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ORIGINAL

Integrated Project-Based Learning (PIL) with STEM and Ethnomathematics "Sipak Rago" and "Lari dan Beku" in Junior High Schools with bibliometric and experiments in Junior High Schools

Aprendizaje basado en proyectos integrados (PIL) con STEM y etnomatemáticas "Sipak Rago" y "Lari dan Beku" en la escuela secundaria con bibliometría y experimentos en la escuela secundaria

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ABSTRACT

The PIL model was chosen because it offers the potential to encourage student engagement in constructing Knowledge through investigation and real-world project completion. The real-world projects were embodied in traditional games from Minangkabau and Malay cultures. Sipak rago was chosen as a traditional Minangkabau (Indonesia) game to explore the concept of the surface area of a sphere. Meanwhile, the lari and beku game from the Malay (Malaysia) tradition provided a context for students to understand the relationships between complementary, supplementary, and reflex angles. This study aims to design learning tools using the Project-based Inquiry Learning (PIL) model integrated with STEM and ethnomathematics. A validation study was chosen as it is the appropriate method for this research. The subjects of the study were nine students selected from three different schools in Padang city. The data were collected using interview guidelines, journals, and observation sheets. Data analysis was conducted by transcribing the interviews, reducing the data, presenting it, and drawing conclusions. The results of the study show that regardless of whether the culture used matches the students' own culture, they are still able to solve the given mathematical problems. The implication of this research highlights the potential of STEM-based PIL integrated with ethnomathematics as an innovative approach that can be adopted into the national curriculum to enhance students' STEM literacy and cultural identity.

Keywords: Project-based Inquiry Learning; STEM; Ethnomathematics; Validation Study; Traditional Game.

RESUMEN

Se eligió el modelo PIL porque ofrece la posibilidad de fomentar la participación de los estudiantes en la construcción del conocimiento a través de la investigación y la realización de proyectos del mundo real. Los proyectos del mundo real se plasmaron en juegos tradicionales de las culturas minangkabau y malaya. Se eligió el sipak rago como juego tradicional minangkabau (Indonesia) para explorar el concepto de la superficie de una esfera. Por su parte, el juego lari y beku de la tradición malaya (Malasia) proporcionó un contexto para que los estudiantes comprendieran las relaciones entre los ángulos complementarios, suplementarios y reflejos. El objetivo de este estudio es diseñar herramientas de aprendizaje utilizando el modelo de aprendizaje basado en la investigación (PIL) integrado con STEM y etnomatemáticas. Se optó por un estudio de validación, ya que es el método adecuado para esta investigación. Los sujetos del estudio fueron nueve estudiantes seleccionados de tres escuelas diferentes de la ciudad de Padang. Los datos se recopilaron mediante guías de entrevista, diarios y hojas de observación. El análisis de los datos se llevó a cabo transcribiendo las entrevistas, reduciendo los datos, presentándolos y extrayendo conclusiones. Los resultados del estudio muestran que, independientemente de si la cultura utilizada coincide con la propia cultura de los estudiantes, estos son capaces de resolver los problemas matemáticos planteados. Las implicaciones de esta investigación ponen de relieve el potencial del aprendizaje basado en proyectos (PIL) integrado con la etnomatemática como enfoque innovador que puede adoptarse en el plan de estudios nacional para mejorar la alfabetización STEM y la identidad cultural de los estudiantes.

Palabras clave: Aprendizaje Basado en Proyectos; STEM; Etnomatemática; Estudio de Validación; Juego Tradicional.

INTRODUCTION

Mathematics education in schools is expected to focus not only on procedural mastery and calculation skills but also on fostering a strong conceptual understanding, as well as nurturing students' logical, systematic, and critical thinking abilities. Beyond that, mathematics learning should enable students to connect the material being studied with various real-life situations, so that mathematics is not perceived as an abstract discipline disconnected from reality.[1,2,3,4,5] According to Su, The learning process should be active, participatory, and stimulate students' curiosity through exploration and problem-solving activities.[6] Therefore, mathematics education should ideally serve as a platform for developing students' intellectual abilities while also shaping resilient, creative, and adaptive character traits in response to the demands of an ever-evolving world.[7,8,9]

However, mathematics education in schools still faces challenges in enhancing students' active engagement, conceptual understanding, and ability to apply Knowledge in real-life contexts.[10,11] Various studies have shown that the learning process tends to be procedural, teacher-centered, and lacks connection to cultural or multidisciplinary context.[12,13,14,15] This has led to low student motivation and learning outcomes, as well as underdeveloped 21st-century competencies.[16,17,18,19]

Twenty-first-century competencies, which include critical thinking, creativity, collaboration, and communication, are key to shaping individuals who are adaptive, innovative, and competitive in the digital era. According to Lestari, critical thinking enables students to analyze and solve problems in a rational manner.[20] Furthermore, Ndiung state that creative thinking encourages students to generate new and practical ideas.[21] Andrews-Todd emphasize that collaboration enhances the ability to work effectively in diverse teams.[22] Effective communication is essential for conveying ideas clearly and persuasively.[23] Unfortunately, various studies have shown that these competencies have not been fully integrated into classroom practices.[18,24,25] Therefore, research is needed to identify effective instructional strategies for developing these four competencies in an integrated manner within the educational process.

To address these challenges, the Project-based Inquiry Learning (PIL) model offers potential as an instructional approach that encourages active student engagement in constructing Knowledge through investigation and the completion of a real-world project.[26,27] According to Ng, when combined with the STEM (Science, Technology, Engineering, and Mathematics) approach, learning becomes more integrative and applicable, as it prompts students to connect mathematical concepts with other disciplines as well as with technology and engineering.[26] However, while the STEM approach in mathematics education already incorporates real-world contexts, it often overlooks meaningful local cultural values that are relevant to students.[28,29]

The integration of ethnomathematics serves as a strategic solution to contextualize mathematics learning within students' local cultures. Through ethnomathematics, students can understand mathematical concepts within cultural practices they are familiar with, making learning more relevant, inclusive, and meaningful.[13,29,30,31] Nurjanah state that while the use of ethnomathematics in education holds great potential, it is still rarely implemented systematically.[32] In the Minangkabau context, for instance, various structures and patterns found in traditional rumah gadang architecture, customary systems, traditional games, and woven arts contain mathematical principles. Meanwhile, in Malaysia, Indonesia's neighboring country, there is a culture similar to that of the Minangkabau. Cultural heritage, such as batik, wau (traditional kites), and wood carvings, also holds rich mathematical value that can be utilized in education. Both examples demonstrate that culture is not merely a social background but also a valuable source of Knowledge for learning.

The visualization results from the VosViewer application show the relationships often associated with mathematical critical thinking skills and terms that frequently appear in ethnomathematics research indexed in Scopus, which have been stored in RIS format. A total of 33 frequently occurring research topics were identified. The visualization results of the 33 topics after processing using VosViewer can be seen in the figure 1.

