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ENHANCING SECONDARY STUDENTS' MATHEMATICAL CREATIVE THINKING THROUGH STEM PROJECT-BASED LEARNING

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ABSTRACT

Studies have highlighted the persistently low levels of mathematical creative thinking skills among students, emphasizing the need for innovative learning interventions. The STEM-PjBL model, which integrates science, technology, engineering, and mathematics through project-based learning, offers a structured framework to enhance these skills by fostering innovative problem-solving. This study investigates the implementation of the STEM-PjBL model to improve students' mathematical creative thinking skills. A quantitative quasi-experimental approach with pre- and post-tests control group design was used, involving two purposively selected ninth-grade classes from a population of 298 students. Analysis using the Mann-Whitney U test showed a statistically significant improvement in mathematical creative thinking skills following the STEM-PjBL intervention ($p < 0.05$), with a normalized gain ($g = 0.43$), indicating that the results for the experimental group were higher than those of the control group. These findings suggest that the STEM-PjBL model is an effective strategy for improving creative thinking in mathematics education.

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INTRODUCTION

The digital era, a form of technological modernization, has advanced rapidly in the twenty-first century (Rahmatullah et al., 2020). This highlights the multifaceted role of technology in the digital world, challenging individuals to utilize it effectively and creatively to compete globally across various fields. This aligns with Nakano and Wechsler's (2018) perspective, which emphasizes that the challenges of the twenty-first century require people to think critically and produce creative solutions. Therefore, fostering creative thinking is one of the most essential skills to improve in this century (Azeem et al., 2021; Thornhill-Miller et al., 2023).

Creative thinking, which plays an integral role in fields such as science, technology, medicine, and art, arises from mental processes that combine various elements into innovative ideas, derived from the fusion of previous concepts (Lynch et al., 2019). For instance, education today is evolving based on creative thinking, allowing new ideas to emerge that can be applied within the educational field (Syahrin et al., 2019). Thus, the ability to think creatively is crucial in many areas and must be nurtured and developed.

Creative thinking skills involve students' ability to generate, evaluate, and develop ideas that lead to unique and effective solutions (OECD, 2023a). In the context of mathematics education, these skills are part of higher-order thinking, which includes the ability to think creatively by developing unconventional solutions (Hidajat, 2021). Moreover, when solving complex mathematical problems, the development of innovative solutions is driven by creative thinking (Yaniawati et al., 2020). Specifically, mathematical creative thinking skills involve using unconventional ideas to approach mathematical challenges (Hadar & Tirosh, 2019). These skills are characterized by sensitivity, fluency, flexibility, originality, and elaboration (Noer, 2010; Fajri et al., 2023).

The exploration of creative thinking in mathematics education has evolved significantly over time. Historically, mathematics education focused heavily on procedural fluency and standardized problem-solving, often neglecting creativity (Sriraman & Lee, 2011). owever, in recent decades—particularly since the early 2000s—there has been a shift toward recognizing creative thinking as a vital component of mathematical learning. Research by Saefudin et. al (2023) highlights that studies on mathematical creativity have rapidly increased over the past two decades (2000–2022). For example, research by Leikin & Elgrably (2020) emphasizes how creative thinking fosters fluency, flexibility, and originality in solving open-ended mathematical problems. In the last decade, studies have increasingly emphasized integrating interdisciplinary approaches, such as STEM (English, 2016; Kelley & Knowles, 2016; Millar, 2020) and leveraging technology to enhance creativity in mathematics (Abramovich & Freiman, 2022; Freiman & Tassel, 2018). This evolution is evident in frameworks like PISA 2022, which now assesses creative thinking as a key competency (OECD, 2023a).

Despite these advancements, challenges persist. Many educational systems, particularly in developing countries like Indonesia, still rely on teacher-centred, rote-learning approaches, limiting opportunities for creative thinking (Sutarto et al., 2020). Future opportunities include developing culturally responsive pedagogies, integrating advanced technologies such as learning tools, and designing curricula that balance creativity with conceptual understanding (Li et al., 2022). These gaps highlight the need for innovative approaches to foster mathematical creativity effectively.

