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Investigating the effects of Realistic Mathematics Education on mathematical creativity through a mixed-methods approach

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ABSTRACT

This study investigates the effect of Realistic Mathematics Education (RME) on mathematical creativity among 96 seventh-grade students in North Kalimantan. Using an embedded experimental design, students were assigned to an experimental group (RME) and a control group (conventional teaching), each consisting of 32 students. The pretest and posttest showed a significant increase in mathematical creativity in both groups, with a greater increase in the RME group. Interviews indicated that RME positively impacted students' mathematical self-efficacy, proficiency in fractions, and enjoyment of learning. Students also favored teaching on the blackboard and mathematics games, which increased their interest. These findings confirm the effectiveness of RME in enhancing mathematical creativity and suggest further exploration of diverse learning media and icebreakers. This study highlights the potential of RME to foster creativity and recommends its integration into the mathematics curriculum.

Menyelidiki pengaruh *Realistic Mathematics Education* terhadap *mathematical creativity* melalui pendekatan metode campuran

Kata Kunci:

Berpikir kreatif
Metode campuran-tertanam
Sekolah menengah pertama
Masalah terbuka-tertutup
Realistic mathematics education

ABSTRAK

Penelitian ini menyelidiki pengaruh *Realistic Mathematics Education* (RME) terhadap *mathematical creativity* di antara 96 siswa kelas tujuh di Kalimantan Utara. Dengan menggunakan desain eksperimen tertanam, ditugaskan siswa ke dalam kelompok eksperimen (RME) dan kelompok kontrol (pengajaran konvensional), masing-masing dengan 32 siswa. Tes sebelum dan sesudah menunjukkan peningkatan *mathematical creativity* yang signifikan pada kedua kelompok, dengan peningkatan yang lebih besar pada kelompok RME. Wawancara menunjukkan bahwa RME berdampak positif terhadap efikasi diri matematis siswa, kemahiran dalam pecahan, dan kesenangan belajar. Siswa juga lebih menyukai pengajaran di papan tulis dan permainan matematika, yang meningkatkan minat siswa. Temuan ini mengkonfirmasi efektivitas RME dalam meningkatkan *mathematical creativity* dan menyarankan eksplorasi lebih lanjut terhadap beragam media pembelajaran dan pemecah kebekuan. Penelitian ini berimplikasi menyoroti potensi RME untuk menumbuhkan kreativitas dan merekomendasikan integrasinya ke dalam kurikulum matematika.

1. INTRODUCTION

Creativity, recognized as one of the most remarkable skills, plays a pivotal role in problem-solving and the advancement of civilization. In alignment with this notion, mathematics educators and teachers advocate cultivating creativity in mathematics education. This advocacy often involves adopting or modifying Guilford's components of general creativity: fluency, flexibility, originality, and elaboration [1]–[3]. Experts assert that mathematical creativity, a specific form of creativity, is intricately linked to mathematical ability. Kattou et al. reveal a positive correlation between mathematical creativity and mathematical ability, identifying mathematical creativity as a subcomponent of mathematical ability [3]. In line with Suherman and Vidákovich, mathematical creativity holds significant importance in mathematics education as it enhances the overall quality of education because this construct enables students to apply their knowledge more effectively to various problems [4]. Mathematical creativity empowers individuals to generate new, original, or unconventional solutions when faced with problems or unfamiliar situations [5], [6]. Accordingly, further research is still essential to explore this construct and identify the optimal classroom environment for fostering mathematical creativity and nurturing creativity in every student within the mathematics class [7]–[11].

Although researchers and mathematics educators widely acknowledge the importance of developing mathematical creativity, a fundamental challenge in mathematical creativity research emerges in the need for more clarity regarding its definition [12]. In this study, aligning with the perspectives of various experts, mathematical creativity is defined as the student's capacity to provide correct answers fluently, flexibly, and originally when dealing with open-ended mathematical problems [13]–[15]. Fluency entails providing multiple correct solutions, flexibility involves offering correct solutions across different categories, and originality refers to the ability to generate unfamiliar or unique solutions. Although some mathematical creativity research is conducted within settings involving exceptional mathematical talent or gifted students, there is a genuine need for research within 'normal school' settings, catering to a broader student population [16]. Insights into mathematical creativity development, including the roles of teachers and teaching environments, will be grounded in such research [17]. Consequently, this study involves tasks and open-ended mathematical problems of moderate difficulty [16].

Regarding refinement instructional approaches, mathematics teachers can utilize Realistic Mathematics Education (RME) as a suitable instructional strategy for enhancing mathematical creativity. Widely adopted, particularly in Indonesia, RME plays a prominent role in mathematics education [18], [19]. Despite initial criticisms and disappointments regarding students' arithmetic and algebraic skills, RME has continuously evolved and diversified in recent decades [20]. RME empowers students to understand the relevance of mathematics to the real world by solving authentic problems and developing mathematical concepts through self-invented strategies [21].

RME emphasizes using "realistic" situations, encompassing real-world scenarios and contexts students can imagine, to develop mathematical concepts [22]. RME views mathematics as a human activity involving guided reinvention, linking math concepts with real-life phenomena and learning processes through didactic phenomenology and differentiating between horizontal (applying math to real-world problems) and vertical (abstract reorganization of math) mathematization [23]. Principles of RME include active participation, starting with meaningful problems, progressing from informal to formal understanding, integrating mathematical domains, emphasizing individual and group learning, and guided trajectories [22]. Essential to RME is the "model of" and "model for" concepts, helping students transition from specific problem situations (e.g., a pizza for fractions) to generalized tools (e.g., ratio tables), thus developing broader, abstract concepts [24]. Guided reinvention encourages independent problem-solving analysis while evolving concrete models into formal symbols to help evaluate information and strategies [25]. Integrating RME into education enhances mathematical creativity by providing relevant contexts, supporting mathematical creativity development, preparing students for complex challenges, and helping them understand, interpret, and apply mathematical concepts, aligning with RME's goal of deepening mathematical understanding.

Research has shown that RME significantly improves students' mathematical creativity, as evidenced by Iskandar and Juandi's systematic literature review, which concluded that RME effectively enhances the skill [26]. A quasi-experimental study by Ismuandar et al. also demonstrated that students' mathematical creativity improved with RME, as posttest scores significantly increased compared to pretest scores [27]. The focus in RME is broader than real-world problems. The approach also encourages teachers to design non-authentic problems as long as students can figure out the provided context. Therefore, introducing fairy tale contexts in mathematical problems within RME classes is still deemed appropriate [22].