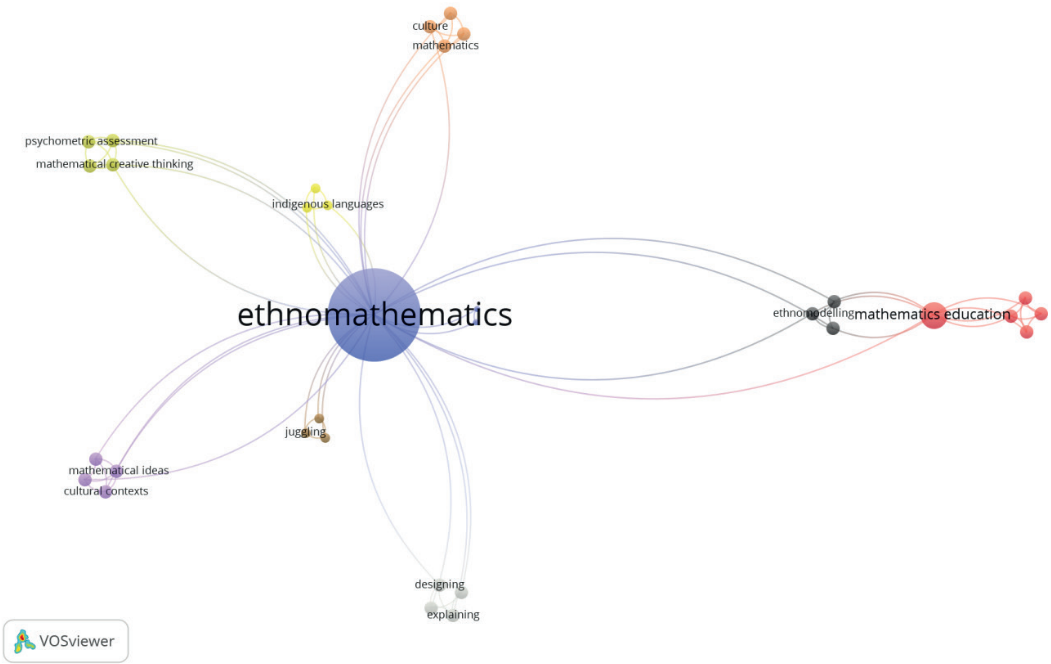


Figure 1. Network Visualization of Ethnomathematics Based on The Co-Occurrence of Author Keywords

Figure 1 shows the main keywords in ethnomathematics research divided into nine main clusters. These clusters are marked with nine colors that appear in the figure. The explanation of the nine clusters is as follows: Cluster 1, colored red, consists of five topics: meaningful learning onto-semiotic approach, preservative mathematics, mathematical and ethnomathematical connections. Cluster 2, orange, consists of 4 topics: global cultural bibliometric analysis, mathematics, and problem-solving. Cluster 3, gray, has 4 topics: designing, constraints, measuring, and explaining. Cluster 4, green, consists of 4 topics: Rasch analysis, secondary school students, mathematical creative thinking, and psychometric assessment. Cluster 5 is purple and consists of four topics: cultural contexts, mathematical ideas, mathematical ideas, and mathematical practice. Cluster 6 is blue and consists of three topics: ethnomathematics, Karawo Gorontalo tradition, and facing and direct isometry. Similar to Cluster 6, Cluster 7 also consists of 3 topics, namely indigenous languages, intercultural bilingual education, and randomized controlled trials, represented by the color yellow. Cluster 8 also consists of 3 topics, namely juggling, local knowledge, and models, represented by the color brown. Finally, cluster 9 consists of 3 topics, namely ethnomodeling, local culture, and realistic ethnographic design, represented by the color black. Based on the network visualization generated through VOSviewer analysis, close relationships between several terms in ethnomathematics research can be identified. Figure 1 shows the relationship between clusters with cluster 6 (Ethnomathematics) as the center. This reflects the development of ethnomathematics, which not only includes the relationship between cultural mathematics and mathematics but is also used in teaching methods, assessment, and mathematical abilities. These relationships indicate a shift toward the integration of ethnomathematics and collaborative learning methods, which promote flexible teaching models to enhance student engagement. This analysis identifies new trends in mathematics education, particularly the integration of culture and active learning.

The implementation of ethnomathematics in education should ideally be rooted in the students' own culture, as mathematical concepts become easier to understand when they are closely related to the students' experiences and environment.[32] However, it is also possible to introduce other cultures that share historical, geographical, or value-based similarities, such as Malay culture (Malaysia), which is closely related to the Minangkabau culture in Indonesia. In this context, the choice to integrate Minangkabau and Malay ethnomathematics is appropriate, as it not only reflects the local culture of Indonesian students but also broadens their understanding of the shared cultural heritage in Southeast Asia. Thus, learning becomes not only more contextual and meaningful but also fosters openness, tolerance, and appreciation for cultural diversity, as long as the introduced culture remains relevant and accessible to students.

Studies on the PIL model, STEM, and ethnomathematics are not new. Laššová state that the Math Trail approach in STEM education is effective in enhancing students' spatial abilities while creating engaging and meaningful learning experiences.[33] This approach encourages students to think critically, collaborate, and apply STEM concepts in real-world context.[33] In the study by Lasa, mathematical content is identified as a key element in the success of STEM activities, as it supports contextual and interdisciplinary understanding of concepts.[25] This highlights the importance of deliberately designing STEM activities to incorporate mathematical elements, thereby maximizing learning outcomes.[24,25,34] Beyond mathematics, Ng discuss the integration of STEM through a Project-Based Inquiry Learning (PIL) approach in a space-themed unit for first-grade students.[26] According to Ng, the PIL model, when integrated with STEM, enhances students' understanding of scientific concepts, critical thinking skills, and learning motivation through project-based learning that emphasizes exploration and inquiry.[26] In addition, Prahmana highlight that formal mathematics education in Indonesia is often inflexible and disconnected from students' socio-cultural contexts, despite Indonesia's rich cultural diversity that could serve as a starting point for learning.[30] Therefore, based on the previous explanations, there has been no study that explores the integration of the PIL model, STEM, and ethnomathematics in mathematics learning, as examined in this research.

The limited number of studies that develop mathematics learning by simultaneously integrating PIL, STEM, and ethnomathematics highlights a significant research gap that needs to be addressed. These three approaches have the potential to complement one another—PIL as an active and inquiry-based approach, STEM as an integrative cross-disciplinary framework, and ethnomathematics as a contextual, culture-based perspective. Therefore, there is a need for research that develops learning tools based on the Project-Based Inquiry Learning (PIL) model integrated with STEM and ethnomathematics to create mathematics learning that is more relevant, innovative, and transformative. This study aims to design learning tools based on the Project-Based Inquiry Learning (PIL) model, integrated with STEM and ethnomathematics, for junior high school students, and to examine students' responses to the use of these learning tools.