Based on the PISA 2022 framework, the OECD has added creative thinking skills as part of the survey, with mathematics being the most observed focus in PISA 2022. The creative thinking test items developed in PISA 2022 assess how students apply various methods to solve problems presented through data or geometric information, asking students to derive as many valid answers or conclusions as possible from a given set of data, or to solve open-ended problems requiring innovative, efficient, and effective solutions (OECD, 2023a). According to the PISA study findings in 2022, the average international mathematical skills score was 472, while Indonesia's average mathematical ability score was 366 (OECD, 2023b). Moreover, Indonesia's average mathematical score has shown a trend of minimal improvement despite ongoing participation in the PISA survey. This suggests that significant efforts should be made to improve students' mathematical creative thinking skills.

Zakiah et al. (2020) suggest that engaging students in planning, creating, presenting, and evaluating products during learning activities can stimulate their creative thinking skills. The planning process also involves design activities, through which students are encouraged to generate and develop a variety of creative ideas while considering multiple possibilities for their designs (Koes-H & Putri, 2021). When creating a design, students apply their prior knowledge and represent it visually in the form of drawings, based on the creative ideas they have conceptualized (Prain & Tyler, 2012). This indicates that the design process offers opportunities to develop and express creative ideas, thereby supporting the improvement of students' creative thinking skills.

One of the learning characteristics mentioned above is reflected in the STEM (Science, Technology, Engineering, and Mathematics) approach. According to English (2016), STEM is an interdisciplinary approach that integrates science, technology, engineering, and mathematics to solve real-world problems, fostering both critical and creative thinking. Recent research by Wahono et al. (2020) emphasizes that STEM encourages students to engage in design processes that produce tangible products by applying mathematical and scientific concepts through engineering and technology. These design activities, which allow for multiple possible solutions, enhance creative thinking by fostering innovation and exploration (Stretch & Roehrig, 2021). For instance, Kelley and Knowles (2016) highlight that STEM's emphasis on hands-on, contextual learning supports the development of creative problem-solving skills in mathematics.

According to Honey et al. (2014), the STEM approach can be applied in various forms, including silo, embedded, or integrated approaches, with integrated STEM being the most effective for fostering interdisciplinary connections. Recent studies, such as those by Thibaut et al. (2018), confirm that integrated STEM enhances mathematical understanding by connecting concepts to real-world contexts, making it particularly suitable for nurturing creative thinking. Li et al. (2019) further argue that the STEM approach in mathematics education encourages students to explore diverse representations and generate novel ideas, aligning with the goals of enhancing mathematical creativity.

In the implementation of the STEM approach, it can also be combined with other instructional models, including project-based learning (PjBL) and problem-based learning (PBL) (Wahono et al., 2020). This study proposes the STEM-PjBL model because it combines STEM's interdisciplinary, real-world focus with PjBL's emphasis on student-driven projects and tangible outcomes, which are critical for fostering mathematical creativity. According to Hanif et al. (2019), the STEM-PjBL model engages students in designing and developing products, requiring them to integrate STEM concepts creatively. In contrast, problem-based learning (PBL) focuses primarily on resolving specific problems through inquiry, often without producing a tangible product, which may limit opportunities for creative design (Yew

& Goh, 2016). Similarly, traditional direct instruction, while effective for conceptual mastery, lacks the hands-on, creative elements that STEM-PjBL offers (Capraro et al., 2016). Although inquiry-based learning is student-centered, it typically emphasizes exploration rather than product creation, making it less aligned with fostering creativity through design (McFadden & Roehrig, 2018). Therefore, STEM-PjBL is proposed as a superior approach for enhancing mathematical creative thinking due to its integration of interdisciplinary learning and project-based creativity.

Additionally, STEM-PjBL emphasizes the design and development of products, requiring students to engage with STEM learning processes throughout the project implementation (Samsudin et al., 2020; Putri & Dwikoranto, 2022). These activities have the potential to positively impact creative thinking skills, as students are encouraged to generate original ideas in the process of product creation (Hanif et al., 2019). This suggests that the STEM-PjBL model offers a strong opportunity to improve students' creative thinking abilities.

