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ENHANCING MATHEMATICAL CREATIVE THINKING THROUGH DIFFERENTIATED OPEN PROBLEM-SOLVING IN THE PYTHAGOREAN THEOREM

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Abstract
The Pythagorean theorem is one of the most important mathematical concepts, yet it poses a problem in learning. It is proven that students' mathematical creative thinking abilities related to this material are still low. There have been quite a few studies on the Pythagorean theorem, but not many have focused on learning development. Therefore, this research aims to optimize students' mathematical creative thinking abilities through the development of open-ended problem-solving-based differentiated learning. The research design used for development was the Plomp model. The subjects in this study were thirty junior high school students, three mathematics education experts, and one mathematics teacher. The instruments used were an expert validation sheet, a learning response questionnaire, and a mathematical creative thinking ability test. Data was analyzed by combining qualitative and quantitative data analysis. The research findings revealed that open-ended problem-solving-based differentiated instruction was capable of optimizing students' mathematical creative thinking abilities in learning. This was because differentiated learning facilitated cognitive diversity with various new and creative strategies when solving problems, making learning more meaningful. This research recommended that students be given more opportunities to explore strategies when solving problems.
Keywords: differentiated learning, mathematical creative thinking ability, open-ended problem solving, Pythagorean theorem

INTRODUCTION

The Pythagorean theorem is one of the quite important mathematical concepts because it has various benefits in everyday life (Jackson & Johnson, 2024; Ratner, 2009; Wares, 2017). In building construction, the Pythagorean theorem is used as a tool to ensure that the angles of a house truly form right angles, making the building's structure stronger. Quite a few other fields of science also use the concept of the Pythagorean theorem as a tool. In the fields of design and architecture, the Pythagorean theorem is used to calculate the length of a room's diagonal, the length of the required staircase, or the dimensions of a construction's roof (Chiotis, 2021). In the world of electronics, the Pythagorean theorem is used to calculate the impedance of AC circuits. In the fields of graphics, computers, and games, the Pythagorean theorem is used as a tool to calculate the distance between objects in threedimensional space, collision detection, and animation (Vargas & Stenning, 2019; Wulandari et al., 2021).

Given the importance of the Pythagorean theorem concept, students' understanding of this concept should ideally be good (Ariani et al., 2024; Septimiranti & Hiltrimartin, 2022). However, some previous studies have revealed that the Pythagorean theorem is actually one of the concepts that some students find difficult to understand (Puspitarani & Retnawati, 2020; Taamneh et al., 2024). Some students tend to find it difficult to generate new ideas and innovative and original solutions (mathematical creative thinking) when using the concept of the Pythagorean theorem to solve non-routine problems (Hutapea et al., 2015; Syutaridho et al., 2023; Taamneh et al., 2024). There are quite a few factors that cause students to experience these difficulties, one of which is the teaching methods used by teachers (Maamin et al., 2020; Wang et al., 2023). The teaching methods used by teachers tend not to be aligned with students' characteristics or needs (AlSalouli et al., 2024). However, teaching that is tailored to students' characteristics or needs (differentiated instruction) tends to be optimal for developing students' mathematical competencies (Bal, 2023; Prast et al., 2018; Sari et al., 2025).

There have been quite a few studies examining problems in learning the Pythagorean theorem, but not many have investigated the development of differentiated instruction to optimize students' mathematical creative thinking abilities, particularly those based on open problem-solving (Bicer et al., 2021; Langelaan et al., 2024). Villaseñor (2023) has examined various proofs of the Pythagorean theorem using a theoretical approach. The research findings have revealed that there are several new methods developed for proving the Pythagorean theorem. Engelbrecht and Borba (2024) have used a narrative review to examine the impact of digital technology use in mathematics learning, including the concept of the Pythagorean theorem. The research findings have revealed that there are benefits to using digital technology in mathematics learning. Meanwhile, Wittmann (2021) has examined the pedagogical framework in teaching the Pythagorean theorem using design research. The research findings have revealed the importance of integrating mathematics and pedagogy in teaching the Pythagorean theorem. In summary, the differences between the current research and some previous studies can be seen in Table 1.