METHOD

This research is a validation study. The main objective is to validate the PIL, STEM, and Ethnomathematics-based teaching materials (lesson plans and student worksheets) and the teaching sequence, with validity dimensions covering content validity, construct validity, practicality, and fidelity of implementation. The stages in a validation study include preliminary design, experimental design, and retrospective analysis.[35,36] The process of the validation study is outlined in table 1.

Table 1. Proses Penelitian Validation Study

Validation Study Process	
Preliminary Design	The study begins with a review of the literature related to mathematics learning topics, including the surface area of spheres and angles, the Project-Based Inquiry Learning (PIL) model, the STEM approach, and the Minangkabau and Malaysian cultures. The researcher develops learning tools (lesson plans and student worksheets) using the PIL model integrated with STEM and ethnomathematics, incorporating traditional games such as *sipak rago* (Minangkabau) and *lari dan beku* (Malaysia). These learning tools are developed during the planning phase.
Experimental Design	The study consists of two main stages: the pilot experiment and the teaching experiment. The pilot experiment is conducted to test the learning tools, while the teaching experiment aims to evaluate the learning process. During the teaching experiment, the researcher observes students' learning activities throughout the lessons.
Retrospective Analysis	All data collected during these stages is then analyzed.

Sources: Harisman et al and Rahayu et al.[35,36]

The research was conducted in three public junior high schools in Padang City, West Sumatra, located in Padang Barat and Padang Utara. The schools selected as research subjects were SMPN 3 Padang, SMPN 25 Padang, and SMPN 7 Padang. The research activities were carried out for 3 days, namely 12 to 14 June 2025. The language of instruction was Indonesian language. Class sizes ranged from 28–32 students in grade 2nd of junior high school, with the study taking place during the second semester of the 2024/2025 academic year (January-June 2025). All schools had access to standard mathematics classrooms, whiteboards, projectors, and basic teaching facilities.

Participants

The population of this study consisted of all junior high school students in the city of Padang. From this population, three schools were purposively selected to represent different overall levels of cognitive ability (high, medium, and low), as determined from school achievement records and recommendations from the local education authority. Within each selected school, a group of nine students was chosen as the sample, using stratified purposive sampling to ensure representation of three cognitive levels: high, medium, and low, based on prior academic performance and teacher assessments. This resulted in a total of 27 students, that is 3 schools with 9 students for each school as participating in the study. During the trial, each class was divided into three groups to provide a comparison for the learning process. besides that, each class was divided into three groups, with each group consisting of heterogeneous members, namely one student with high ability, one with medium ability, and one with low ability. This arrangement was intended to facilitate peer learning and to provide balanced group interactions. One teacher delivered the lessons, while the researcher served as an observer during the experimental design stage.

Instrument dan Data Analysis

The instruments and data analysis techniques used in this study were aligned with the stages of the validation study process. In the preliminary design phase, two types of instruments were employed: interview guidelines and a research journal. The interview guidelines consisted of open-ended questions designed to gather information about practical and relevant learning processes. Interviews were conducted with teachers. Sample questions included: "Were the steps in the lesson plan clear and feasible to implement in the classroom?", "How appropriate was the time allocation for each activity as designed in the RPP?", "What challenges, if any, did you encounter when using the LKPD with students?", and "In your view, how did the LKPD support students' engagement and understanding of the material?". The interview was conducted in Indonesian to facilitate clear communication and was carried out individually with the teacher at the end of the trial sessions. To ensure the accuracy and reliability of the data, the session has been field notes taken by the researcher. Meanwhile, the journal was used to record key points that emerged during the development of the learning tools, particularly ideas, initial findings, or development considerations. Data from both instruments were analyzed by transcribing the interview results, reducing the data, presenting it systematically, and drawing conclusions.

In the experimental design phase, the instrument used was an observation sheet. This sheet focused on three main aspects: the positive and negative aspects of the learning process as observed by students, student's stated needs, and an analysis of the teacher's implementation of the learning process. The observation data were analyzed using the same procedure—data reduction, data presentation, and conclusion drawing—to obtain a comprehensive picture of the practicallity and relevance of the developed learning tools.

The success of the trial in this study was measured by the practicality of implementing the designed lesson plans and student worksheets in classroom practice. Practicality was considered achieved if teachers were able to implement the instructional activities as planned without experiencing major obstacles, if students could complete the tasks in the worksheets within the allocated time with only minimal assistance, and if both teachers and students gave positive responses regarding the clarity, usability, and relevance of the materials. In addition, successful implementation was reflected in classroom observations showing that the sequence of learning activities could be followed smoothly and that the process fostered meaningful interaction among students. Prior to the experimental teaching, several modifications were introduced to enhance the feasibility of the lesson plans and student worksheet. These included simplifying instructions in the student worksheet to align with students' reading comprehension, reorganizing the learning steps in the lesson plans to better fit the actual classroom time allocation, integrating contextual examples drawn from students' daily experiences to increase relevance, and arranging group work so that each group consisted of heterogeneous members with high, medium, and low ability levels. The introduction of these changes was motivated by evidence from expert reviews that recommended clearer instructions and a more coherent flow of activities, as well as from preliminary classroom observations that showed students' difficulties in completing tasks on time due to lengthy or unclear instructions. Teacher feedback also revealed that some activities in the original design were too demanding for the available classroom time, while pilot testing with students indicated that they were more engaged and able to understand better when examples were linked to their real-life context especially ethnomathematics using traditional game. Together, these considerations justified the refinement of the lesson plans and student worksheet before the experimental teaching, ensuring that the materials could be implemented practically and meaningfully in real classroom situations.

Ethical Aspects

This study has obtained ethical approval from the Research Ethics Committee of Universitas Negeri Padang with approval number 012/KEPK-UNP/7/2025. Prior to data collection, informed consent was obtained from all participants as well as from parents/guardians in the case of underage students. The participants were assured that their involvement was voluntary and that they had the right to withdraw at any time without any negative consequences. Confidentiality and anonymity of the participants were strictly maintained by coding the data and omitting any identifying information. All procedures in this research were conducted in accordance with ethical principles for educational research.

RESULTS AND DISCUSSION

Preliminary Research

The mathematics learning process was designed in the form of instructional tools, including a lesson plan and student worksheet. The instructional design incorporated the steps of the Project-Based Inquiry Learning (PIL) model, the STEM approach, and ethnomathematics. Ethnomathematics was selected based on the context of traditional Minangkabau and Malay games. The traditional Minangkabau game sipak rago was used to illustrate the concept of the surface area of a sphere. In contrast, the traditional Malay game lari dan beku was used to explore the topics of lines and angles.

As a result, two learning tools were developed: one for discovering the surface area of a sphere through sipak rago, and another for exploring lines and angles through lari dan beku. At this stage, the developed instructional tools were submitted to four experts for evaluation. The experts provided feedback and suggestions, which are summarized in table 2.