According to Laboy-Rush (in Putri & Dwikoranto, 2022) the stages of applying the STEM-PjBL model include reflection, research, discovery, application, and communication. The reflection stage guides students to focus on the context of a given problem or topic, enabling them to generate ideas for potential solutions. In the research stage, students gather information and participate in discussions that support their understanding and the development of ideas. The discovery stage allows students to process and refine the information they have collected, leading to the generation of new ideas. During the application stage, students execute the developed ideas by integrating STEM concepts into the project completion process. Finally, in the communication stage, students present and share the results of their completed projects.

Several studies have demonstrated that the STEM-PjBL approach can enhance students' mathematical creative thinking skills. For example, Nur'aeni et al. (2023) eported that project-based learning with STEM integration significantly improved students' mathematical creative thinking abilities. Jawad et al. (2021) also found that implementing the STEM approach enabled students to generate new ideas and create original works, thus encouraging innovation and enhancing creative thinking skills. Moreover, integrating STEM into mathematics learning has been shown to foster active, creative, critical, and communicative learners (Tolliver, 2016). Therefore, the implementation of project-based learning with STEM integration is expected to support the improvement of students' mathematical creative thinking skills.

Based on the explanation above, this study aims to examine how the STEM-PjBL model can be applied to improve students' mathematical creative thinking skills.

METHOD

This study employed a quasi-experimental research design to investigate the effectiveness of the STEM-PjBL approach in enhancing students' mathematical creative thinking skills. The population consisted of 298 ninth-grade students distributed across 10 classes at a public junior high school in Indonesia during the 2023/2024 academic year. Two classes were selected as research samples using a purposive sampling technique, comprising 29 students in one class (designated as the experimental group) and 27 students in another class (designated as the control group).

Purposive sampling was applied due to practical considerations, including the availability of teachers trained in implementing the STEM-PjBL model and the need to ensure that the selected classes shared comparable characteristics, such as class size and access to learning resources. Additionally, prior academic records and pretest scores were reviewed to confirm that the two classes demonstrated relatively similar proficiency levels in mathematics before the intervention, thereby minimizing baseline differences that could potentially confound the results.

The experimental group received instruction using the STEM-PjBL model, which integrates project-based learning with STEM principles to strengthen mathematical creative thinking skills. In contrast, the control group was taught using a conventional learning model characterized by teacher-centered instruction and traditional problem-solving exercises. The study adopted a pretest-posttest control group design. Data were collected through a descriptive test instrument that was validated for content, yielding a reliability coefficient of 0.78, a discrimination index above 0.30, and a difficulty level exceeding 0.30 (Sudijono, 2018).

Pretest and posttest data were analyzed using Hake's normalized gain (1998) to assess improvement in mathematical creative thinking skills, as this method focuses on individual student progress and is widely applied in educational research for evaluating learning gains. Since the data did not meet the assumptions of normality, as confirmed by preliminary statistical testing, the Mann-Whitney U test was used to compare the improvement in mathematical creative thinking skills between the experimental and control groups.

RESULT AND DISCUSSION

The improvement in students' mathematical creative thinking skills between the experimental and control groups was assessed through an analysis of pretest and posttest results. Descriptive statistics, normality tests, and the Mann-Whitney U test were conducted on the gain scores of students' mathematical creative thinking skills. The results of these analyses are presented in the following table:

Table 1. Statistical Tests on the Gain Scores of Students' Mathematical Creative Thinking Skills

Class	Mean	Std. Deviation	Kolmogorov-Smirnov[a]	Z	Sig. (2-tailed)
			Sig.		
Experiment	0,43	0,16	0,200	-3,10	0,002
Control	0,30	0,13	0,002		

As shown in Table 1, the significance (Sig.) value for the gain in students' mathematical creative thinking skills was 0.200 for the experimental class and 0.002 for the control class. The analysis indicated that the gain data for students' mathematical creative thinking skills did not follow a normal distribution (*Sig.* < 0.05). As a result, the Mann-Whitney U test was used to examine the differences in skill improvement, as recommended by the results of the normality test.