While interest in implementing interventions using RME is growing, studies collecting and analyzing both quantitive and qualitative data – mixed-methods approach – to comprehensively understand the effects of this learning approach are notably scarce. According to Fetters and Molina-Azorin, intervention studies should use mixed methods because this approach maximizes the information gained, enhancing the overall quality and impact of research [28]. In line with this, Creswell stated that researchers can utilize mixed methods to investigate the effectiveness of an intervention by collecting qualitative data through participant interviews [29]. An embedded experimental mixed-methods design can generate more comprehensive insights and perspectives. However, there remains to be a gap in research that employs a mixed-methods approach to thoroughly investigate the effects of RME. Addressing this gap is essential to fully capturing the complexities and impacts of RME interventions.

Exploration of recent research on the effects of RME on mathematical creativity reveals limited use of mixed-methods research, with only one study, namely Dang et al., demonstrating that implementing RME enhances the mathematical creativity of Vietnamese secondary students [30]. Despite numerous studies on RME and mathematical creativity in Indonesia, none have investigated the effects of RME on mathematical creativity using a mixed-methods approach. Current Indonesian research on RME using methods explores other constructs such as mathematical self-efficacy, critical thinking skills, and mathematical representation. For instance, Taubah et al. investigated the effects of Means-Ends Analysis RME on critical thinking and mathematical self-efficacy [31]. Another study by Yuhasriati et al. explored the impact of RME on mathematical representation [32].

Most research examining the effectiveness of RME on mathematical creativity has predominantly utilized quantitative approaches. Recent quantitative studies, such as Herlinda and Hidayat, investigated whether ethno-RME learning affects the mathematical creativity of eighth-grade students at junior high school [33]. However, qualitative investigations into the impacts of RME on mathematical creativity are notably scarce. As of June 22, 2024, a search on Google Scholar revealed only one study by Sitorus and Masrayati that aimed to uncover students' cognitive insights at each stage of the mathematical creativity process through implementing RME [34]. Qualitative approaches are particularly beneficial for capturing the nuanced aspects of mathematical creativity development and understanding students' perspectives and experiences. These methods allow for a deeper exploration of how students perceive and internalize the learning process, providing rich, detailed data that can reveal the underlying mechanisms of RME's effectiveness. Through interviews, qualitative research can uncover subtleties in student experiences that quantitative data might overlook, such as the emotional and cognitive challenges students face, the specific aspects of RME they find engaging or challenging, and how their confidence and problem-solving skills evolve during experimentation. A mixed-methods approach is valuable as it combines qualitative and quantitative research [29]. It addresses the limitations of previous research by providing a more comprehensive understanding of RME's impact on mathematical creativity. While quantitative data can measure the extent of improvement in mathematical creativity and provide generalizable results, qualitative data can explain why and how these improvements occur. For example, quantitative measures might show an increase in test scores. However, qualitative data can reveal that this increase is due to students' enhanced engagement and understanding of mathematical concepts through real-life applications presented in RME.

When considering research and development categorized as mixed-methods, several studies on RME exist but have not explicitly focused on mathematical creativity, including studies by Nurfithriyya et al. [35], Faidah et al. [36], and Erita et al. [37]. For instance, Erita et al.'s research focuses on providing student worksheets based on RME for circle materials to enhance students' mathematical reasoning abilities. These studies show the efficacy of RME and suggest its implementation and development to enhance mathematical abilities. However, they also underscore the ongoing need for comprehensive research to understand the effects of RME on mathematical creativity, particularly within the Indonesian context.

Research on the implementation of Realistic Mathematics Education (RME) in teaching has been extensively conducted, including studies on the application of RME to mathematical creative thinking skills [26], the improvement of mathematical self-efficacy [27], mathematical representation [32], critical thinking skills [31], and mathematical reasoning abilities [37]. However, among these studies, research utilizing mixed methods to investigate the impact of RME on mathematical creativity is still rare.

This study aims to investigate the effects of RME on mathematical creativity to bridge this research gap by adopting a mixed-methods approach that encompasses both quantitative and qualitative aspects. Unlike previous research, this study employs an embedded experimental design with a mixed-method approach that combines quantitative and qualitative data. This method provides a more comprehensive understanding of how RME affects students' mathematical creativity. The results of this study are expected to enrich the literature on the effectiveness of RME and provide recommendations for the development of more innovative and effective learning media.

Contribution to the literature

This research contributes to:

- Providing empirical evidence that RME can significantly enhance students' mathematical creativity, particularly in fluency, flexibility, and originality.
- Demonstrating that using RME can increase students' interest and engagement in mathematics.
- Enriching the literature on effective mathematics learning approaches at various educational levels.

2. METHOD

In this research, we explored the impact of RME on mathematical creativity among 7th-grade students, focusing on fraction learning. We employed an embedded experimental mixed-methods design to achieve our research objective comprehensively [29]. This approach involved collecting and analyzing primary quantitative data through tests and complemented by qualitative insights from interviews. Our hypothesis posited that implementing RME would significantly enhance students' mathematical creativity. We adopted a nonrandomized control group, pretest-posttest design to structure the experimental design [38]. The experiment involved implementing RME in one class over five meetings, while a control group received conventional teaching across the same number of sessions. This design allowed us to compare the effects of RME against traditional teaching methods, providing a precise measure of its impact on students' mathematical creativity.

2.1 Participants

The research was conducted at a public junior high school in Tarakan, North Kalimantan, Indonesia, focusing on two classes. The selection process utilized a cluster sampling technique, targeting groups of individuals rather than selecting individuals [38]. Class 7#1, the control group with 32 participants, was taught the fraction topic using a conventional teaching (CT) approach. Conversely, Class 7#2, the experimental group with 32 participants, received instruction on the same topic using the RME approach. Six participants were selected using a purposive sampling technique for the qualitative dimension, three from each group, designed to reflect the diversity in mathematical creativity levels found in the overall student population. The selection criteria were based on the participants' initial mathematical creativity levels, as determined by pretest scores. The experimental and control groups included one participant, each with high, medium, and low mathematical creativity levels, mirroring the distribution of students' mathematical creativity in the two cohorts. For a thorough comparative analysis, these participants ensured a balanced representation of different mathematical creativity levels in both groups. In Table 1, the demographics of students are presented in qualitative dimensions.

Table 1. Participants' Demography for Qualitative Dimension

Group	Participants	Mathematics Creativity	Sex
Experimental	PQE#1	High	Female
	PQE#2	Medium	Male
	PQE#3	Low	Male
Control	PQC#1	High	Female
	PQC#2	Medium	Female
	PQC#3	Low	Female

2.2 Teaching-Learning Materials, Tests, and Interview Guidelines

Before experimentation, we developed teaching-learning materials, which included lesson plans, student worksheets, and learning implementation sheets. Additionally, we prepared instruments for data collection, consisting of mathematical creativity pretest-posttest, and interview guidelines for use before and after implementing RME. These learning materials were meticulously developed by the authors and validated by experts. The validity and reliability of the tests were further scrutinized and refined based on the experts' valuable input [38].