Table 1. Comparison of current research with previous research

Researchs	Mathematical Competencies	Learning Model	Learning Basis	Research Design
Villaseñor (2023)	Mathematical reasoning and argumentation; mathematical connection making; using symbolic language and operations	Proof-based learning; conceptual integration learning	Calculus and mathematical proof	Theoretical/conceptual research

Engelbrecht and Borba (2024)	Mathematical modeling; mathematical communication; mathematical representation; digital literacy	Technology-enhanced learning; collaborative learning; STEAM education	Digital technology and online learning	Narrative review
Wittmann (2021)	Spatial reasoning; mathematical proof and reasoning; mathematical problem solving; mathematical communication	Design-based learning; collaborative learning; technology-assisted learning	Design science and constructivism	Design research
Current research	Mathematical creative thinking	Differentiated learning	Open-ended problem solving	Plomp Model

Based on the previous description, the purpose of this research is to develop a design for mathematics learning. The learning design being developed is differentiated learning based on open problem-solving to optimize students' mathematical creative thinking abilities in learning the Pythagorean theorem. Open problem-solving is chosen because the Pythagorean theorem has quite a few methods of proof (Jackson & Johnson, 2024; Rothe, 2022; Sarnoko et al., 2024; Taamneh et al., 2024), thus providing room for exploration to optimize students' mathematical creativity abilities. To achieve this goal, several research questions are derived, including:

1. How are the results of the needs analysis in learning the Pythagorean theorem?
2. What does open-ended, problem-solving-based differentiated learning look like in teaching the Pythagorean theorem?
3. How are students' mathematical creative thinking abilities after the implementation of learning?

RESEARCH METHOD

Research Design

This research used Plomp's design and development research model. This design was chosen because its characteristics were relevant to the objectives of this study (developing a design for mathematics learning) (Septriwati et al., 2018; Setyaningsih et al., 2019). This design was systematic, providing researchers with sufficient empirical data to serve as a basis for creating the learning design (Hafiz et al., 2024). Additionally, the Plomp model was relatively flexible because each research step included development activities that could be adapted to the characteristics of the research components (Diputra & Tristiantari, 2024).

Research Subject

The main subjects in this study were thirty students (aged 13 to 15) from a public school in Central Lombok Regency, Indonesia. The students were selected using purposive sampling from all the students in the school. The school was chosen because it was a reference school, but it still faced challenges in understanding the concept of the Pythagorean theorem. This research also involved one teacher who assisted in the implementation stage of learning and three validators in the field of mathematics education who assessed the learning design developed by the researcher.

Research Procedure

The research procedure followed Plomp's model, which consisted of three stages: preliminary research, development, and assessment (Estuhono et al., 2019; Masriyah et al., 2022; Yusmarni et al., 2019). In the preliminary research stage, the researcher analyzed needs and context, conducted a literature review, and developed the conceptual or theoretical framework required for the study. At this stage, the researcher analyzed the characteristics of the Pythagorean theorem material in the curriculum, student characteristics, and the learning environment. In the development stage, the researcher developed a problem-based, open-ended, differentiated learning prototype in the form of a textbook, learning module, student worksheet, and test questions. At this stage, the researcher also conducted expert validation, limited trials, and the first phase of field testing, revising the prototype during each of these activities. Meanwhile, in the assessment stage, the researcher implemented learning on a broader scale, which was then evaluated and revised. The results of this stage then led to the conclusion of whether the developed learning met validity tests, was practical, and was effective in optimizing students' mathematical creative thinking abilities. In summary, the research procedure could be seen in Figure 1.