Based on the Mann-Whitney U test results for hypothesis testing, the *Sig.* (2-tailed) value was 0.002, as presented in Table 1. Therefore, it can be concluded that there was a statistically significant difference in the improvement of mathematical creative thinking skills between students in the experimental and control classes (*Sig.* < 0.05). Furthermore, the experimental class demonstrated better performance compared to the control class, both in terms of the overall average gain and the average gain across each indicator of mathematical creative thinking skills. These findings indicate that students who participated in learning through the STEM-PjBL model showed higher improvement in their mathematical creative thinking skills than those who were taught using conventional learning methods.

Figure 1 illustrates the average gain for each indicator of students' mathematical creative thinking skills after the learning intervention. The data show that the experimental class consistently achieved higher average gains both overall and for each individual indicator, compared to the control class. This suggests that the STEM-PjBL model has a greater positive impact on enhancing students' mathematical creative thinking skills than the conventional learning model.

Notably, the experimental group achieved its highest gain score of 0.59 in the sensitivity indicator, reflecting substantial progress in identifying and creatively addressing mathematical challenges. Additionally, the most significant difference between the two groups was observed in the originality indicator, with a gap of 0.15, highlighting the model’s effectiveness in fostering innovative solutions. These improvements are closely linked to the model's integration of challenging, project-based tasks that encourage creative engagement with mathematical content.

This finding is supported by Nur'aeni et al. (2023), who reported that students’ mathematical creative thinking skills could be enhanced through project-based learning with STEM integration. Similarly, research by Fajri et al. (2023) and Prajoko et al. (2023), confirmed that the STEM-PjBL model had a significant positive impact on students' creative thinking skills.

