability of the media in the learning process [need citation]. Furthermore, the effectiveness of the digital comic is examined through its impact on students' numeracy skills. This study also aims to investigate how the use of digital comic media influences students' self-regulated learning. By integrating cultural context and technology, this research seeks to provide a more engaging and meaningful learning environment. Ultimately, this study is expected to contribute to the development of innovative mathematics learning media that support 21st-century education.

## LITERATURE REVIEW

Mathematics education in the 21st century emphasizes the development of higher-order thinking skills, including critical thinking, problem-solving, and reasoning abilities. Among these competencies, numeracy skills are considered fundamental because they enable students to apply mathematical concepts in real-life situations. Numeracy is not limited to arithmetic proficiency but also involves the ability to interpret data, analyze patterns, and make informed decisions (Díez-Palomar et al., 2023; Gal et al., 2020; Hoogland, 2023; Reyna & Brainerd, 2023). The development of numeracy skills is closely linked to students' understanding of mathematical concepts and their ability to transfer knowledge across contexts (Díez-Palomar et al., 2023; Litkowski et al., 2020; Manfreda Kolar & Hodnik, 2021). However, many students still experience difficulties in applying mathematics meaningfully, particularly when dealing with contextual problems. This issue is often attributed to traditional teaching approaches that focus on procedural knowledge rather than conceptual understanding. As a result, students tend to memorize formulas without fully understanding their applications. Effective mathematics learning should therefore provide opportunities for students to engage actively in constructing their own understanding (Koskinen & Pitkäniemi, 2022; Lugosi & Uribe, 2022; Polman et al., 2021; Vale & Barbosa, 2023). This requires instructional approaches that emphasize context, relevance, and meaningful learning experiences. Consequently, innovative teaching strategies are needed to enhance students' numeracy skills in a comprehensive manner.

One approach that has gained attention in mathematics education is ethnomathematics, which integrates mathematical concepts with cultural practices. Ethnomathematics provides a contextual

learning environment where students can relate mathematical ideas to their daily experiences and cultural backgrounds (Payadnya et al., 2024; Sari et al., 2023). This approach helps students perceive mathematics as a meaningful and relevant discipline rather than an abstract subject. By connecting mathematics with culture, students are more likely to develop deeper conceptual understanding and increased motivation to learn. Ethnomathematics also supports the preservation of cultural heritage by incorporating local knowledge into formal education (Batiibwe, 2025). In addition, it promotes inclusivity by recognizing diverse cultural perspectives in mathematics learning. The use of cultural contexts in teaching mathematics has been shown to improve student engagement and participation (Alrajeh & Shindel, 2020; Anyichie et al., 2023; Lo & Hew, 2021; Shé et al., 2023). Students become more actively involved in learning when they recognize familiar elements within the instructional content. Furthermore, ethnomathematics fosters a sense of identity and belonging, which can positively influence learning outcomes. Therefore, integrating ethnomathematics into mathematics education is considered a promising strategy for enhancing both cognitive and affective aspects of learning.

In the context of ethnomathematics, cultural elements such as music can be used as meaningful representations of mathematical concepts. Music contains patterns, rhythms, and structures that can be analyzed mathematically. These characteristics make music an effective medium for illustrating concepts such as sequences, patterns, and ratios. Hadroh music, in particular, presents repetitive rhythmic patterns that can be modeled into number sequences. This allows students to explore mathematical concepts through auditory and experiential learning. By using music as a learning context, students can better understand abstract ideas through concrete representations. This approach also supports multimodal learning by engaging multiple senses during the learning process. Furthermore, integrating music into mathematics learning can increase students' interest and motivation. It creates a more enjoyable learning environment that encourages active participation. The use of culturally relevant music also strengthens the connection between learning and students' everyday lives. Therefore, incorporating music-based ethnomathematics can provide an innovative and effective approach to mathematics learning.