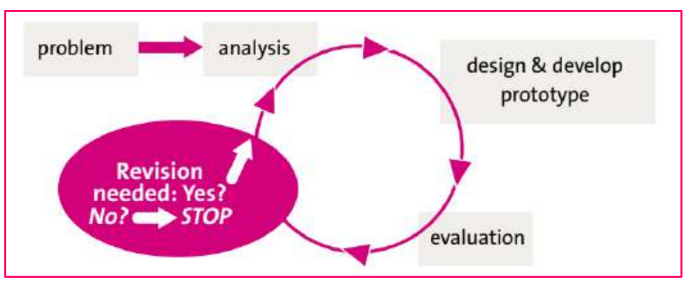

Figure 1. Prosedur penelitian

Instruments and Data Collection Techniques

There were several instruments used in this study. First, a validation sheet consisting of 36 statements for the textbook validation sheet, 19 statements for the teaching module validation sheet, and 19 statements for the teaching material validation sheet. This instrument was used to obtain data related to the results of product validation, which was done by asking for assessments from three experts in the field of mathematics education. Second, a response questionnaire consisting of a teacher response questionnaire with 15 statements and a student response questionnaire with 10 statements. The response questionnaire was used to obtain data related to teacher and student responses to the developed product by asking students to respond to the statements on the questionnaire after the learning activity was implemented. Third, a test of mathematical creative thinking ability consisting of 4 essay questions that students had to answer after the implementation activity. This test aimed to determine the students' proficiency level and the effectiveness of the developed learning. Fourth, an interview guide consisting of 9 questions that students had to answer. This guideline aimed to gain a deeper understanding of students' mathematical creative thinking abilities. Fifth, the textbooks, teaching modules, and student worksheets were used to collect student response data during the implementation of learning. The teaching module could be accessed on the following page: *Open Problem-Solving Based Differentiated Learning Teaching Module*.

Data Analysis Technique

The compilation of qualitative and quantitative data analysis was used to analyze the data obtained from the validation sheets and response questionnaires. Researchers first scored both instruments and then categorized them using statistical formulas and specific criteria (Nazari et al., 2023; Raharjanti et al., 2022). The data obtained from the test instruments were analyzed quantitatively by calculating the percentage of students who were declared proficient after the implementation of the learning activities. Meanwhile, the interview data were analyzed using qualitative data analysis with the stages of data reduction, data display, and conclusion drawing (Miles et al., 2014).

RESULTS AND DISCUSSION

How Are the Results of the Needs Analysis in Learning the Pythagorean Theorem?

Based on the analysis of the curriculum, it was found that higher-order thinking skills, such as creative thinking ability, were a target in the mathematics learning outcomes for middle school students (Bicer et al., 2021). This indicates that mathematical creative thinking ability is one of the important competencies that must be optimized during learning (Susilawati et al., 2024; Turan et al., 2025). This is because mathematical creative thinking ability is one of the essential skills in the 21st century that is positively correlated with students' performance and psychology in school (Asare et al., 2025; J. Yang & Zhao, 2021). These skills also train students' cognitive flexibility and optimize them when solving more complex problems (Sadak et al., 2022; Saputri et al., 2020).

In addition, the mathematics education curriculum in Indonesia also emphasized the use of active, collaborative, contextual, and differentiated learning approaches (Hadi & Retnawati, 2025; Prahmana et al., 2020). Therefore, differentiated learning is one form of effort to optimize students' mathematical creative thinking competencies. This means that students learn according to their individual conditions, making learning more relevant to them (Lestari et al., 2024; Sitorus et al., 2022). The curriculum also emphasized assessment that not only measured final results but also students' thinking processes and their ability to openly explain and present solutions (Zana et al., 2024). The existence of this assessment then recommends the use of open-ended problems as one of the situations in learning (Agustianingsih & Putri Sasalia, 2025). This is intended to get students used to thinking about a variety of solutions or processes for solving problems (Indah et al., 2018).

Based on the analysis of the students, it was found that the majority of students experienced difficulty in solving non-routine problems. In fact, students' creative thinking abilities were also considered low, especially in the indicators of flexibility and originality. Students tended to be less courageous in trying strategies when solving problems. The results of this study are consistent with Maulana and Yuniawati (2018), who found that students' creative thinking abilities tend to be low when solving non-routine problems. This is because students are not accustomed to solving problems using methods or processes different from the intended procedures (Bolat & Arslan, 2024; Jonsson et al., 2022).

The analysis results also revealed that students preferred interactive learning. This finding aligns with Carlos et al. (2023), who stated that interactive learning that facilitates active student engagement tends to be desirable for students. This is because interactive learning provides students with opportunities to explore ideas or combine various competencies during the learning process (Koç & Kanadlı, 2025; Song & Cai, 2024). Interactive learning tends to be suitable for the characteristics of the digital generation, which requires visual, audio, and kinesthetic stimulation, as well as feedback during learning (Vidak et al., 2024). Based on the previous description, it can be concluded that open-ended problem-solving-based differentiated learning is expected to be one alternative solution in optimizing students' mathematical creative thinking abilities in learning the Pythagorean theorem.

What Does Open-Ended, Problem-Solving-Based Differentiated Learning Look Like in Teaching the Pythagorean Theorem?