2.2.1 Lesson Plans

This study implemented an experimental approach to teaching, requiring the development of lesson plans (LPs) to ensure a clear and consistent teaching standard [38], [39]. The LPs were designed to align with the study's objectives and to provide insights into factors contributing to learning outcomes. Researchers developed LPs for RME and CT, encompassing five meetings that covered realistic fraction problems. Two experts in mathematics education and one junior high school mathematics teacher reviewed the LPs. Validators assessed the construction and language appropriateness, resulting in an average validity score of 4.50 for both RME and CT (on a scale of 5.00).

2.2.2 Students Worksheets

Student worksheets (SWs) are essential in supporting the implementation of RME, particularly for providing realistic problems for students to solve collaboratively [40]. Thus, SWs were developed for each meeting according to the RME-LPs. Similar to the LPs, the SWs were reviewed by two experts and one practitioner. The validation process revealed that the SWs met the "valid" criteria, with an average score of 4.20 (on a scale of 5.00). Reviewers examined construction, language appropriateness, how well the SWs stimulated student curiosity, task suitability with students' cognitive levels, the realism of the problems, and the appropriateness of the material sequence. An example of a worksheet assignment is shown in Figure 1.

Translation:
On the day of the Independence of the Republic of Indonesia celebration, two groups of students representing SMPN Bakti Bangsa will participate in the ceremony at Merdeka Stadium, namely Davit Group and Hari Group. The Davit Group comprises six students, while the Hari Group comprises three students. After the ceremony, the Davit Group received three loaves of bread, while the Hari Group received two loaves. Determine which group, Davit or Hari, received the fewest bread slices. Use fractions to describe the number of bread slices each group received.

Figure 1. An Example of Task on Worksheet

2.2.3 Learning Implementation Sheets

Learning implementation sheets (LIS) for experimentation observation are crucial in experimental or implementation studies as they help comprehensively monitor, document, analyze, and evaluate the teaching process [38]. Accordingly, LIS was developed in line with the LPs. There were LIS based on RME and LIS based on CT, and the LISs were completed during each experiment meeting. Reviewers examined construction and language appropriateness. The validation process indicated that the LISs achieved "valid" criteria, with an average score of 4.20 (on a scale of 5.00).

2.2.4 Mathematical Creativity Tests

We developed tests to measure mathematical creativity in line with how we defined the construct. Validated pretests and posttests were developed to measure students' mathematical creativity. The test's validity covered internal validity (expert/practitioner assessment) and external validity (item validity, discrimination index, difficulty index) [38]. Experts and practitioners suggested that the developed tests were valid. Item validity using product moment Pearson correlation for the pretest and posttest was at least "high," criterion (the most negligible value 0.704) with two items for the pretest (0.810 and 0.843) and one item for the posttest was "very high" (0,844). The discrimination index met the "moderate" criterion. Additionally, all pretest items had a "moderate" difficulty level. Furthermore, the pretest and posttest demonstrated "very high" reliability, with values of 0.870 and 0.874. We chose the five highest validities from seven items and developed a pretest and posttest to measure students' mathematical creativity (see Appendix 1 for an example problem on the posttest).

2.2.5 Interview Guidelines

Semi-structured interviews were conducted three times to investigate the effectiveness of RME by exploring participants' experiences and perceptions of RME and CT as instructional methods. Consequently, we developed guidelines for these interviews [41].

2.3 Experimentation Procedure

In the implementation of this experiment, the steps are presented in Table 2 and Table 3.

Table 2. Steps and Teacher Activities in Implementing Realistic Mathematics Education

Steps	Teacher Activities
Introduction	Motivating students and communicating learning objectives
	Connecting the current lesson with previous lessons
Core	Explaining contextual problems
	Guiding students to discover answers and ways to solve problems by providing limited assistance
	Observing how students solve problems
	Acting as a motivator for students to solve problems in their way
	Optimizing student interaction during work
	Leading class discussions and taking control of the class
	Appreciating various student responses
	Directing students to discover and conclude mathematical concepts
	Encouraging students to ask questions, express opinions, or answer questions
	Providing exercises to students
Closing	Concluding the lesson
	Conducting an ice-breaking activity
	Closing the meeting

Table 3. Steps and Teacher Activities in Implementing Conventional Teaching

Steps	Teacher Activities
Introduction	Motivating students and communicating learning objectives
	Connecting the current lesson with previous lessons
Core	Gathering information about students' knowledge related to the study material
	Explaining the material and provide examples
	Assigning practice problems to students
	Offering assistance to students when they are facing obstacles
	Directing students to present their answers
	Encouraging students to ask questions, express opinions, or answer questions

	Appreciating various student opinions
	Directing students to discover and conclude mathematical concepts
	Encouraging students to ask questions, express opinions, or answer questions
	Providing exercises to students
Closing	Concluding the lesson
	Conducting an ice-breaking activity
	Closing the meeting

2.4 Data Analysis

By the experimental design, pretest-posttest data were gathered before RME was implemented. The collected data underwent analysis through t-tests utilizing SPSS® (Statistical Program for Social Science 27) for Windows. Concurrently, data detailing how teaching-learning activities were operationalized throughout the experimentation phase were systematically collected during each meeting, employing observation sheets for comprehensive documentation.

As mentioned before, qualitative data were obtained through semi-structured interviews conducted in conjunction with the tests. The qualitative data underwent analysis following Creswell's approach [29]. Initially, the collected data were thoroughly read multiple times to gain a comprehensive understanding. Subsequently, the data were coded before identifying and testing themes through triangulation and member checking [42]. The established themes were then described and interpreted, ultimately leading to the formulation of robust conclusions. Throughout the data organization and analysis process, NVIVO® 12 was instrumental, particularly in generating codes and themes.

The convergence of quantitative and qualitative findings was meticulously examined, ultimately culminating in the comprehensive reporting of the research. Figure 2 shows the flowchart of the Embedded Experimental Mixed Methods implemented.