In addition to cultural integration, the use of digital learning media has become increasingly important in modern education. Technology offers opportunities to design interactive and engaging learning environments that support diverse learning styles (Cheung et al., 2021; Dixit et al., 2024; El-Sabagh, 2021; Kumi-Yeboah et al., 2020). One type of digital media that has shown potential in education is the digital comic. Digital comics combine visual illustrations, narratives, and interactive elements to present information in an accessible and engaging way (Çeken, 2025; Chen et al., 2026; Kumar & Dhar, 2024). This format is particularly effective for explaining abstract concepts, as it provides concrete visual representations. Digital comics also support self-paced learning, allowing students to control the pace and sequence of their learning activities (Boucher et al., 2025; Chen et al., 2026; Tong et al., 2022). This feature is essential for fostering self-regulated learning, where students take responsibility for their own learning process. Moreover, digital comics can incorporate multimedia elements such as audio and animation to enhance understanding. These features can improve student engagement and motivation during learning activities. The integration of digital media in mathematics education also aligns with the demands of 21st-century learning. Therefore, digital comics are considered a valuable tool for enhancing both learning outcomes and student autonomy.

Self-regulated learning is another important aspect of modern education that influences students' academic success. It refers to students' ability to plan, monitor, and evaluate their own learning processes. Students with strong self-regulated learning skills are more independent, motivated, and capable of managing their learning effectively. In mathematics learning, self-regulated learning plays a crucial role in helping students overcome difficulties and persist in

problem-solving. However, many students still rely heavily on teacher guidance and lack the initiative to learn independently. This condition indicates the need for learning environments that support autonomy and active engagement. The integration of ethnomathematics and digital comic media offers a potential solution to address this issue. By providing contextual and interactive learning experiences, students are encouraged to explore concepts independently. The combination of cultural relevance and digital interactivity can enhance both motivation and learning responsibility. This integrated approach not only improves numeracy skills but also fosters learning independence. Therefore, developing a learning medium that combines ethnomathematics, digital comics, and music-based context is expected to provide a comprehensive solution for improving mathematics learning.

## METHOD

### Research Design

This study employed a Research and Development (R&D) approach aimed at designing and evaluating a technology-integrated ethnomathematics digital comic based on a hadroh music context. The development process followed the 4D model, which consists of four systematic stages: Define, Design, Develop, and Disseminate. The Define stage involved conducting a needs analysis, including front-end analysis, student characteristics analysis, concept analysis, and formulation of learning objectives. The Design stage focused on developing the initial prototype of the digital comic, including the integration of ethnomathematics concepts, visual design, and the preparation of evaluation instruments. The Develop stage included expert validation, product revision, and limited trials to assess the quality of the developed media. The Disseminate stage involved distributing the final product through teacher forums and digital platforms. This model was selected because it provides a structured framework for developing instructional media that meets the criteria of validity, practicality, and effectiveness. In addition to product development, this study also incorporated a quasi-experimental design to evaluate the effectiveness of the developed media. The design involved an experimental group and a control group to compare learning outcomes. This approach allowed for a comprehensive evaluation of both the product quality and its impact on students' learning. Therefore, the research design integrates development and experimental evaluation to ensure robust findings.

### Participant

The participants in this study were Grade VIII students from SMP Negeri 1 Pekuncen during the 2025/2026 academic year. The sample consisted of two classes selected using cluster random sampling to ensure representativeness and minimize selection bias. The experimental group (Class VIII-B) consisted of 32 students who used the ethnomathematics digital comic based on hadroh music, while the control group (Class VIII-A) also consisted of 32 students who received conventional instruction. The participants were chosen based on their relatively similar academic backgrounds and learning conditions. In addition to students, this study involved several expert validators to assess the quality of the developed product. These experts included a mathematics education lecturer, a media expert, a subject matter expert, and a practicing mathematics teacher. Their involvement ensured that the digital comic met both pedagogical and technical standards. Teachers also participated in providing feedback regarding the usability and practicality of the media in classroom settings. The inclusion of multiple participants allowed for a more comprehensive evaluation of the product. Furthermore, the diversity of participants helped ensure that the findings were applicable to real classroom conditions. Therefore, the selected participants were appropriate for achieving the objectives of the study.