Following up on the findings of previous research, the syntax of open problem-solving-based differentiated learning developed at this stage was learning profile mapping, responsive adaptation, process adaptation, product diversification, and evaluation. During the learning profile mapping activity, teachers conducted diagnostic assessments to determine students' initial readiness regarding the material being studied. This activity is based on the theory that confirming students' understanding of prerequisite material is one of the important aspects that must be done at the beginning of learning (Isnawan et al., 2024; Sridana et al., 2025; Sukarma et al., 2024). This activity is also in line with several previous studies (Muntazhimah et al., 2021; Zakariya et al., 2023) that revealed that students should have an adequate understanding of prerequisite material in order to learn mathematics well.

The next activity was responsive adaptation. At this stage, the teacher presented open-ended problems that students had to solve using various strategies and levels of complexity. The integration of open-ended problems is based on several previous studies (Rahayuningsih et al., 2021; Wijaya, 2018) that revealed that open-ended problems are capable of facilitating the development of students' mathematical abilities, including creative thinking skills. This is because open-ended problems provide students with the opportunity to use various new strategies in solving problems (Rizos & Gkrekas, 2023). The problems presented must also be contextual so that students feel familiar with them (Thomaneck et al., 2025; Wijaya et al., 2015). One example of an open-ended problem given by the teacher can be seen in Figure 2. Figure 2 shows an example of a miniature house building that students will determine the dimensions of the component parts of before creating the requested miniature.

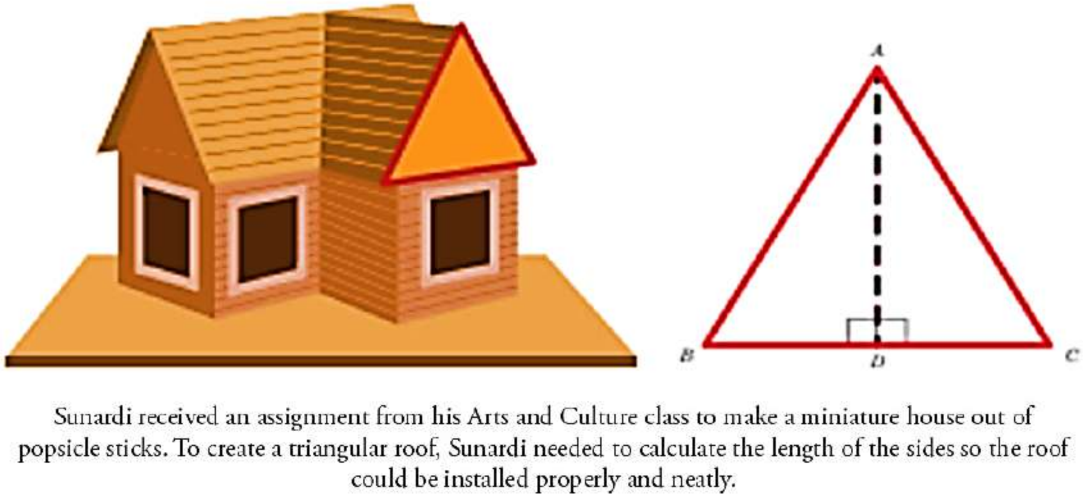

Figure 2. Example of an open problem

Next, students worked in heterogeneous groups based on their learning readiness level to investigate and explore various solutions to open-ended problems (identifying important information, designing strategies, and creating problem-solving procedures). In this activity, students solved problems in groups by following the instructions on the worksheet. This activity is inspired by several previous studies (Fatmanissa et al., 2023; Klang et al., 2021) that revealed that students should be given the opportunity to work in groups and discuss when solving problems. This is intended to facilitate a learning process during the discussion activity. Students with better mathematical competence help students with lower mathematical competence (Alegre et al., 2019; Moliner & Alegre, 2020). Additionally, providing scaffolding helps students more easily construct solutions when solving open-ended problems in mathematics learning (Arifin et al., 2020; Ekawati et al., 2025; Yusnidar et al., 2023). However, the presence of this scaffolding also limits students' flexibility in exploring ideas or strategies to solve problems. Figure 3 shows an example of student work results for this activity.