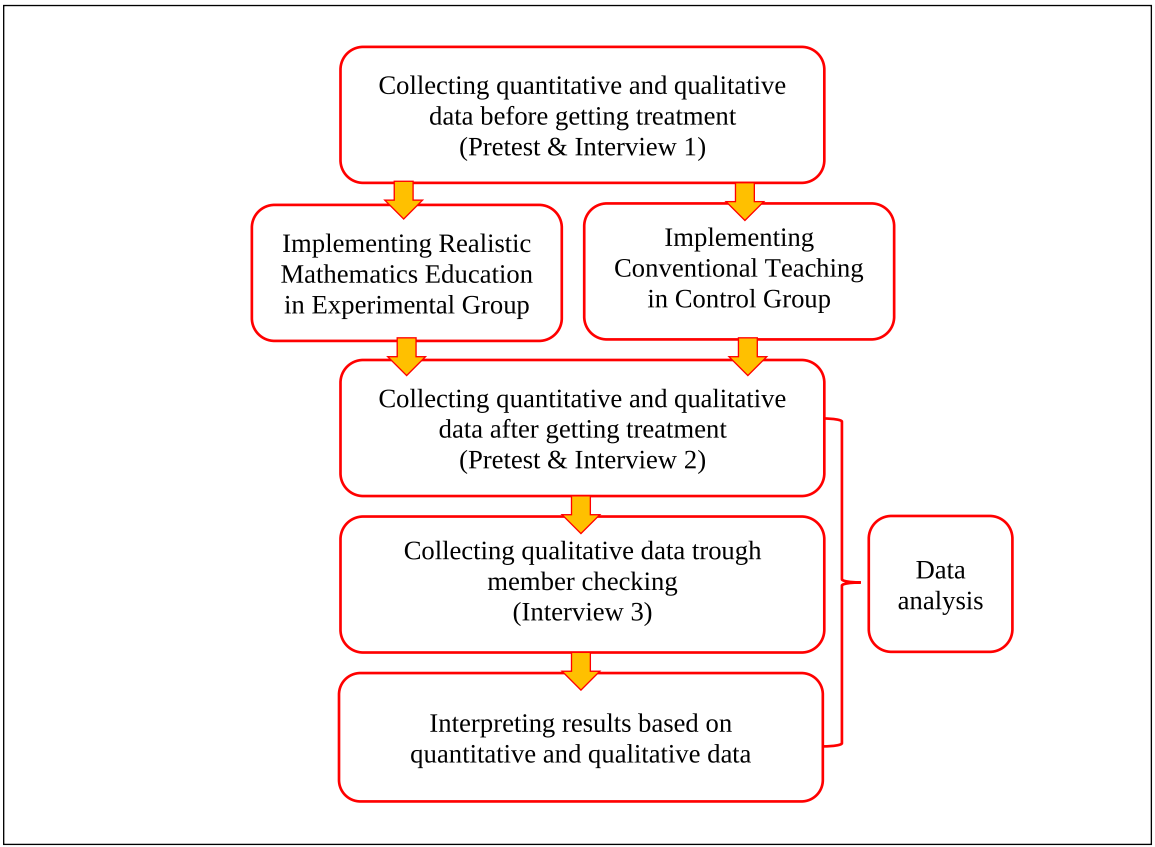

Figure 2. Embedded-Experimental Mixed-Methods Implemented

3. RESULTS AND DISCUSSION

The comprehensive analysis of both quantitative and qualitative data yielded compelling findings regarding the impact of RME on students' mathematical creativity. The results indicated a notable increase in mathematical creativity for students exposed to RME. Interestingly, the CT approach also demonstrated an improvement in mathematical creativity, albeit to a lesser extent compared to the effectiveness of RME. The qualitative insights from the experimental and control groups provided valuable perspectives. Notably, students preferred whiteboards over PowerPoint as a medium, highlighting the significance of the instructional environment. Additionally, integrating games as an icebreaker was identified as a beneficial practice, fostering a positive learning experience. These nuanced findings underscored the positive impact of RME on mathematical creativity while shedding light on valuable insights that could enhance instructional strategies in mathematics education.

3.1 Quantitative Analysis

The pretest-posttest analysis demonstrated a significant improvement in mathematical creativity following the implementation of RME. Initially, the pretest results indicated a comparable mathematical creativity level between the experimental and control groups. However, after learning using the RME approach, the mathematical creativity of students in the experimental group exhibited a substantial and statistically significant increase compared to the control group. Observations of teacher performance throughout the five meetings in both groups consistently met the 'good' criterion. The teacher effectively implemented the RME approach in the experimental group and conducted CT with the planned approach in the control group.

An independent t-test indicated no significant differences between the pretest scores of the experimental group ($M = 28.75$, $SD = 7.750$) and the control group ($M = 28.69$, $SD = 6.537$). Furthermore, following the experimentation, the independent t-test revealed a substantial difference in the posttest scores of the experimental group ($M = 76.63, SD = 8.071$) compared to the control group ($M = 63.44$, $SD = 10.476$). Students learning through the RME approach demonstrated significantly higher mathematical creativity than those in the CT group, $t(62) = 5.641$, $p = 0.001 < 0{,}05$, $M_E - M_C = 13.188$. The pretest-posttest results for the experimental and control groups are shown in Figure 3 and Figure 4.

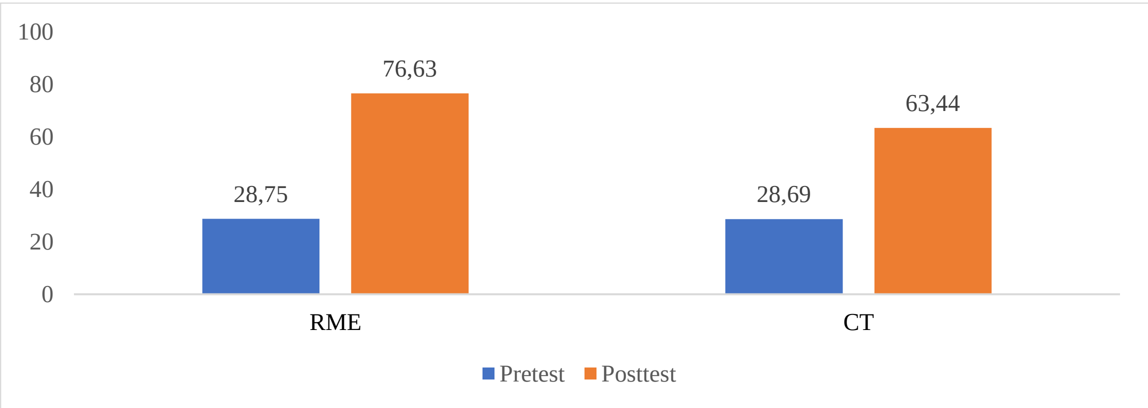

Figure 3. The Pretest-Posttest Results of the Experimental and Control Groups

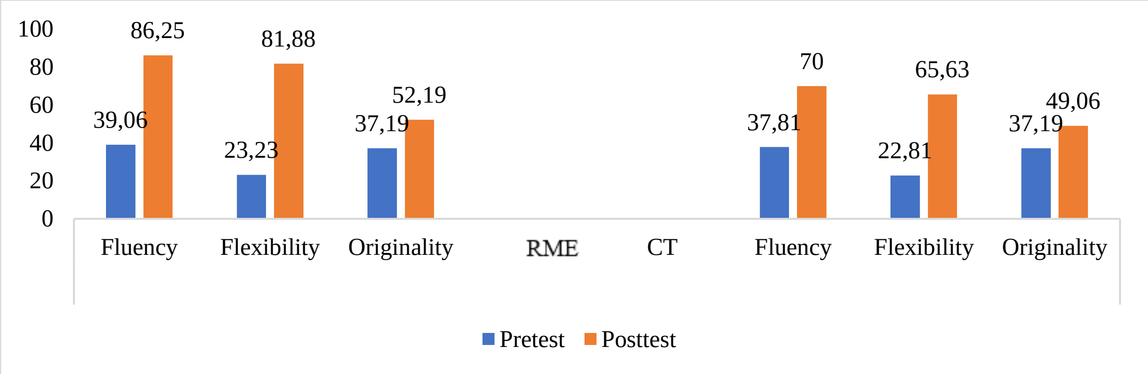

Figure 4. The Pretest-Posttest Results of the Experimental and Control Group Regarding Mathematics Creativity Aspects