## Instrument

Data were collected using a combination of qualitative and quantitative instruments to ensure comprehensive analysis. The instruments used in this study included interview guidelines, needs assessment questionnaires, expert validation sheets, response questionnaires, observation sheets, self-regulated learning questionnaires, and numeracy tests. Interview guidelines were used to explore initial information related to students' learning difficulties and perceptions of cultural integration in learning. Needs assessment questionnaires were administered to identify students' and teachers' expectations regarding culturally based learning media. Expert validation sheets were used to evaluate the feasibility of the product in terms of content, media design, language, and integration of ethnomathematics. Response questionnaires were used to measure the practicality and attractiveness of the digital comic based on feedback from students and teachers. The self-regulated learning questionnaire was designed based on indicators such as planning, monitoring, control, and reflection. The numeracy test was used to measure students' ability to understand number patterns in a cultural context. An example of the test item required students to analyze rhythmic patterns in hadroh music and determine sequence patterns. Scoring for the numeracy test ranged from 0 to 4 based on accuracy and problem-solving process, while questionnaires used a Likert scale from 1 to 5. Instrument validity was assessed through expert judgment and empirical testing using Pearson correlation, while reliability was tested using Cronbach's Alpha. The data collection process was conducted through pretest and posttest procedures to measure learning improvement. Therefore, the instruments were designed to capture both learning outcomes and learning processes comprehensively.

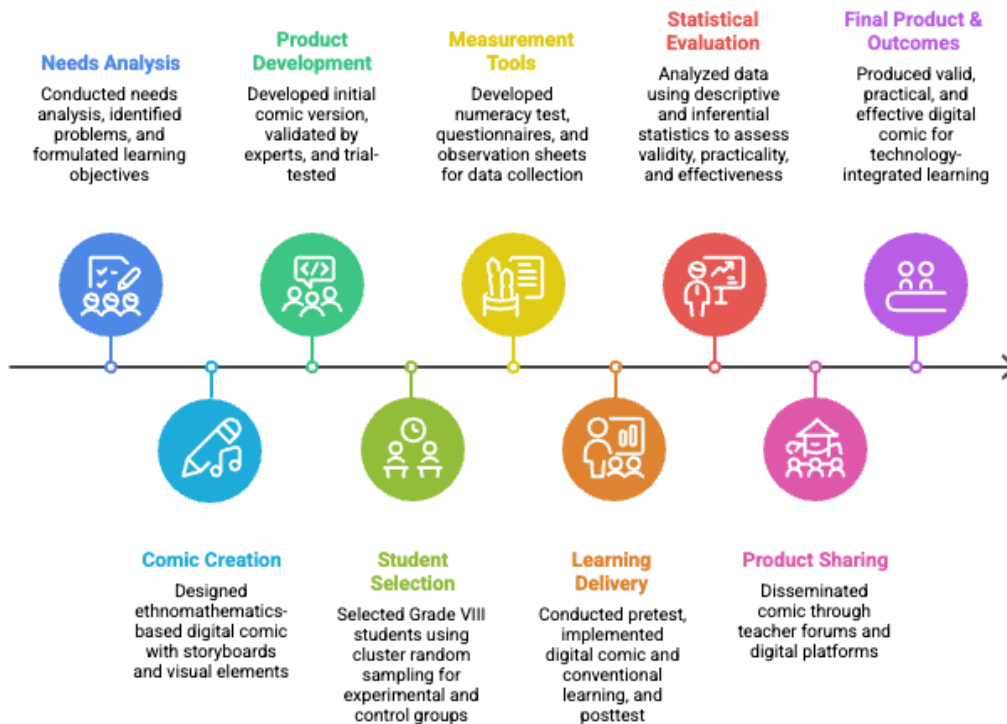
## Data Analysis

The data collected in this study were analyzed using both descriptive and inferential statistical techniques. Descriptive analysis was used to summarize validation results, questionnaire responses, and overall student performance. The validity and practicality of the digital comic were determined based on percentage scores categorized into predefined criteria. Inferential analysis was conducted to evaluate the effectiveness of the developed media. Prior to hypothesis testing, prerequisite tests were performed, including normality and homogeneity tests. The normality test was conducted using the Kolmogorov-Smirnov and Shapiro-Wilk tests to determine whether the data were normally distributed. The homogeneity test was conducted using Levene's test to examine the equality of variances. To evaluate the effectiveness of the intervention, paired sample t-tests were used to analyze improvements within each group. Independent sample t-tests were used to compare the differences between the experimental and control groups. The level of significance was set at 0.05. If the data did not meet the assumptions of normality, non-parametric tests such as the Mann-Whitney U test were used as alternatives. The hypotheses tested included the presence or absence of significant differences in numeracy skills and self-regulated learning between the two groups. Therefore, the data analysis ensured statistical rigor and accurate interpretation of results.