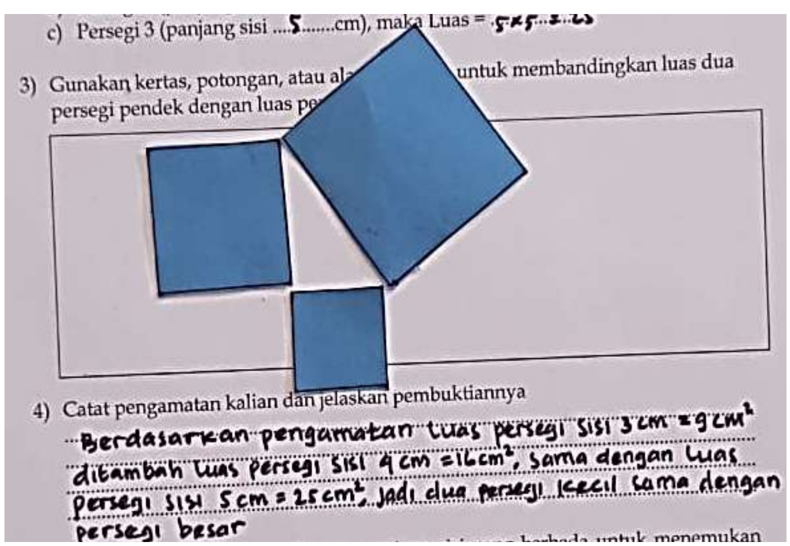

Figure 3. Excerpts from student responses during the product diversification activity

The next activity was product diversification. In this activity, students presented solutions using various forms of representation, such as sketches, drawings, and mathematical models. In this activity, the teacher assesses the work results using a creative thinking rubric. Teachers and students together reflect on thinking strategies and identify opportunities for improvement. This activity is based on introspective theory in learning. The theory reveals that students need to introspect on the solutions or processes they use when solving problems (Farnila et al., 2021; Martin et al., 2023). his introspection is a form of validation that students perform on the solutions, processes, or concepts of the Pythagorean theorem they have learned (Isnawan et al., 2024; Naza & Syamsuri, 2022).

Finally, there was the evaluation. In this activity, teachers conduct formative and summative learning evaluations and provide open and constructive feedback to improve, refine, or develop creative ideas. In this activity, students are asked to solve new open-ended problems using concepts they have already learned. This activity is based on a theory in learning that reveals that students need to practice problems as a means of strengthening their understanding of mathematical concepts they have already learned (Avvisati & Borgonovi, 2020). A sample of the practice questions provided can be seen in Figure 4.

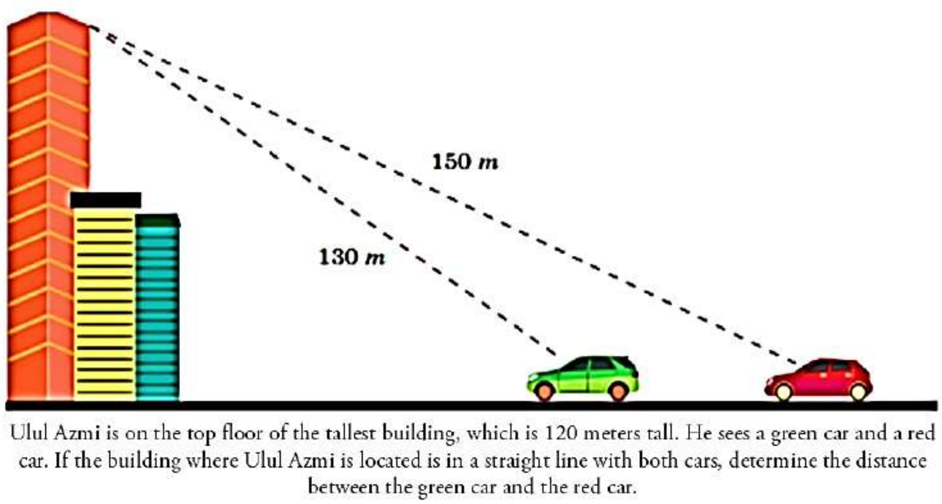

Figure 4. Sample exercise questions

Evaluation activities are also reflective activities used to confirm students' understanding of the Pythagorean theorem concepts they have already learned. This activity aims to determine whether the learning objectives have been achieved or not. This activity aims to identify students' weaknesses in the aspect of mathematical creative thinking ability. This activity aligns with the research by Sukarma et al. (2024), which revealed that reflection activities are an important element in learning. This is because these activities are related to the extent of students' understanding of the mathematical concepts they are learning, their level of mathematical competence, and their social-emotional competence (Sridana et al., 2025; Tomar et al., 2024; L. P. Yang & Xin, 2022).