Mathematical creativity encompasses the capacity to solve math problems accurately, fluently, flexibly, and originally. Fluency, an indicator of mathematical creativity, is demonstrated by a student's ability to accurately generate diverse and complete answers. In this study, students showed fluency by providing at least two complete answers for each math problem during the mathematical creativity test. The results indicated a remarkable improvement in fluency for the RME group, increasing from 39.06 to 86.25, more than doubling their pretest scores. Flexibility, another indicator, reflects the student's ability to offer correct solutions across different categories. Students demonstrated flexibility by producing at least two complete and correct answers using different strategies. The RME group's flexibility scores increased significantly from 23.23 to 81.88, highlighting their enhanced ability to adapt their thinking paths and find multiple solutions to problems. Originality, the third indicator, is reflected in a student's ability to present unique or unfamiliar answers compared to other students. Students demonstrated originality by providing at least two complete answers, each unique compared to other students' answers during the mathematical creativity test. Although originality showed the most modest posttest scores, the RME approach still significantly increased students' ability to generate unique solutions.

These fluency, flexibility, and originality improvements underscore the RME approach's efficacy in enhancing students' mathematical creativity. Figure 2's bar chart illustrates changes in mathematical creativity, with flexibility registering the lowest pretest score and originality showing the most modest posttest scores after experimentation. These results further underline the effectiveness of RME in fostering mathematical creativity among students.

3.2 Qualitative Analysis

3.2.1 Before Experimentation

Before the experimentation commenced, an exploration was conducted to understand how participants in both groups perceived fractions, a foundational topic in mathematics. These participants had previously encountered the topic during elementary school and right before the experimentation. The qualitative analysis unveiled four prominent themes: a lack of skill in operating fractions, a sense of accomplishment when successfully solving mathematics problems, the perception that pretest problems were challenging, and the recognition of the practical benefits of fractions in daily life.

All participants acknowledged their lack of skill in operating fractions, with even the participant with the highest mathematical creativity in the experimental group expressing a need for improvement. Participant PQE#1 mentioned, "*I often forget* (how to deal with fraction problems). *I am still lacking the ability in fractions.*" [Int._1] Similarly, the participant with the highest mathematical creativity in the control group admitted, "*I am not too capable* (in fractions)." [Int._1] However, all participants conveyed a sense of achievement when successfully tackling fraction problems. Participant PQC#2 emphasized the positive experience: "*When I successfully answer a difficult mathematics problem, it is a good experience. I feel proud after making an effort to answer the question finally.*" [Int._1]

More than half of the participants highlighted the practical benefits of fractions in everyday life, emphasizing their relevance. Simultaneously, all participants found the pretest problems before experimentation challenging, particularly the open-ended problems. For example, PQC#1 expressed, "*Confusing, Miss*. (A problem with) *only one answer sometimes makes me confused, Miss*. *This one has more than one. It is also rare to be given such problems, Miss*." Four participants mentioned that it was their first experience dealing with mathematics problems that had multiple correct answers. PQC#3 shared, "*When I first read the problem, I was surprised and confused, Miss, because it was the first time I encountered a problem like that. Usually, we are not asked for many answers.*" Four participants emphasized the advantage of learning fractions, citing their practical applications in everyday life, such as buying flour or sugar. PQE#1 illustrated, "(Fractions) *are beneficial. For example, in buying flour ¼ or ½ kg, as well as when buying sugar.*" [Int._1] Of six participants, two admitted uncertainties regarding the topic's practicality. "*I do not know, Miss. I have no idea.*" [PQE#2, Int._1]

3.2.2 After Experimentation

Data from the experimental group unveiled three primary themes: participant perceptions of RME, the changes experienced after participating, and participant expectations for enhancing mathematics learning. Initially, participants expressed confusion when learning mathematics through RME but eventually found the approach enjoyable. RME was perceived as a new and valuable experience, particularly emphasizing the significance of the discussion stage. Participants highlighted the element of learning while playing, with PQE#1 stating,

I felt confused when learning at the beginning because I had to independently answer (given tasks in the worksheet), *but then I got used to it. I followed the strategy provided by the teacher. Now, I can solve (mathematics problems) on my own. Eventually, the learning became fun because of the chance for discussion with my friends and the inclusion of games.* [Int._3]

The approach facilitated easy comprehension of materials, provided opportunities for exploration through tasks on worksheets, and was deemed challenging yet enjoyable.

As anticipated, participants in the control group reported that the CT approach was not new to them. PQC#2 mentioned, "(The learning approach) *was not new because, as usual, the teacher explains the material and then provides examples. If there was anything different, it might be the teacher's fun demeanor, making her teaching less stressful.*" [Int._2] Despite the familiarity with CT, all participants perceived the learning experience as enjoyable and easy to comprehend. PQC#3 noted, "*She* (=the teacher) *was fun, so the class was not silent*, (the class was) *fun*." [Int._2] The participant added, "*Miss Sury usually used games. The teachers usually just explain the material without using games.*" [Int._3]

The participants exhibited improvement in self-efficacy, mathematics ability, and engagement in learning. They perceived the posttest to be easier than the pretest, even though the problems were designed to be of the same difficulty. Participants expressed a general increase in their mathematical creativity, particularly noting improvements in fluency. Participant PQE#3 remarked, "*It is smooth, Miss. When I see the problem, I already know which method to use and what to do with it.*" [Int._3] They also mentioned enhancements in originality when dealing with problems, although not to the same extent as fluency. However, when discussing flexibility, participants said there was no significant transformation in this aspect.