## Procedure

The research procedure followed the stages of the 4D model in a systematic manner. In the Define stage, the researchers conducted observations, interviews, and questionnaires to identify problems related to students' numeracy skills and learning independence. The findings indicated that students experienced difficulties in understanding number patterns and relied heavily on conventional teaching methods. In the Design stage, the digital comic was developed by creating storyboards, visual layouts, and integrating hadroh music patterns into mathematical concepts. The design also included the development of evaluation instruments to measure learning outcomes. In the Develop stage, the initial product was validated by experts and revised based on their feedback. A limited trial was conducted to assess the practicality and usability of the digital comic. Afterward,

the product was implemented in the experimental class using a quasi-experimental design. Pretest and posttest were conducted to measure students' numeracy skills and self-regulated learning before and after the intervention. The control group received conventional instruction for comparison purposes. In the Disseminate stage, the final product was introduced through teacher forums and shared via digital platforms such as LMS and online media. The entire procedure was carried out within a structured timeframe to ensure consistency. Therefore, the research procedure ensured a systematic and comprehensive implementation of both development and evaluation processes.



**Figure 1.** Research method flow

## RESULTS AND DISCUSSION

### Results

The development of the ethnomathematics-based digital comic using a hadroh music context was carried out through the 4D model, consisting of the Define, Design, Develop, and Disseminate stages. Each stage produced findings that support the feasibility and effectiveness of the developed learning media. The results are presented sequentially according to the stages of development and the statistical analyses conducted. In the Define stage, the needs analysis showed that mathematics learning in Grade VIII at SMP Negeri 1 Pekuncen was still dominated by conventional instruction, with minimal use of digital media. Students also showed limited independence in learning, as they relied heavily on teacher explanations and rarely explored learning materials independently. These findings indicate the need for an innovative learning medium that is more engaging, contextual, and capable of promoting autonomous learning. In response to these needs, an ethnomathematics digital comic was developed to support the teaching of number patterns through a culturally relevant context. The product was designed to make abstract mathematical concepts easier to understand by connecting them with rhythmic structures found in hadroh music. Therefore, the Define stage confirmed the relevance of developing this medium as an instructional innovation.

Student analysis further revealed that most learners were around 13 years old and were already familiar with digital technology in their daily lives. However, their use of technology for educational purposes remained limited. Students were more accustomed to relying on textbooks and

teacher explanations than exploring digital resources independently. This condition suggested that an interactive digital medium would be appropriate for their learning characteristics. Concept analysis also showed that the number pattern topic required students to understand patterns in number sequences, generalize relationships, interpret object configurations, and solve contextual problems. Based on this analysis, the learning objectives were formulated to ensure that students would be able to understand, generalize, and apply number pattern concepts in meaningful contexts. These objectives became the basis for the design of the digital comic. Thus, the Define stage provided a clear foundation for subsequent product development.

In the Design stage, the initial prototype of the digital comic was prepared by determining its format, content organization, and learning components. The media was designed in a digital format that could be accessed through smartphones and webtoon-style interfaces, making it suitable for students' technological habits. Interactive features such as panel navigation, visual illustrations, and hadroh rhythm audio were incorporated to strengthen the connection between mathematics and culture. The storyboard and narrative were constructed to guide students gradually from introductory contexts to mathematical pattern recognition and problem solving. In addition, evaluation instruments were designed to assess students' numeracy skills and self-regulated learning after the intervention. This stage resulted in a structured digital comic framework that combined visual, narrative, cultural, and mathematical elements into a coherent learning medium. The main components of the product design are presented in Table 1.