How Are Students' Mathematical Creative Thinking Abilities after the Implementation of Learning?

Before presenting the criteria for students' mathematical thinking abilities, the results of the analysis of expert validation and trial test results were first described. The analysis of the expert validation results revealed that the aspects of the learning model's basic concepts and principles, syntax, social system, interaction principles, support system, instructional and accompanying impact, and the interconnections between components within the learning model were categorized as valid. In fact, the practicality aspect of the learning model was categorized as highly valid. Similarly, the analysis of the validation results for the textbook and teaching modules revealed that all validators stated the textbook and teaching modules were already categorized as valid. The mathematical creative thinking ability test had also met the evidence for validity and reliability estimation. Based on the statistical analysis results, it was found that the *Pearson Correlation* values for each test item were greater than 0,396; meeting the validity criteria. Meanwhile, the *Cronbach's Alpha* value was 0,737; meeting the reliable criteria. Although there were some minor revisions to the model, textbooks, teaching modules, and previous tests of students' mathematical creative thinking abilities.

This positive result aligns with Amiruddin et al. (2023), which states that learning developed with student needs in mind tends to have good validity evidence and reliability estimates. This is because the developed learning design is based on student characteristics or needs (Pozas et al., 2021). The resulting learning design is also more contextual, which tends to indicate a positive impact on students' mathematical competence (Fundal & Fuentebilla, 2025).

This positive indication was then empirically confirmed through student test results. Analysis of student mathematical creative thinking ability test results revealed that approximately 53.33% of students were categorized as very creative, 33.33% of students were categorized as creative, and 13.33% of students were categorized as moderately creative. This positive result was then confirmed by the conclusions of student interview results, which revealed that open-ended problem-solving-based differentiated learning provided space for students to explore ideas, use various types of strategies, and collaborate in generating creative solutions while solving problems. The results of this study are consistent with Lestari et al. (2024), which revealed that differentiated learning can optimize students' mathematical abilities, including creative thinking skills. This is because differentiated learning provides more opportunities for students to explore various ideas according to their abilities (Kamarulzaman et al., 2022; Ningsih et al., 2024; Shodiq, 2025). The results of this study are also consistent with Darma (2018), which revealed that problem-based learning sparks students' cognitive abilities to solve problems according to their existing competencies (Susbiyanto et al., 2019). Figure 5 provides an example of one student's answer when answering a test question.

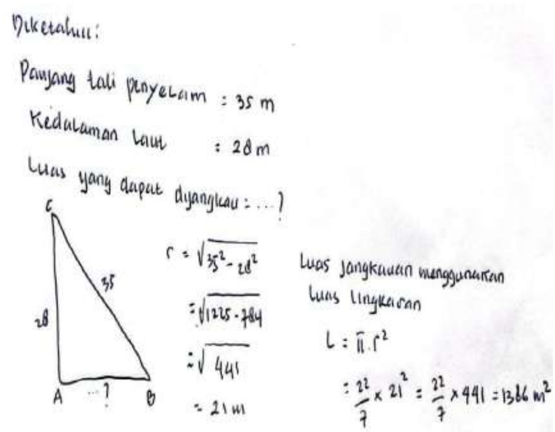

Figure 5. Student answer excerpts

CONCLUSION

Based on the previous explanation, several findings can be concluded from this research. First, open problem-solving-based differentiated learning has a positive impact on the development of students' mathematical creative thinking abilities in learning the Pythagorean theorem. It is proven that most of the students' competencies are categorized as very good. Second, differentiated learning provides instruction that is more relevant to students' cognitive development, making learning more meaningful. Third, the use of open problem-solving provides students with the opportunity to try various alternative strategies or creative new solutions while solving problems using the concept of the Pythagorean theorem. During the implementation of the research, students are assisted with scaffolding when solving open-ended problems. The existence of scaffolding actually limits students' freedom to explore creative and innovative ideas or strategies when solving problems. Therefore, future research is expected to provide space for students to explore ideas by limiting the amount of scaffolding when students solve open-ended problems.

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AUTHOR CONTRIBUTIONS

The first author was responsible for conceptualization, methodology, investigation, formal analysis, and writing (original draft preparation). The second author conducted a formal analysis, prepared resources, data curation, and handled visualization. The third author was responsible for validation, methodology, writing (review and editing), and supervision. The fourth authors were involved in validation, methodology, and formal analysis.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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