Researcher : "*According to you, do you feel more capable of changing your approach when facing difficulties or being stuck, especially when working on fraction problems?*"
PQE#3 : "*I think it's a bit, Miss, because when I find it a bit difficult, I still ask the teacher, so it's not always smooth.*"
PQE#2 : "*Sometimes yes, sometimes no, Miss. Sometimes, I think of using one method; sometimes, it takes me a bit longer to think about which method to use.*"
PQE#1 : "*Sometimes no, Miss, but sometimes suddenly I think of using this method. Sometimes, I take a long time to think about which method to use.*" [Int._3]

In alignment with the quantitative results and mirroring the experimental group, all participants in the control group perceived the posttest to be easier to handle. However, one participant noted that her creativity in mathematics remained. Participants in the control group acknowledged a noticeable increase in self-efficacy, as Participant PQC#2 expressed, "*It seems like* (confidence in understanding learning mathematics or solving fraction problems) *has increased, but there are some* (parts of the material) *that need to be reviewed.*" [Int._3] Nevertheless, two participants mentioned that fractions, particularly mixed ones, still posed difficulties. For example, Participant PQC#1 stated, "*I still have difficulty operating mixed fractions, Miss.*" [Int._2]

Similar to participants in the experimental group concerning mathematical creativity, participants in the control group highlighted that fluency was the most achievable aspect. At the same time, originality posed the most significant challenge. Notably, in the flexibility aspect, all participants in the control group mentioned that they did not feel more capable of changing their approach when faced with difficulties in tackling fraction problems. For instance, one participant expressed, "*Nope* (=I still cannot change my approach when I face difficulty dealing with fraction problems), *Miss. However, sometimes, I wanted to change my strategies, but I still doubted how to implement them.*" [Int._3]

At the outset of the experimentation, we did not anticipate that all participants would emphasize the importance of learning through whiteboards and incorporating games as icebreakers. Participants in both the experimental and control groups preferred learning using whiteboards over PowerPoint, and they highlighted the significance of integrating games into mathematics teaching. They hoped that mathematics educators would continue to utilize these media and incorporate games into their teaching. Participants indicated they needed more time to record materials from PowerPoint, whereas teachers using PowerPoint tended to explain the materials more quickly than those using whiteboards. The whiteboard texts were deemed clearer and more visible than those on PowerPoint.

Participant PQE#2 mentioned, "*With PowerPoint, sometimes it is too bright, and the writing is small. It is also too fast, Miss, so I do not have time to take notes. The display is attractive, but it is too fast.*" [Int._3] In agreement with PQE#2, PQE#1 stated, "*Yes, Miss. With PowerPoint, sometimes it is too bright, and the writing is too small. The explanation is too fast, so there is no time to take notes.*" [Int._3] participants also emphasized the importance of games to enhance their enjoyment of the teaching-learning activity. For example, PQE#2 stated, "*It is crucial, Miss. I am personally much more interested because of the games. Even though they were* (math) *questions, they were fun. It felt like being encouraged to think quickly so that I could answer smoothly.*" [Int. 3]

The integration of quantitative and qualitative findings in this study underscores the pronounced efficacy of RME in elevating students' mathematical creativity compared to CT. While initial mathematical creativity levels showed no significant disparity between the experimental and control groups, post-implementation analysis revealed a substantial and noteworthy increase in the mathematical creativity of the experimental group. It is essential to acknowledge that CT also facilitated a significant enhancement in the mathematical creativity of the control group. Qualitative insights further corroborate these results, highlighting the comprehensive and enriching learning experiences of participants in the RME group.

Before the experimentation, participants' qualitative responses revealed perceptions of fractions characterized by difficulty, a sense of accomplishment when solving problems, the challenge of pretest problems, and the practical benefits of fractions. All participants admitted to struggling with fractions, even those with high mathematical creativity, expressing pride in solving complex problems but finding the pretest particularly challenging, especially the open-ended questions. While most participants acknowledged the everyday usefulness of fractions, a few were uncertain about their practicality. After the experimentation, qualitative analysis revealed three main themes: perceptions of RME, changes post-experiment, and expectations for future learning. Initially confusing, RME was eventually found enjoyable and beneficial, mainly due to the discussion. Participants in the experimental group improved self-efficacy, mathematical ability, and engagement. They found the posttest easier and noted increased fluency and originality in problem-solving, though flexibility remained challenging. In the control group, the CT approach was familiar and enjoyable because of the teacher's engaging demeanor. Participants also found the posttest easier, with improved self-efficacy and fluency, though originality and flexibility were still too complex. Both groups preferred learning with whiteboards over PowerPoint for clarity. They emphasized the importance of integrating games into lessons, finding that whiteboards allowed more time for note-taking while games increased engagement and enjoyment in learning.

Quantitatively, before the experimentation, participants demonstrated a lack of preparedness in fractions, as indicated by their pretest scores, with the experimental group averaging 28.75 ($SD = 7.750$) and the control group averaging 28.69 ($SD = 6.537$). This result is supported by qualitative data revealing that all participants lacked skill in operating fractions. Despite learning fractions in elementary and junior high school, participants could not sum, subtract, multiply, or divide fractions such as $1/5$ by $3/4$. All participants found the pretest problems challenging, aligning with findings by Kamara et al. and Simamora et al. which indicated that junior high school students face difficulties in learning mathematics due to a lack of basic operations in fractions even though they have learned fractions in elementary and junior high school [43], [44]. After experimentation, the experimental group initially found RME confusing but eventually appreciated it, especially the discussions that facilitated understanding. The control group found traditional teaching familiar and enjoyable due to the teacher's engaging demeanor. Both groups showed improved self-efficacy and mathematical ability, perceiving the posttest as more accessible, noting enhancements in fluency but not flexibility. However, quantitative data indicated that students' mathematical creativity in the RME group was significantly higher than in the CT group, with a gain of 13.188.

Interestingly, a contrast emerged between fluency and originality. Quantitative data showed that the gain in flexibility was higher than originality in both the experimental and control groups. However, qualitative data revealed that all students perceived the increase in flexibility as less than that of originality. This finding suggests the need for more mixed-methods studies to explore the gain of each aspect of mathematical creativity. Despite the qualitative findings, challenges in cultivating originality emerged as a notable facet of this study, representing the capacity to furnish unique solutions. This finding echoes Corazza's idea, highlighting that creativity is difficult to achieve originality, and proving effectiveness can be challenging [45]. Furthermore, the interplay between general creativity and mathematical ability gains prominence through the works of Leikin and Guberman [5] and Schoevers et al. [46], suggesting that robust mathematical creativity necessitates concurrent development of general creativity within mathematics.

The increase in students' mathematical ability by implementing RME aligns with previous research. For instance, Tamur et al. conducted a meta-analysis assessing the effectiveness of RME on students' mathematical abilities, finding that RME significantly improves mathematical abilities compared to CT [47]. The effectiveness varied with sample size and experiment duration, suggesting that RME is particularly beneficial in Indonesia when considering CT. Samritin et al. also found that RME significantly improves mathematics learning outcomes, shifting teaching and learning styles from teacher-oriented to student-oriented [48]. Dang et al. [30] further assert that a creativity-enriched mathematics instruction model rooted in RME principles nurtures mathematical creativity by fostering meaningful experiences, providing realistic contexts, and instigating an enthusiastic approach to learning.

The effectiveness of RME in this study is also attributable to the well-developed and validated teaching materials, including lesson plans (LPs) and student worksheets (SWs), which achieved the 'good' criterion in every session. The implemented RME demonstrated its efficacy in enhancing mathematical creativity through engaged learning activities. Initially confusing, RME was eventually found enjoyable and beneficial due to discussions. This finding indicates that RME's principles, such as the *activity* principle (students are active participants, learning by doing mathematics), the *interactivity* principle (mathematics learning is both an individual and social activity), and the *guidance* principle (teacher's guide student learning through well-planned trajectories and scenarios) [22], were effectively applied.