Table 2. Expert Feedback Summary

No.	Expert	Feedback
1	Expert 1,2,3	The learning tools were well-structured.
2	Expert 4	It was recommended to add a reflection stage in the student worksheet (LKPD).
3	Expert 5	Additional questions should be included during the exploration stage. In the LKPD involving Malay culture, it was suggested that students be guided to independently discover the relationships between complementary, supplementary, and reflex angles through visual representations.

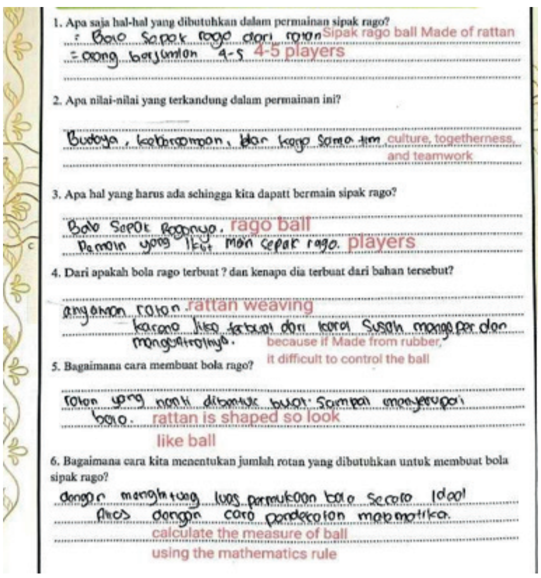
Experimental Design

In the pilot experiment stage, several revisions were made to the learning tools based on the trial results. The trial was conducted in three schools, selected based on their academic performance levels, categorized as high, medium, and low. Furthermore, the detailed description of each phase of the pilot experiment aligns with the stages of the Project-Based Inquiry Learning (PIL) model. The outcomes of this stage indicated that the learning process aligned well with the intended instructional design. The learning activities conducted during the process are outlined as follows.

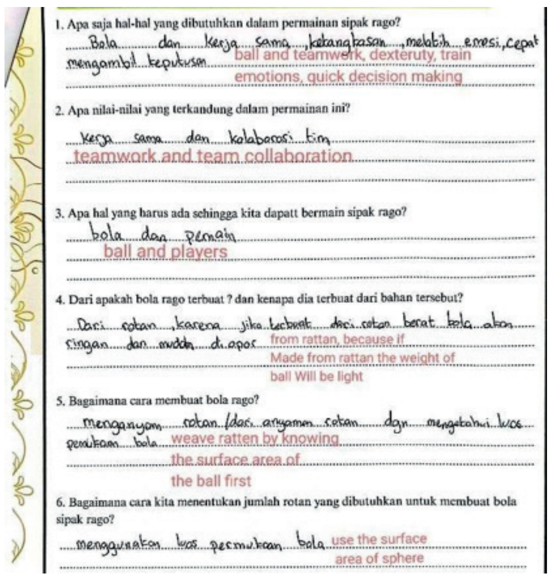
Step 1: Inquiry

At this stage, students began by exploring information related to the traditional games sipak rago and lari dan beku. This information was also provided in the student worksheet (LKPD) for their reference. Next, students answered the questions provided in the LKPD based on the context they had previously explored.

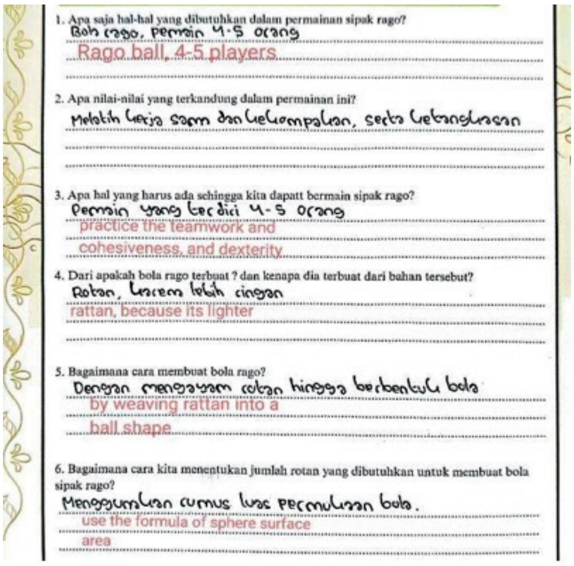
Minangkabau Culture (Sipak Rago Game)



(a)



(b)


1. Apa saja hal-hal yang dibutuhkan dalam permainan sipak rago?
Bola rago, pemain 4-5 orang
Rago ball, 4-5 players
2. Apa nilai-nilai yang terkandung dalam permainan ini?
Melatih kerja sama dan kekompakan, serta ketangkasan
3. Apa hal yang harus ada sehingga kita dapatt bermain sipak rago?
Pemain yang terdiri 4-5 orang
practice the teamwork and cohesiveness, and dexterity
4. Dari apakah bola rago terbuat ? dan kenapa dia terbuat dari bahan tersebut?
Rotan, karena lebih ringan
rattan, because its lighter
5. Bagaimana cara membuat bola rago?
Dengan menganyam rotan hingga berbentuk bola
by weaving rattan into a ball shape
6. Bagaimana cara kita menentukan jumlah rotan yang dibutuhkan untuk membuat bola sipak rago?
Menggunakan rumus luas permukaan bola.
use the formula of sphere surface area

(c)

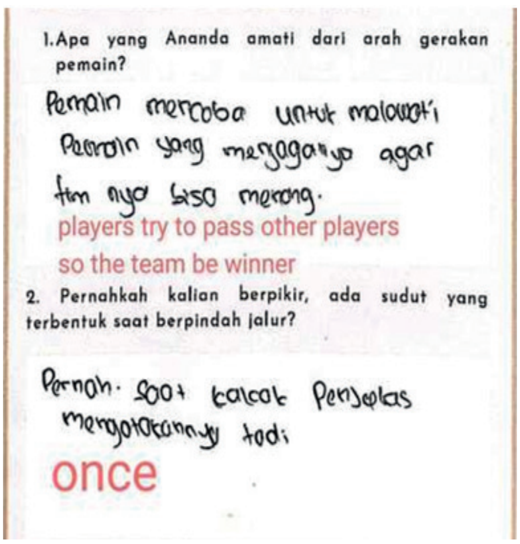
Figure 2. Inquiry Step of Minangkabau Culture on School Ability (a) High, (b) Middle, and (c) Low

Sipak Rago, a traditional Minangkabau game that served as the precursor to sepak takraw, can be connected to mathematical concepts, one of which is the surface area of a sphere. In this game, a woven rattan ball is the main element that players kick to keep in the air or direct to others. Understanding the surface area of a sphere is relevant for analyzing the ball's design, such as the strength of the rattan weave or the contact area between the ball and the player's foot when kicking. This Knowledge can help players understand the distribution of force during a kick and choose an optimally sized ball for gameplay, demonstrating how mathematics supports the strategy and dynamics of Sipak Rago. Furthermore, the findings from students during the inquiry stage across schools with high, medium, and low ability levels are presented in figure 2.