**Table 1.** Design components of the ethnomathematics digital comic

No.	Design Component	Description
1	Cover	Cover of the ethnomathematics digital comic based on hadroh music
2	Learning outcomes	Learning outcomes to be achieved through the digital comic
3	Introductory dialogue	Introductory conversation for learning number patterns through hadroh music
4	Learning illustration	Illustration of number pattern learning through observing hadroh sounds
5	Numeracy task	Number pattern numeracy questions linked to hadroh music

To strengthen the presentation of the design stage, the visual appearance of the developed product should be placed immediately after the explanation of its components. The figure may include the comic cover, sample panels, contextual illustrations, and examples of numeracy tasks embedded in the digital comic. This figure functions as visual evidence of how the mathematical content was integrated with the hadroh music context. Therefore, the product visualization should be positioned after Table 1 to provide a clearer representation of the developed learning medium. The Develop stage focused on product validation, revision, and limited trials. Expert validation results showed that the developed digital comic met the criteria of a feasible instructional medium. The media expert gave a score of 84%, which was categorized as very valid, indicating that the visual design, layout, and interactivity of the comic were highly appropriate. Meanwhile, the material expert gave a score of 77.7%, categorized as valid, showing that the mathematical content and its integration with ethnomathematics were suitable for classroom use. These results indicate that the product had a satisfactory level of quality before classroom implementation. The validation results are summarized in Table 2.

**Table 2.** Expert validation results

Validator	Percentage (%)	Category
Media expert	84.0	Very valid
Material expert	77.7	Valid

The practicality of the digital comic was then examined through teacher and student response questionnaires. Teacher responses ranged from 61% to 78%, indicating that the media was considered effective and useful in supporting mathematics learning. Student responses yielded an average score of 85.8%, categorized as very effective and very useful. These findings suggest that the digital comic was positively received by both teachers and students and was practical for classroom implementation. In particular, students perceived the media as attractive, accessible, and supportive of their learning process. The practicality results are shown in Table 3 and Table 4.

**Table 3.** Teacher response questionnaire results

Respondent	Percentage (%)	Category
Wah	74	Effective and useful
Ptr	78	Effective and useful
Lin	61	Effective and useful
Prs	78	Effective and useful

**Table 4.** Students response questionnaire results

Respondent	Percentage (%)	Category
Trial class	85.8	Very effective and very useful

In addition to validity and practicality, the effectiveness of the digital comic was evaluated through students' numeracy performance and self-regulated learning scores. The initial descriptive analysis showed that the experimental group outperformed the control group in both variables. The mean numeracy score of the experimental group was 78.2815, whereas the control group achieved 55.6250. Similarly, the average self-regulated learning score of the experimental group was 64.6563, which was higher than the control group mean of 58.7813. These results indicate a positive trend in favor of the digital comic intervention. The descriptive statistics are presented in Table 5.

**Table 5.** Descriptive statistics of numeracy skills and self regulated learning

Variable	Group	Mean	Standard Deviation	N
Numeracy score	Experimental	78.2815	16.39283	32
Numeracy score	Control	55.6250	22.56710	32
Self-regulated learning	Experimental	64.6563	11.65252	32
Self-regulated learning	Control	58.7813	11.38118	32

To complement the descriptive presentation, a bar chart comparing the mean scores of the experimental and control groups for both variables should be placed after Table 5. This figure would help readers visually identify the difference in performance between the two groups. It would also make the results section more accessible and visually informative. Before conducting inferential analysis, normality and homogeneity tests were performed. The Shapiro-Wilk results showed significance values above 0.05 for all variables in both groups, indicating that the data were normally distributed. For numeracy scores, the significance values were 0.231 in the experimental group and 0.254 in the control group. For self-regulated learning, the values were 0.149 and 0.577, respectively. These results confirm that the assumption of normality was satisfied. The normality test results are presented in Table 6.

**Table 6.** Normality test results

Variable	Group	Kolmogorov-Smirnov Sig.	Shapiro-Wilk Sig.
Numeracy	Experimental	0.200	0.231
Numeracy	Control	0.200	0.254
Self-regulated learning	Experimental	0.200	0.149
Self-regulated learning	Control	0.200	0.577

The homogeneity test using Levene's Test also showed that the data met the assumption of equal variance. The significance value for numeracy was 0.058, while the value for self-regulated learning was 0.640. Since both values were greater than 0.05, the variance between groups could be considered homogeneous. This result justified the use of parametric tests for further analysis. The homogeneity results are presented in Table 7.