The initial phase of RME implementation in each session presented challenges by having students collaboratively solve problems in SWs. Students faced realistic problems requiring independent problem-solving strategies. This approach was designed to fulfill the *realistic* principle – mathematics education should start from meaningful problem situations and aim to apply mathematics to real-world problems [22] – and induce productive struggles, aligning with the notion that students learn optimally when actively resolving intricate problems or grappling with complex concepts [49]. Incorporating open-ended problems during this phase encouraged students to provide multiple correct and unfamiliar answers, fostering a deeper understanding of mathematical concepts [50], [51].

Furthermore, incorporating exploratory tasks and discussions in response to the challenges significantly elevated students' engagement levels. Ice-breaking activities and mathematical games played a pivotal role in enhancing the overall quality of learning. We did not anticipate that all participants would emphasize the importance of learning through whiteboards and incorporating games as icebreakers at the outset of the experimentation. Notably, the RME approach created an environment that promoted an exploratory mindset, discussion, problem-solving, risk-taking, and reinvention – fundamental aspects contributing to the development of mathematical creativity [17], [49]. The emphasis on productive struggle in the findings underscores the importance of tasks that challenge students to explore materials independently and collaboratively [49]. While designing and implementing learning with productive struggle demands creative efforts, the resulting enhancement of mathematical competence justifies the endeavor [51].

Participants in the control group, exposed to CT methods, reported finding the approach enjoyable and understandable. This observation suggests that CT still holds promise in fostering mathematical creativity, provided teachers effectively articulate the material and create a supportive learning environment. The control group's exposure to open-ended problems and mathematics games, similar to the experimental group, further substantiates the adaptability of CT approaches. It is essential to note that the CT method is characterized by its efficiency in terms of lesson preparation time and demands a lower level of teacher competence, primarily relying on describing solution methods [51]. The study highlights the merits of both RME and CT approaches in enhancing Mathematical creativity. However, it emphasizes the superiority of the RME approach, which prioritizes engaged and exploratory learning, offering a more comprehensive and impactful method for cultivating deep mathematical understanding among students.

The findings underscore the need to carefully weigh the trade-offs between the efficiency of traditional teaching methods and the transformative potential of innovative approaches like RME to enhance mathematical creativity. Crucially, the study recognizes the pivotal role of mathematics teachers in developing mathematical creativity. Creative teachers are seen as critical contributors to fostering creative students. Existing research, exemplified by Moore-Russo and Demler, affirms that mathematics teachers play a central role in shaping mathematical creativity within the school environment [52]. Teacher competencies are crucial in designing teaching approaches and implementing appropriate pedagogies [53]. Consequently, the study suggests that mathematics teachers should be discerning in teaching approaches, with RME emerging as a viable and beneficial option based on the findings. This finding underlines the importance of empowering teachers to make informed decisions that contribute to the holistic development of students' mathematical competence.

Our findings suggest that both groups reported increased self-efficacy and creativity post-experimentation, particularly in fluency. Correlations between students' perception, self-efficacy, and achievement align with Regier and Savic's study, exploring the positive impact of fostering mathematical creativity on students' self-efficacy for proving and emphasizing enduring effects on their long-term mathematical trajectories [54]. In addition, the investigation by Bicer et al. focuses on problem-posing as an effective intervention and measurement tool for students' mathematical creativity [55]. Positive impacts across grade levels challenge misconceptions, establishing a correlation between mathematical creative ability and self-efficacy. The studies advocate for problem-posing integration in classrooms, recognizing the need for teacher training and suggesting further research on successful in-service teacher integration and theoretical model refinement.

RME emphasized strengthening students' understanding of mathematical concepts through rediscovery and problem-solving guided by teachers. Students' learning experiences, particularly reinvention and problem-solving [22], [56], enhanced students' understanding of mathematical concepts. This finding aligned with Komaruddin et al.'s [57] research, which investigated the effect of RME-based Krulik-Rudnick Heuristics on mathematical concept understanding, considering self-efficacy. Regardless of the student's levels of mathematics self-efficacy, the study found an increase in mathematical concept understanding among the students. Furthermore, Siregar and Prabawanto found that RME could enhance students' mathematical self-efficacy [58]. This study indicated that students' attitudes responded positively to implementing RME.

The ongoing evolution of RME, exemplified by its adaptability to incorporate technology and resonate with diverse cultural school settings, is exemplified by studies such as Suparatulatorn et al. [59] and Prahmana's [60] Ethno-Realistic Mathematics Education (E-RME) framework. Suparatulatorn et al.'s research underscores the importance of integrating technology and Polya's problem-solving approach within the framework of RME, showcasing its potential to enhance preservice mathematics teachers' understanding and problem-solving abilities. Prahmana's E-RME framework, a fusion of RME and Ethnomathematics strengths, sparks curiosity about its potential impact on mathematical creativity within the context of school settings, opening avenues for further exploration and investigation.

A surprising but significant revelation emerged from the semi-structured interviews, where participants unanimously recognized the pivotal role of games as icebreakers in learning activities, irrespective of the teaching approach. This recognition emphasizes the utility of incorporating fun and games in educational settings, aligning with existing literature that underscores the positive impact of such approaches on learning and anxiety reduction [61], [62]. Sasan et al. emphasize problem-posing as an effective intervention and measurement tool for students' mathematical creativity [63]. Quantitative analysis showed a significant increase in self-reported engagement levels after icebreaker participation, supported by qualitative findings indicating an improved classroom atmosphere and increased willingness to participate in discussions. These insights suggest that incorporating icebreakers can establish a positive classroom atmosphere, enhance student comfort, foster peer connections, and cultivate essential social skills. The study also reveals the transformative perception of mathematics games, adding enjoyment and engagement to the learning process. Aligned with educational philosophies promoting a comfortable and anxiety-free classroom [53], this research emphasizes the benefits of icebreaker activities. It underscores the need for future exploration into different icebreaker types, their impact on diverse student outcomes, and factors influencing effectiveness, such as class size and demographics. The study contributes valuable insights to creating inclusive and engaging learning environments.

The study uncovered a surprising preference for traditional whiteboards over modern PowerPoints, challenging assumptions about technological superiority. Despite PowerPoints offering visual advantages, students appreciated the clarity, hands-on interaction, and cognitive benefits of handwriting on whiteboards. Both groups favored whiteboards for visibility, clarity, and note-taking. Meeker and Thomson's historical exploration traced the evolution of visual aids from lantern projections to PowerPoint, showcasing technological advancements [64]. However, the enduring appeal of whiteboards, rooted in simplicity and hands-on engagement, remained evident.