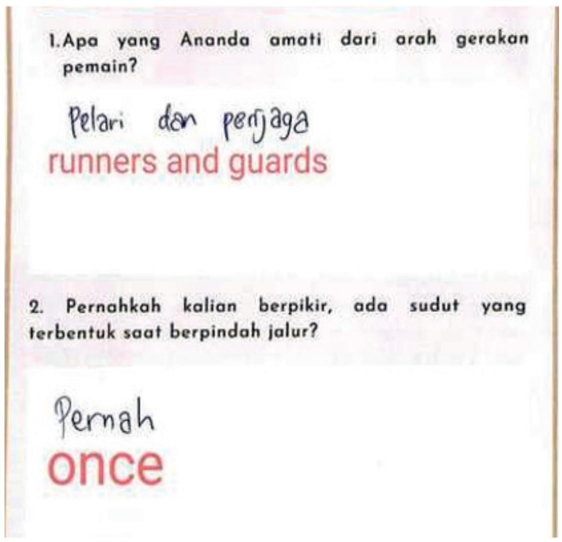
Based on figure 2, students from each school generally mentioned that Sipak Rago is a game played with a rattan ball and involves teams of 4 to 5 players. The values embedded in this game include teamwork, togetherness, collaboration, as well as the ability to manage emotions and make quick decisions. To play the game, a rago ball and cooperative players are required. Rattan is chosen as the material for the ball because it is lightweight, durable, and easy to weave. The ball is made by weaving rattan into a spherical shape.

Students also demonstrated mathematical understanding by explaining that the amount of rattan needed to make the ball can be calculated using the surface area of a sphere, applying either a mathematical approach or geometric formulas. Overall, the students' responses reflected an integration of cultural Knowledge, scientific skills, and mathematics within the context of a traditional game.

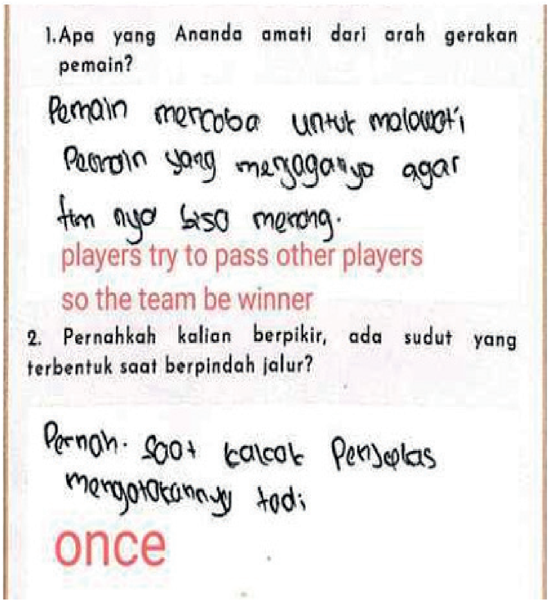
Malay Culture (Lari and Beku Game)


1.Apa yang Ananda amati dari arah gerakan pemain?
Pemain mencoba untuk melewati pemain yang menjaganya agar tim nya bisa menang.
players try to pass other players so the team be winner
2. Pernahkah kalian berpikir, ada sudut yang terbentuk saat berpindah jalur?
Pernah. saat kakak penjelas mengatakannya tadi
once

(a)


1.Apa yang Ananda amati dari arah gerakan pemain?
Pelari dan penjaga
runners and guards
2. Pernahkah kalian berpikir, ada sudut yang terbentuk saat berpindah jalur?
Pernah
once

(b)



(c)

Figure 3. Inquiry Step of Malay Culture on School Ability (a) High, (b) Middle, and (c) Low

Lari and Beku is a traditional game where players run to avoid being tagged by the "catcher" and must freeze in place if touched, remaining still until freed by another player. In a mathematical context, the relationships between complementary, supplementary, and reflex angles can be connected to the strategies used in players' movements. The rules of the game are illustrated in worksheet before the student play the traditional game. The findings from students during the inquiry stage at schools with high, medium, and low ability levels are presented in figure 3.

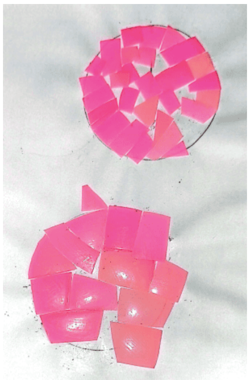
Based on figure 3, students' responses reflect efforts to answer questions based on the video they watched about the traditional Malay game lari and beku. Overall, their answers demonstrate an initial understanding of the game. In figures 3a and 3b, students expressed that they had previously considered the possibility of angles being formed during the game. However, this was not the case in Figure 3c, where the student did not perceive any connection between the game and the concept of angles. The questions at this stage served as a stimulus to encourage students to continue exploring the mathematical ideas in the next phase of learning.

Step 2: Exploration

At this stage, students began to explore the topic more deeply through group discussions, question-and-answer sessions, and initial information gathering. They engaged in project-based activities to abstract their prior Knowledge. The goal was to help students gain a deeper understanding of mathematical concepts while developing their critical and creative thinking skills. Through this process, students were encouraged to construct their mathematical Knowledge and abilities via exploration and discovery.

Minangkabau Culture (Sipak Rago Game)

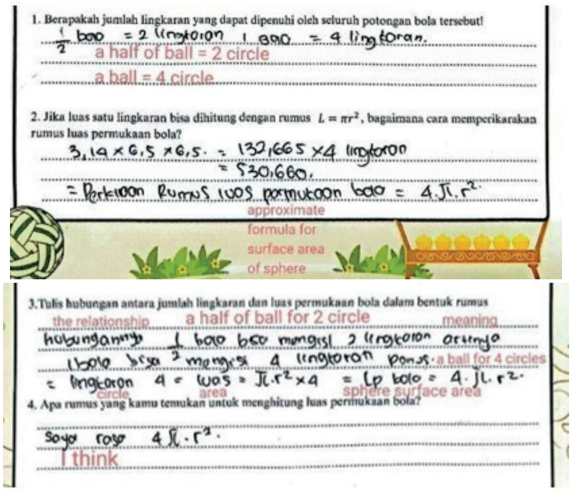
(a) (b)



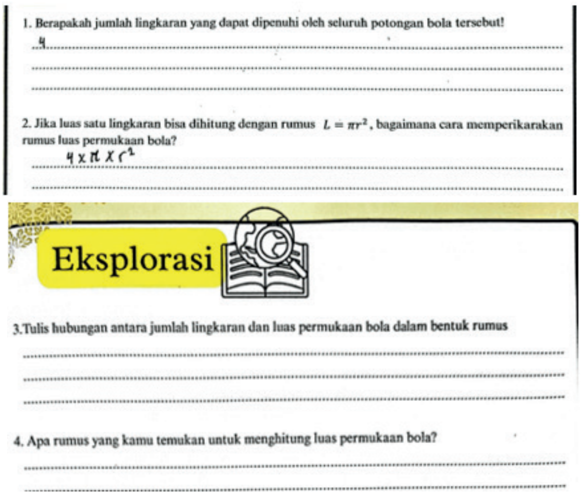
(c)

Figure 4. Exploration Step Student Project on School Ability (a) High, (b) Middle and (c) Low

Based on figure 4, students from high-, medium-, and low-performing schools arrived at the same answer, but through different thinking processes. The detailed explanations of the students' answers are presented in figure 5.