**Table 7.** Homogeneity test results

Variable	Levene Statistic	df1	df2	Sig.
Numeracy	3.718	1	62	0.058
Self-regulated learning	0.221	1	62	0.640

The independent samples t-test was then conducted to determine whether the differences between the experimental and control groups were statistically significant. For numeracy, the significance value was 0.058, which is slightly above the 0.05 threshold. This indicates that the difference in numeracy scores between groups was not statistically significant, although the experimental group showed a higher mean score. For self-regulated learning, the significance value was 0.046, indicating a statistically significant difference between the two groups. Thus, the digital comic intervention had a significant effect on students' self-regulated learning, while its effect on numeracy was positive but not statistically significant. The results of the independent samples t-test are shown in Table 8 and Table 9.

**Table 8.** Independent samples t-test results for numeracy

Variable	Levene's Sig.	T	df	Sig. (2-tailed)	Interpretation
Numeracy	0.058	2.250	62	0.058	Not statistically significant

**Table 9.** Independent samples t-test results for self regulated learning

Variable	Mean Difference	Std. Error Difference	Sig. (2-tailed)	Interpretation
Self-regulated learning	5.87500	2.87941	0.046	Statistically significant

Finally, a MANOVA test was conducted to determine whether there was a simultaneous difference between the experimental and control groups when numeracy and self-regulated learning were considered together. The results showed that the multivariate significance value was 0.017 across Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root. Since this value was below 0.05, it can be concluded that there was a statistically significant multivariate effect of the intervention. This means that the digital comic had a combined impact on the two dependent variables. The MANOVA results are presented in Table 10.

**Table 10.** MANOVA results

Effect	Test	Value	F	Hypothesis df	Error df	Sig.
Class	Pillai's Trace	0.125	4.360	2.000	61.000	0.017
Class	Wilks' Lambda	0.875	4.360	2.000	61.000	0.017
Class	Hotelling's Trace	0.143	4.360	2.000	61.000	0.017
Class	Roy's Largest Root	0.143	4.360	2.000	61.000	0.017

Overall, the findings indicate that the ethnomathematics-based digital comic integrating hadroh music was valid, practical, and effective in supporting mathematics learning. The product showed strong feasibility based on expert validation and positive user responses. The descriptive results revealed higher performance in the experimental group for both numeracy and self-regulated learning. Inferential analysis further confirmed that the intervention significantly improved self-regulated learning and produced a significant combined effect across the two dependent variables. Although the difference in numeracy was not statistically significant at the 0.05 level, the higher mean score in the experimental group suggests a favorable instructional trend. Therefore, the developed digital comic demonstrates substantial potential as an innovative medium for culturally responsive and technology-enhanced mathematics learning.

## Discussion

The findings of this study provide strong evidence that the development of an ethnomathematics-based digital comic integrating hadroh music constitutes an effective instructional innovation for improving students' numeracy skills and self-regulated learning. This effectiveness can be attributed to the synergy between culturally responsive pedagogy and interactive digital media, which together create a meaningful and engaging learning environment (Cheng et al., 2021, 2022; Engerman & Otto, 2021). The integration of local cultural elements allows abstract mathematical concepts to be presented in a more concrete and relatable form, thereby reducing cognitive barriers (Ntumi et al., 2026; Payadnya et al., 2025). At the same time, the use of digital comic media enhances student engagement through visual, narrative, and interactive features. This dual approach aligns with contemporary learning theories that emphasize contextualization and learner-centered environments. Compared to conventional instruction, which often relies on symbolic and procedural teaching, the developed media provides a richer and more dynamic learning experience. The results indicate that students exposed to the digital comic demonstrated better engagement and learning outcomes than those in traditional settings. These findings reinforce the importance of combining pedagogical innovation with technological integration. Furthermore, they highlight the relevance of local culture as a powerful resource in mathematics education. Therefore, the study contributes to bridging the gap between abstract mathematical instruction and students' lived experiences.