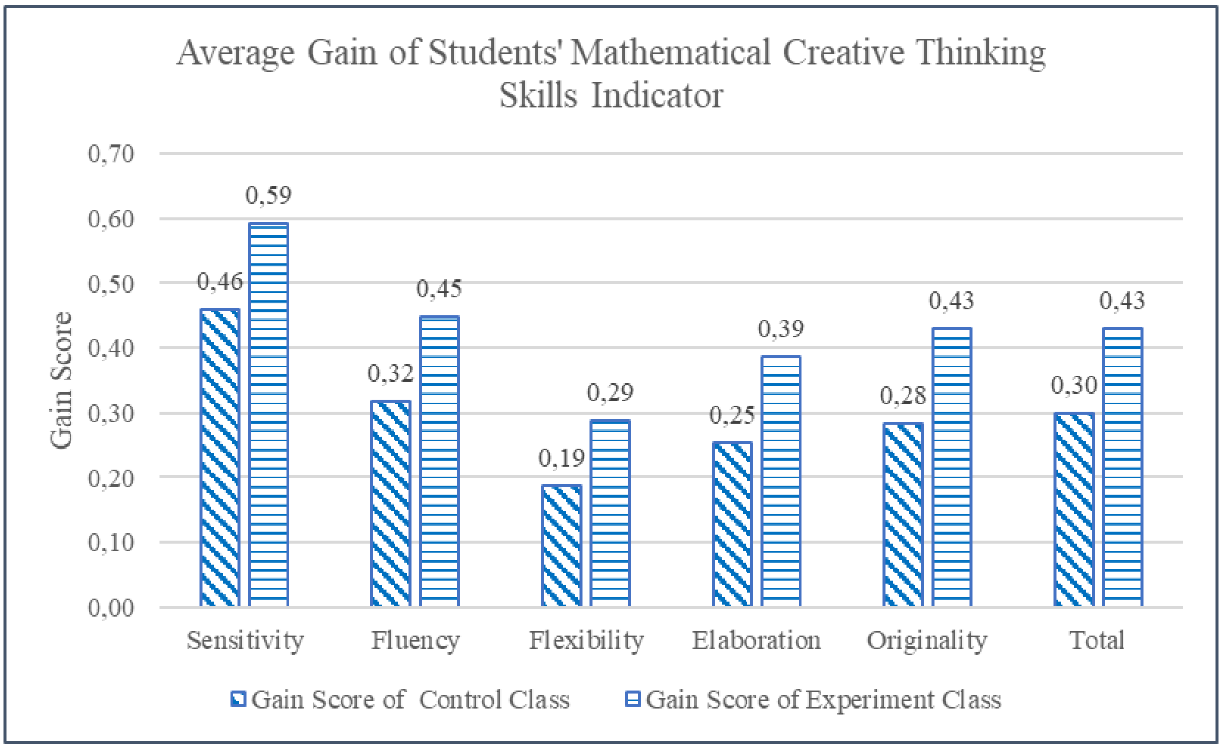

Figure 1. Average Gain of Students' Mathematical Creative Thinking Skills Indicators

According to the findings of this study, the implementation of the STEM-PjBL model in the experimental class enhanced students' mathematical creative thinking skills through two STEM-based projects. Each project was structured following the stages of the STEM-PjBL model: reflection, research, discovery, application, and communication. Both projects were designed to relate to real-world phenomena, with mathematics serving as the primary integrative component. This aligns with the key characteristics of the STEM approach, which emphasizes real-world problem-solving to strengthen higher order thinking skills, including creative mathematical abilities (Lee et al., 2019; Wahono et al., 2020).

The two projects assigned to students differed in emphasis. The first project focused primarily on science and technology aspects, while the second project emphasized engineering and technology, with mathematics at the core. The first project addressed the parabolic motion function of distance over time, whereas the second involved the construction of an arch bridge. Both projects were rooted in the concept of quadratic functions. This is consistent with Moore et al. (2014) who state that integrated STEM learning involves the combination of two or more STEM components with other disciplines.

The improvement in the average score of each mathematical creative thinking skill indicator was supported by the design-based nature of the projects. Through project design tasks, students explored a wide range of conceptual possibilities and adapted them to real-world contexts. The design process involved complex activities, such as generating multiple functional equations for the intended design. Students utilized digital tools such as GeoGebra and Desmos to visualize the curves formed by these equations. Through this exploration, students identified the distinct characteristics and uniqueness of the equations they created, which encouraged them to approach mathematics beyond the formulas typically found in textbooks. This exploration promoted the development of creative ideas and strengthened their creative thinking skills, particularly in sensitivity and fluency. Arsy and Syamsurizal (2021) emphasized that involving students directly in the process of designing and producing creative products fosters the development of creative thinking skills. Similarly, Suherman et al. (2020), found that real-world STEM education can sharpen students' sensitivity to real-world issues and help them propose a variety of solutions along with explanations for the phenomena they encounter.

In the *reflection stage*, students explored STEM-related topics and engaged with the material through project guides. At this point, they observed everyday phenomena to stimulate inquiry and research. In the first project, students connected the concept of quadratic functions to the projectile motion of objects, using physics principles drawn from the *Angry Birds*

Friends game (covering science and technology aspects). In the second project, the focus was on engineering through the design of modern arch or suspension bridges (covering engineering and technology aspects). Students identified connections between real-world phenomena and the disciplines of science, technology, engineering, and mathematics through their investigations. This approach is consistent with Agustina (2019) and Wiratman et al. (2019), who argue that the reflection stage of STEM-PjBL helps students connect classroom learning to real-world experiences.

In the *research stage*, students gathered information related to scientific concepts based on the phenomena they had observed. Under the teacher's guidance, students consulted various sources and devices to develop valid conceptual foundations for their projects. This process is aligned with Octaviyani et al. (2020), who note that students are supported in collecting information, designing, and refining relevant conceptual understandings during the research stage. Furthermore, group discussions during this stage allowed students to exchange ideas and explore diverse opinions, enhancing their elaboration and fluency in mathematical creative thinking. This finding resonates with Aliyah's (2017) who suggested that project-based learning encourages students to shift from simply receiving facts to exploring ideas.