(a)



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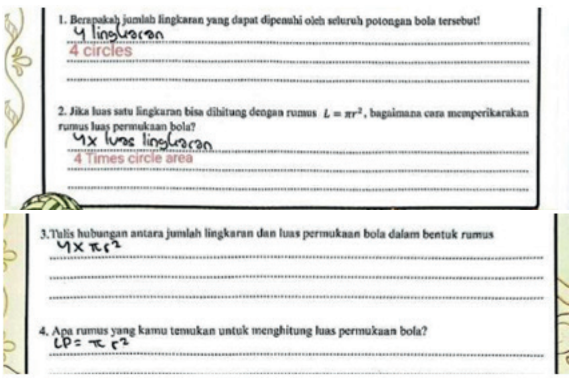

(c)

Figure 5. Exploration Step of Minangkabau Culture on School Ability (a) High, (b) Middle, and (c) Low

Based on figure 5a in Question 1, the student correctly answered that two circles can be obtained from half of a sphere, thus concluding that four circles can be obtained from one entire sphere. For Question 2, the student used the formula for the area of a circle (prior Knowledge), L=πr^2, and calculated it as L=3,14×6,5×6,5=132,665. Then, I multiplied the result by four circles, resulting in 530,660. The student then wrote: "Estimated surface area formula = $4\pi r^2$", indicating that they were starting to connect the number of circles to the sphere's surface area. For question 3, the student formulated the relationship as $L = \pi r^2 \rightarrow 4 \times L = 4\pi r^2$ and concluded that the surface area of a sphere is $4\pi r^2$. In Question 4, the student wrote, "I think $4\pi r^2$",

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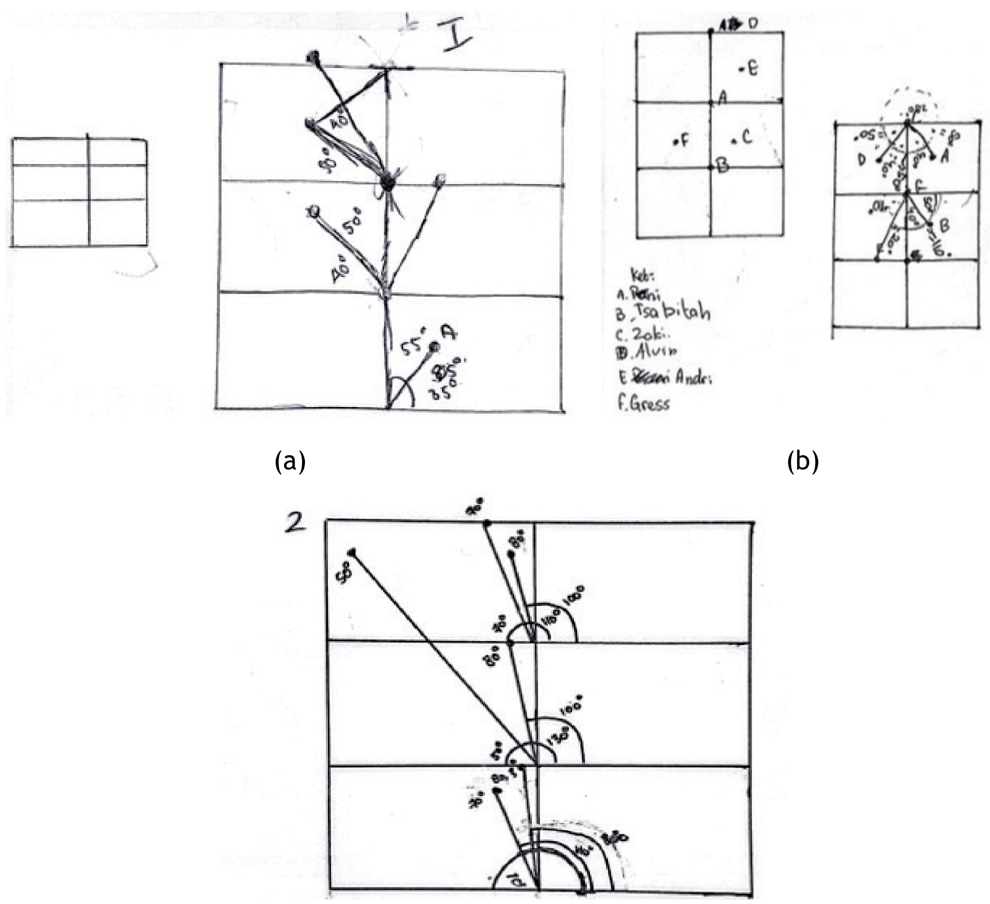
showing an understanding of the final surface area formula.

In figure 5b, for question 1, a student from the medium-performing school directly answered that the number of circles obtained from a sphere is four. In question 2, the student applied the formula for calculating the area of a circle. L=πr^2 And multiplied it by four, demonstrating an emerging understanding of the connection between the number of circles and the surface area of a sphere. However, the student did not answer questions 3 and 4. Despite this, during the learning process, the student demonstrated awareness that there is a relationship between the surface area of a sphere and the area of a circle.

According to figure 5c, in question 1, the student estimated that the surface area of a sphere is equivalent to four times the area of a circle, consistent with their earlier findings (as shown in Figure 4c). For question 2, the student's response indicated an understanding that the surface area can be represented by multiplying the area of one circle by four, which reflects a solid initial grasp of the concept. In the exploration section (question 3), the student successfully identified the mathematical relationship between the area of a circle and the sphere's surface area in formula form. Finally, the student's answer to question 4 was also mathematically correct and complete, successfully stating the formula for the surface area of a sphere.

Malay Culture (Lari and Beku Game)

Students participated enthusiastically in the *"lari* and *beku"* game, which was played according to the rules with three taggers and three runners in each group. The game lasted for one minute or until the teacher gave the stop command. After the match ended, one student from each group illustrated the positions of the runners and taggers on the Student Worksheet based on their observations at the moment the game was stopped. Interestingly, students across high-, medium-, and low-performing schools demonstrated strong teamwork and creativity in devising joint strategies to win the game. This reflected collaboration and tactical thinking skills that were developed through this enjoyable physical activity. The findings from students during the exploration stage at schools with high, medium, and low ability levels are presented in figure 6.