The improvement in numeracy skills observed in the experimental group indicates that contextual learning through ethnomathematics can enhance students' conceptual understanding. Although the statistical significance of the improvement was limited, the higher mean scores suggest a meaningful instructional impact. The contextualization of number patterns using hadroh music enables students to visualize and interpret mathematical relationships more effectively (Hibi, 2025). This finding is consistent with prior studies that emphasize the role of contextual and culturally relevant learning in improving mathematical understanding. The rhythmic patterns in hadroh music serve as a concrete representation of number sequences, allowing students to engage in pattern recognition and generalization processes (Budiawan & Ananda, 2023). Compared to traditional approaches that rely heavily on symbolic representation, this method provides a more intuitive learning experience. The use of HOTS-based tasks within the digital comic also supports the development of higher-order thinking skills. Previous research has shown that ethnomathematics can enhance students' motivation and learning outcomes, and the present study extends this by embedding it within a digital platform. In addition, the combination of visual and auditory elements further supports multimodal learning. This suggests that the integration of culture and media can significantly enhance the effectiveness of mathematics instruction. Therefore, the observed improvement in numeracy reflects the potential of this integrated approach.

The significant improvement in self-regulated learning further demonstrates the effectiveness of the digital comic as an instructional medium. The interactive nature of the media encourages students to take an active role in their learning process, which is essential for developing autonomy (Díaz-Noguera et al., 2022; Han, 2021; Susanti et al., 2023; Tsai, 2021). Features such as narrative flow, visual guidance, and interactive navigation enable students to learn at their own pace. This aligns with the principles of differentiated learning, where students are given flexibility in accessing and processing information. Compared to conventional learning environments, which often limit student autonomy, the digital comic provides opportunities for independent exploration (Apostolou & Linardatos, 2023; Bachri et al., 2023). The inclusion of reflective elements within the comic also supports students in monitoring and evaluating their own learning progress. Previous studies have highlighted the potential of digital media in enhancing motivation and engagement, but fewer studies have explicitly linked these features to self-regulated learning outcomes. The present study contributes by demonstrating that digital comics can effectively support the development of learning independence. In addition, the integration of cultural context enhances students' emotional engagement with the content. This emotional connection can further motivate students to engage in self-directed learning. Therefore, the improvement in self-regulated learning confirms the effectiveness of the digital comic as a learner-centered instructional tool.

The combined improvement in numeracy skills and self-regulated learning highlights the broader contribution of the ethnomathematics digital comic. By integrating cultural context, digital technology, and pedagogical design, the developed media addresses both cognitive and affective aspects of learning. This holistic approach distinguishes the present study from previous research that often examines these components separately. The use of hadroh music as a cultural context introduces a novel dimension that enriches the learning experience. Unlike visual cultural artifacts commonly used in ethnomathematics studies, music provides a dynamic and temporal representation of mathematical patterns. This allows students to experience mathematics through multiple sensory modalities. The digital comic format further enhances this experience by combining text, images, and audio into a unified learning medium (Cotiangco et al., 2024; Rutta et al., 2021). This multimodal approach is particularly suitable for contemporary learners, who are accustomed to digital and interactive environments. In comparison with traditional textbooks, the digital comic offers a more engaging and flexible learning platform. The findings suggest that such integration can significantly improve both learning outcomes and student engagement. Therefore, the study provides valuable insights into the design of innovative mathematics learning media.

Overall, this study contributes to the advancement of mathematics education by demonstrating the potential of integrating ethnomathematics and digital media. The results support the growing body of research that emphasizes the importance of contextual and technology-enhanced learning. Compared to conventional teaching approaches, the developed media offers greater opportunities for engagement, understanding, and independent learning. The findings also highlight the importance of cultural relevance in making learning more meaningful and accessible. However, the study also indicates that the impact on numeracy may require longer implementation periods to achieve statistically significant results. Future research could explore the long-term effects of similar interventions and their application in different educational contexts. In addition, further development of interactive features could enhance the effectiveness of the digital comic. Comparative studies involving larger samples would also provide more robust evidence. Despite these limitations, the present study offers a strong foundation for further innovation in mathematics education. Therefore, the integration of culture and technology should be considered a key strategy in developing effective learning environments.