The *discovery stage* played a pivotal role in the process, as it required complex planning and problem-solving. Students engaged in experiments and design tasks using tools such as Desmos and GeoGebra to graph and analyze function equations. For example, in the first project, students experimented with the *Angry Birds Friends* game to observe parabolic trajectories and determine corresponding quadratic equations. These activities helped students develop the ability to recognize unique mathematical patterns and generate original ideas in response to real-world scenarios. Perdana et al. (2020) found that group observation and investigation activities enhance students' sensitivity and their ability to identify and generate innovative solutions.

Designing was another essential component of the discovery stage. Through design tasks, students encountered challenges that required them to apply previously learned mathematical concepts creatively. In the second project, students designed an arch bridge based on the quadratic function equation. This process encouraged students to approach problems from new perspectives, improving their originality and flexibility in mathematical creative thinking. Octaviyani et al. (2020), noted that the discovery stage cultivates students' ability to propose multiple solutions, collaborate, and organize design strategies. Similarly, Zakiah et al. (2020), highlighted the role of planning, making, presenting, and evaluating products in stimulating students' creativity and creative thinking skills.

In the *application stage*, students implemented their project designs using selected tools, materials, and procedures. During this phase, students refined their designs, incorporated creative solutions, and adapted their projects to produce unique outcomes. This process is consistent with the characteristics of project-based learning, which fosters collaboration, enhances creative thinking skills, and promotes self-directed learning (Chiang & Lee, 2016). Additionally, some project activities extended beyond school hours, allowing students more time to collaborate and reflect on their design choices, leading to deeper learning and more refined products.

Hanif et al. (2019), emphasized that STEM-based project implementation fosters novelty, including both originality and germinal thinking (the generation of new ideas). In this context, students demonstrated novelty by developing original problem-solving strategies for quadratic functions and by modifying their products through iterative design processes. The germinal aspect was evident in students' ability to generate a wide variety of ideas, inspired by the information they gathered during earlier stages. Throughout the design process, students continually sought optimal solutions and improvements for their projects.

In the *communicating stage*, students presented the outcomes of their projects through group presentations. This stage, the final part of the STEM-PjBL cycle, allowed students to share and reflect on the results of their collaborative work. These presentations often sparked meaningful discussions, as students responded to questions and offered explanations based on their project experiences. This interactive exchange nurtured their elaboration and fluency in articulating ideas. Mentzer (2011), highlighted that, at this stage, students share their ideas and discoveries with peers, much like professional engineers seeking feedback on their work.

Throughout the project, the teacher played an essential role in guiding students through the planning, execution, and evaluation phases. This is in line with Ahmad et al. (2020), who stressed the importance of teacher support in helping students navigate problem-solving, develop project plans, and draw conclusions. When designing STEM-integrated projects, students were also encouraged to evaluate multiple possibilities and perspectives, which helped strengthen their creative thinking. Astuti et al. (2019) similarly emphasized that project-based learning enhances student engagement, encourages teamwork, and fosters creativity through hands-on project experiences.

CONCLUSION

The analysis of the research results demonstrates that the STEM-PjBL model effectively enhances students' mathematical creative thinking skills. Statistical findings from the Mann-Whitney U test confirm a significant improvement in the experimental group, which was taught using the STEM-PjBL model, compared to the control group, which received conventional instruction. Additionally, the normalized gain scores reveal that students in the experimental group outperformed their peers across various indicators of mathematical creativity.

The strength of the STEM-PjBL model is particularly evident in specific areas, as illustrated in Figure 1. The highest gain score in the experimental group was 0.59 for sensitivity, reflecting substantial growth in the ability to recognize and address mathematical challenges creatively. Furthermore, the most notable difference between the two groups was observed in the originality indicator, with a gap of 0.15, highlighting the model's capacity to foster innovative problem-solving. These improvements can be attributed to the model's emphasis on challenging, project-based tasks that stimulate creative engagement with mathematical concepts. In conclusion, the STEM-PjBL model is a powerful and effective approach for enhancing students' mathematical creative thinking skills.

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