(a) (b)

(c)

Figure 6. Exploration Step of Malay Culture on School Ability (a) High, (b) Middle, and (c) Low

Figure 6 represents the lari and beku game that was previously played in the schoolyard. Students followed the game instructions provided in the LKPD. Afterward, they calculated the measures of complementary angles, supplementary angles, and reflex angles based on their observations, using a protractor as a measuring tool.

Based on figure 6, it can be seen that students were able to calculate angle measures correctly, demonstrating their understanding of the angle concepts through direct, contextualized experience.

Step 3: Experiment

This stage marks a critical phase in which students begin to design and develop concrete solutions based on their prior exploration and investigation. At this point, students work collaboratively to design a project or product that addresses the inquiry questions and problems previously identified. They begin to test ideas, create sketches or prototypes, conduct experiments, and select appropriate materials and tools based on their designs. This process encourages students to integrate conceptual Knowledge with practical skills, while also considering the functionality, aesthetic aspects, and relevance of their projects.

Minangkabau Culture (Sipak Rago Game)

In their efforts to solve the measurement problem, students first focused on determining the radius or diameter of the *bola rago*. The thinking processes and strategies employed by students in the medium-performing school reflected a diverse range of approaches. One notable method involved placing two books parallel to each other and in contact with the ball, then measuring the distance between the books using a ruler to estimate the diameter of the ball. Meanwhile, students in the high-performing school used a more creative technique by breaking a ruler and inserting it into the gaps of the woven rag ball to obtain the diameter value directly. On the other hand, students in the low-performing school still demonstrated initiative by inserting a pencil into the ball and then measuring the pencil's length with a ruler. These activities highlighted the integration of STEM elements, particularly in Engineering and Mathematics, as students applied measurement principles, designed simple tools, and solved problems through hands-on exploration and creativity. After determining the radius of the *bola rago*, students proceeded to calculate its surface area using the formula they had discovered in the previous stage. The findings from students during the experiment stage at schools with high, medium, and low ability levels are presented in figure 7.

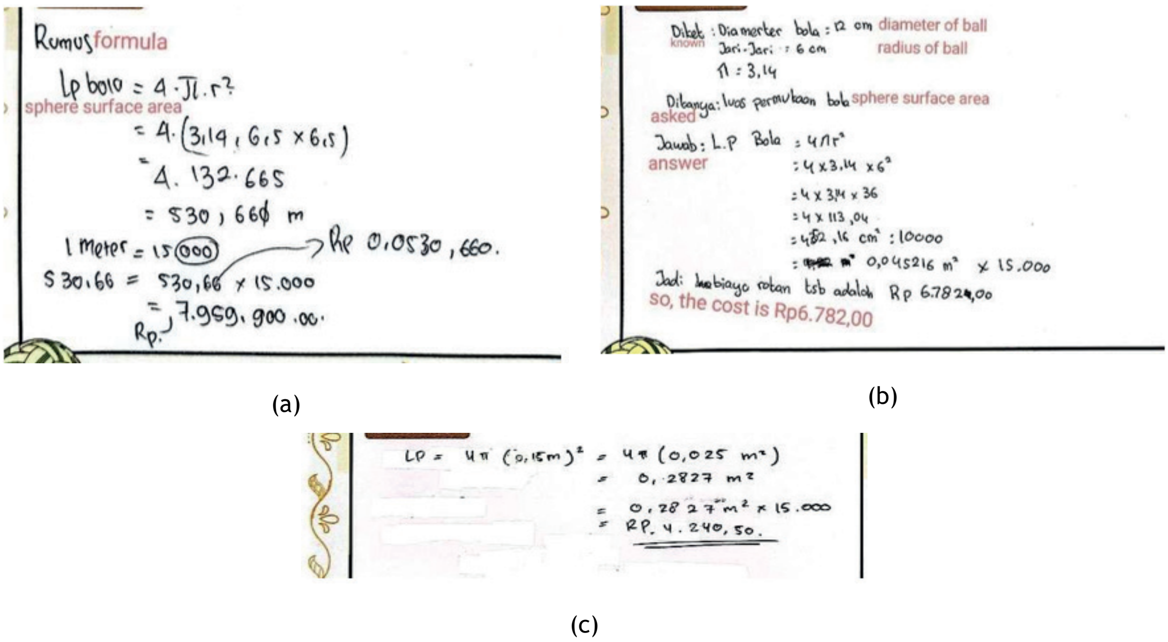


Figure 7. Experiment Step of Minangkabau Culture on School Ability (a) High, (b) Middle, and (c) Low

Based on figure 7a, the task required students to estimate the cost of purchasing rattan material to make one sipak rago ball, using the surface area of the sphere as a reference. Since the surface area couldn't be measured directly, a mathematical approach was used by calculating the ideal surface area using the formula discovered during the exploration phase. In the student's response, there was a minor error in converting units from cm^2 to m^2, Which led to an incorrect final result. Nevertheless, the student demonstrated an understanding of the surface area concept and was able to apply it to a real-world context, estimating material requirements. This case highlights the need for reinforcing unit conversion skills to ensure more accurate calculations.

In figure 7b, the student solved the problem using a systematic and accurate approach. First, they correctly determined the radius from the given diameter of 12 cm, resulting in a radius of 6 cm. Then, they applied the surface area formula for a sphere and substituted the values correctly, obtaining a surface area of 452,16 cm^2.

This was then converted to square meters by dividing by 10 000, resulting in 0,045216 m^2. Using the given price of Rp 15 000,00 per square meter, the student calculated the total cost by multiplying, arriving at a final answer of Rp 678 240,00. These steps show the student's solid grasp of the concept, correct unit conversion, and ability to apply mathematics to solve contextual problems logically.

In figure 7c, the student was given a diameter of 14 cm, which means the correct radius should be 7 cm or 0,07 meters. However, the student incorrectly used a radius of 0,15 meters, which didn't align with the provided data. Despite this, the student proceeded to use the surface area formula and calculate the area, then multiplied it by the rattan price of Rp 15 000,00 per m^2, obtaining a total cost of Rp 4240,50. At the same time, the calculation steps were mathematically structured. They demonstrated an understanding of the formula and unit conversion, but the error in selecting the radius rendered the final result invalid. This highlights the importance of accuracy in interpreting and substituting problem data, particularly in unit conversions and value selection for formulas.

Malay Culture (Lari and Beku Game)

Students from schools with high, medium, and low ability levels were able to model their findings from the exploration stage into more concrete mathematical forms. During the exploration, they identified several types of angles—complementary, supplementary, and reflex angles—that could be formed. They then formulated a mathematical conclusion that complementary angles add up to 90 degrees, supplementary angles to 180 degrees, and similarly applied understanding to reflex angles. Students then presented these concrete findings during the reflecting stage.