## Implications

The findings of this study have important implications for the development of mathematics education, particularly in integrating cultural context and digital technology into classroom learning. The use of ethnomathematics-based digital comics demonstrates that culturally relevant content can enhance students' engagement and conceptual understanding of abstract mathematical topics. This suggests that teachers should consider incorporating local cultural elements into instructional design to make learning more meaningful and relatable for students. In addition, the successful integration of hadroh music as a contextual representation indicates that non-traditional cultural forms, including music, can be effectively utilized to support mathematical reasoning. The positive impact on self-regulated learning highlights the role of interactive digital media in promoting student autonomy and active participation in learning. Therefore, educators are encouraged to adopt technology-enhanced learning tools that support independent learning processes. From a curriculum perspective, these findings support the implementation of the Merdeka Curriculum, which emphasizes contextual learning and the development of essential competencies such as numeracy and learner independence. The study also implies that the design of instructional media should consider multimodal elements, including visual, narrative, and auditory features, to accommodate diverse learning styles. Furthermore, the results indicate that combining pedagogical innovation with digital platforms can create more flexible and accessible learning environments. For policymakers, this study provides evidence that investment in culturally responsive and technology-based learning resources can improve the quality of education. For future research, the findings suggest the need to explore the long-term impact of such media on students' cognitive and affective development. Overall, this study underscores the importance of integrating culture, technology, and pedagogy to create effective and sustainable learning innovations in mathematics education.

## Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting the findings and planning subsequent research. First, the duration of the intervention was relatively short, which may have limited the observable impact on students' numeracy skills, particularly in achieving statistical significance. Second, the sample size was restricted to two classes within a single school, which may affect the generalizability of the results to broader educational contexts. Third, the study focused only on the topic of number patterns, so the effectiveness of the ethnomathematics digital comic in other mathematical topics remains unexplored. Fourth, the integration of hadroh music as a cultural context, while innovative, represents a specific local culture that may not be directly applicable to different regions or cultural settings. Fifth, the study relied primarily on quantitative measures and limited observational data, which may not fully capture the depth of students' learning experiences and cognitive processes. Sixth, students' familiarity with digital media varied, which may have influenced their interaction with the digital comic and affected the outcomes. Seventh, the novelty effect of using a new learning medium may have contributed to increased engagement, potentially influencing the results independently of the instructional design. Based on these limitations, future research is recommended to implement longer intervention periods to examine sustained effects on numeracy development. In addition, studies involving larger and more diverse samples across multiple schools are needed to enhance the generalizability of the findings. Future research could also explore the application of ethnomathematics digital comics in different mathematical topics and educational levels. Furthermore, integrating qualitative methods such as interviews and learning analytics would provide deeper insights into students' cognitive and behavioral changes. Finally, comparative studies using different cultural contexts and more advanced interactive features are suggested to further refine and expand the potential of culturally responsive digital learning media.

## CONCLUSION

This study concludes that the development of an ethnomathematics-based digital comic integrating hadroh music represents a valid, practical, and effective innovation in mathematics learning. The development process using the 4D model successfully produced a learning medium that aligns with instructional objectives and students' characteristics. The validation results from experts indicate that the content and media design meet appropriate quality standards for classroom implementation. The practicality findings further demonstrate that both teachers and students respond positively to the use of the digital comic in learning activities. The effectiveness analysis shows that the digital comic contributes to improved learning outcomes, particularly in enhancing students' self-regulated learning. Although the improvement in numeracy skills was not statistically significant, the higher mean scores in the experimental group indicate a positive instructional impact. This suggests that the integration of cultural context and digital media can support conceptual understanding of mathematical concepts. The use of hadroh music as a contextual representation provides a meaningful way to bridge abstract mathematical ideas with real-life experiences. Furthermore, the digital comic format supports student engagement through visual, narrative, and interactive elements. These features also promote independent learning by allowing students to explore content at their own pace. Overall, the study highlights the importance of combining ethnomathematics and technology in creating effective learning environments. Therefore, the developed digital comic can be considered a promising approach for supporting 21st-century mathematics education.

## AUTHOR CONTRIBUTIONS STATEMENT

Kartika Rusiyaningsih designed the study, developed the technology-integrated ethnomathematics digital comic using hadroh music context, and led the analysis of students' numeracy skills and self-regulated learning outcomes. Gunawan contributed to the conceptual and methodological framework, refined the theoretical background, and supported the interpretation of statistical findings and research results. All authors contributed to writing, reviewed the manuscript critically for important intellectual content, and approved the final version.

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