Step 4: Reflecting

This stage is a crucial phase in which students evaluate the entire learning process and its outcomes. Here, students are invited to reflect on their experiences throughout the project, from formulating questions and conducting investigations to producing the final product. Reflections were carried out in groups through presentations. During this process, students identified what they had learned, the challenges they encountered, the strategies that worked, and the areas needing improvement. The teacher facilitated this process by posing guiding questions and offering constructive feedback to promote critical thinking and metacognitive awareness. Through this stage, students not only gained a better understanding of the lesson content but also learned to reflect on their thinking processes and how to collaborate effectively in teams. Reflection served as an essential means to foster openness, responsibility, and motivation for continuous learning.

Through each stage of the Project-Based Inquiry Learning (PIL) model integrated with STEM and ethnomathematics, whether based on Minangkabau or Malay culture, students were able to engage in meaningful learning. This learning process also involved the application of mathematical concepts and skills in scientific thinking. For instance, students were invited to consider how to construct a bola rago from rattan and how to calculate the amount of rattan needed. Several students explained that this could be done by calculating the surface area of the ball using mathematical formulas. This reflects a strong integration between local cultural Knowledge and STEM concepts (Science, Technology, Engineering, and Mathematics). Such activities provide evidence that culture-based learning, such as the traditional sipak rago game, can stimulate critical thinking, creativity, and active student engagement in the learning process. Besides introducing cultural heritage, this approach also instills life values and reinforces mastery of academic content.

The traditional Malay game "lari and beku" is a physical activity involving groups of children in which one group chases and tags opponents, who must then "beku" or stop moving until all players are caught or a teammate frees them by touching them again. In the context of STEM education, this game can be used as a medium for interdisciplinary learning. From a scientific perspective, students can explore human body movement and the health benefits of physical activity. Technology can be incorporated by using timers or motion sensors to analyze speed and strategies. Engineering is involved in designing a safe and efficient playing area, while mathematics is utilized in calculating distances, speeds, or probability-based strategies for tagging.

From an ethnomathematical perspective, the game reflects traditional Malay mathematical concepts embedded in local culture. The movement patterns and frozen positions can be analyzed as spatial geometry, where students identify angles, distances, and coordination within the play area. The learning process can be enriched by linking these patterns to traditional number systems or simple calculations used in the Malay community, such as manually counting time or scores. With this approach, students not only learn STEM concepts in a contextualized manner but also develop a cultural appreciation while enhancing their critical thinking and collaborative skills through play. Thus, findings from the implementation of the Sipak Rago and Lari and Beku games demonstrate that cultural elements can serve as valid learning resources for constructing mathematical concepts, such as the surface area of a sphere and angle measurement.

Theoretically, this study makes a significant contribution to the development of a culture-based mathematics learning model that integrates Project-Based Inquiry Learning (PIL) with STEM (Science, Technology, Engineering, and Mathematics) and ethnomathematics. Previous research has emphasized that mathematics learning can be derived not only from textbooks, but also from authentic cultural practices.[31,37,38,39,40] This aligns with constructivist theory, which asserts that Knowledge is constructed through direct and meaningful experiences.[41,42,43,44] The STEM-integrated PIL model reflects the constructivist paradigm, emphasizing that students actively build Knowledge through exploration, inquiry, and engagement with real-world problems.[45,46,47,48] In this model, students are positioned as active learners, engaging in inquiry and project-based learning grounded in everyday life context.[49,50] The use of the PIL model integrated with the STEM approach in mathematics learning has a significant impact on the development of learning theories and modern pedagogical approaches.[51,52,53]

Another implication relates to cross-disciplinary integration. The STEM approach encourages connections between different fields of Knowledge in the process of mathematics learning, which theoretically strengthens the concept of connected learning.[24,54] This highlights that meaningful learning occurs when students can see the relevance between what they learn and real-world applications, as well as how mathematical skills are applied in science, technology, and engineering.[55,56] Therefore, STEM integration through the PIL model supports the theory of interdisciplinary learning and provides a stronger foundation for a relevant and applicable curriculum.[57,58,59]

Furthermore, the use of the Project-Based Inquiry Learning (PIL) model integrated with STEM also supports the development of 21st-century learning theories, which emphasize the importance of 4C skills: critical thinking, collaboration, communication, and creativity. Through project-based learning that involves solving complex problems and working in teams, students not only gain a deeper understanding of mathematical concepts but also develop metacognitive and social skills.[60,61,62] This implication reinforces the role of mathematics education as a medium for fostering students' holistic competencies.[55] Thus, the PIL-STEM integrated model not only aligns with modern learning theories but also broadens the perspective on how mathematics can be taught in a contextual, connected, and relevant way to prepare students for real-world challenges.[63,64,65]

This learning model provides an alternative instructional strategy that is both contextual and engaging, while also fostering a connection to local cultural values.[66,67] Teachers can utilize cultural heritage as a medium for teaching to facilitate the understanding of abstract mathematical concepts, while simultaneously increasing student engagement and motivation.[14,29,30,31,39] Therefore, this study can serve as inspiration for educators and education policymakers in designing culturally-based curricula that are relevant and meaningful for students across nations, particularly in Southeast Asia, a region rich in local cultures.

This study has several limitations. First, the cultural scope is limited to Minangkabau and Malay cultures; generalizing the findings to other cultures requires further investigation. Second, the implementation of the PIL-STEM learning model based on ethnomathematics was conducted in a limited context, specifically on the topics of surface area of a sphere and angle measurement, and thus does not yet cover broader mathematical issues. Third, since this study is primarily qualitative and descriptive, and was conducted within a limited timeframe, the long-term impact on students' mathematical abilities could not be comprehensively measured.

Based on these limitations, future research is recommended to develop a similar approach using other local cultures in Indonesia and neighboring countries to gain a broader understanding of the effectiveness of culture-based learning. Additionally, the development of the PIL model, integrated with STEM and ethnomathematics, can be applied to other mathematical topics, such as algebra, solid geometry, statistics, and probability. Further studies may also employ quantitative or mixed-method designs to more objectively measure improvements in students' mathematical abilities, critical thinking, and creativity.

CONCLUSIONS

The results of this study indicate that the approach is effective in enhancing students' understanding of mathematics through the Project-Based Inquiry Learning (PIL) model integrated with STEM (Science, Technology, Engineering, Mathematics) and ethnomathematics. This approach is not limited to students' own cultures but can also incorporate cultures different from theirs. Students were able to concretely discover the surface area of a sphere through Minangkabau culture and the relationships between complementary, supplementary, and reflex angles through Malay culture.

The implications of this study highlight the potential of STEM- and ethnomathematics-based PIL as an innovative approach that can be adopted in national curricula to enhance students' STEM literacy and cultural identity. However, the artistic scope was limited to Minangkabau and Malay cultures, which presents a limitation in this research. Therefore, generalizing the findings to other cultures requires further investigation. Additionally, since the study was qualitative and descriptive, and conducted within a limited timeframe, the long-term impact on students' mathematical abilities has yet to be thoroughly measured. Future research is recommended to expand the sample to various regions, conduct long-term assessments, and develop more structured learning modules to support consistent implementation across a broader range of cultural contexts.

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