Furthermore, Billman et al.'s South African university case study highlighted a subject-culture dynamic, with many mathematics staff favoring chalkboards over technology [65]. Preferences were influenced by gender and academic qualifications, with a noticeable shift towards technology among female staff and larger groups. In addition, Rudow & Fink's student-focused study emphasized a clear preference for chalk/whiteboards over PowerPoint in college science classes [66]. Students highlighted attention retention, favoring traditional methods. The study challenges assumptions by revealing a strong preference for traditional whiteboards. The findings suggest a nuanced approach, considering traditional and technological tools to meet diverse learning preferences and optimize educational experiences.

This research legitimation is evaluated through quantitative and qualitative dimensions [29]. Valid and reliable instruments serve as measures of validity in the quantitative dimension, while meticulous data analysis, particularly in the coding stage, and member checking serve as an effort to enhance qualitative credibility [29], [42]. This study is classified as relatively short-term research (a pilot study) due to the limited number of sessions for implementation, with only five meetings allocated and two meetings for testing (pre- and posttests) for each experimental and control group. Additionally, the learning material is restricted solely to the topic of fractions. The limited number of sessions could not be extended due to time constraints imposed by the collaborating schools. Researchers interested in replicating the theme and research design outlined in this report are strongly encouraged to conduct research with a more significant number of sessions covering a variety of subjects to assess the effectiveness of RME in enhancing mathematical competence. Furthermore, the participants in this research's qualitative data collection consisted of only six individuals, comprising three from the experimental group and three from the control group. It would be beneficial if mixed-method research adopted theoretical sampling to enhance the credibility of the research by iteratively recruiting participants to achieve data saturation [67].

Students in the RME group reported increased self-efficacy and fluency alongside a broader engagement with mathematical concepts. RME fostered meaningful experiences, provided realistic contexts, and encouraged an enthusiastic approach to learning. Challenges were noted during the initial phase of RME adoption as students grappled with problems requiring independent problem-solving strategies. Both groups showed increased self-efficacy and creativity, including those taught using CT methods. This finding suggests that when effectively implemented, CT can also foster mathematical creativity. However, the RME approach's emphasis on engaged and exploratory learning offers a more comprehensive method for cultivating deep mathematical understanding. The study also found that students preferred traditional whiteboards over PowerPoints for better visibility and clarity, emphasizing the need for a balanced approach that includes traditional and modern teaching tools. Moreover, incorporating games and icebreaker activities significantly enhanced engagement and reduced anxiety, creating a more positive learning environment.

It is suggested that future research expand both the duration and scope of the studies to build on these findings. The current research, classified as relatively short-term, was limited in the number of sessions. More sessions covering a broader range of mathematical topics could provide a comprehensive understanding of RME's long-term effectiveness on mathematical creativity. The qualitative data in this study came from a small sample size of only six participants. Future studies should consider increasing this sample size and using theoretical sampling to achieve data saturation, thereby enhancing the credibility and richness of the findings. A balanced approach incorporating traditional whiteboards and modern technological tools could cater to diverse learning preferences and optimize educational experiences. Despite the visual advantages of PowerPoints, students preferred the clarity, hands-on interaction, and cognitive benefits of handwriting on whiteboards. Finally, the positive impact of games and icebreaker activities on engagement and reducing anxiety highlights the value of these methods. Future research should explore different types of icebreakers, their effects on various student outcomes, and factors influencing their effectiveness, such as class size and demographics. Incorporating these activities can create a more inclusive and engaging learning environment.

4. CONCLUSION

This study shows that the RME approach significantly enhances the mathematical creativity of 7th-grade students compared to conventional teaching methods. Pretest and posttest results indicate greater fluency, flexibility, and originality in the group taught with RME. Furthermore, interviews revealed that students enjoyed learning more, felt more confident in their mathematical abilities, and showed greater interest in mathematics when using RME. These findings imply that implementing RME can be an effective strategy to boost mathematical creativity and student engagement in mathematics learning and encourage the development of more innovative and interactive learning media in the mathematics education curriculum.

AUTHOR CONTRIBUTION

RES contributed to conceptualizing the research, analyzing data, and writing and visualizing the reported manuscript. SAR contributed to collecting data, analyzing data, and writing the manuscript.

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APPENDIX

Appendix 1. An Example Problem on Posttest

Use 1, 2, 3, and 4 to create the fraction a/b to complete the problem, where $a < b$. Ujang owns a piece of land. He uses 25% of his land to build a pond and $\frac{\square}{\square}$ the other parts to create a garden. What fraction of Ujang's land can be used to make a garden?

Appendix 2. Member Checking Interview Items

Core Questions

1. "*Class 7#2 students have revisited fractions topics with Ms. Sury. In your opinion, is Ms. Sury's approach considered new?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
2. "*You have experienced learning in a new way with Ms. Sury. Some students mentioned that Ms. Sury's approach was initially confusing but later enjoyable. What is your perspective?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
3. "*Learning with Ms. Sury involved Realistic Mathematics Education (RME). In this type of learning, do students learn while playing?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
4. "*Did learning with RME make it easier for you to understand?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
5. "*In RME-based learning, students were given the opportunity to discuss with their peers. Based on your experience, do you think it is important for students to have the chance to discuss with classmates in Mathematics lessons?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
6. "*In RME-based learning, students were given the opportunity to explore the material. From your experience, do you think it is important for students to have the opportunity to explore the material first?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
7. "*Students said that learning Mathematics using RME was challenging. Do you agree with this statement?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
8. "*Some students said that learning Mathematics with RME is enjoyable. Do you agree with this statement?"*
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")
9. "*Besides the aspects mentioned earlier, such as RME being new, initially confusing, later enjoyable; learning while playing; easier understanding; opportunities for discussion with peers; opportunities for exploration; challenging, and enjoyable, what other aspects do you find remarkable in this teaching method?*"

(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, explain in more detail!")

10. "*Do you feel more confident in understanding or mastering Mathematics, particularly solving fraction problems, after learning with RME?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
11. "*In your opinion, has your ability in Mathematics, especially in the fraction topic, improved after learning with RME?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
12. "*In your opinion, has your proficiency in solving mathematical problems, especially in the fraction topic, increased after learning with RME?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
13. "*In your opinion, do you feel more capable of changing your approach when facing difficulties or challenges, especially when solving fraction problems?*"
(If the participant responds briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
14. "*In your opinion, do you feel more capable of providing unique or uncommon answers compared to your peers, especially when solving fraction problems?"*
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
15. "*Perhaps, there are other changes you have noticed after experiencing lessons with Mrs. Sury's new teaching method. Please share."*
(If the participant answered "Yes," ask for a more detailed explanation, "Please, elaborate further!")
16. "*In your opinion, is solving posttests easier compared to pretests when learning fractions with Ms. Sury?*"
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
17. "*In your opinion, is explaining using a chalkboard better than PowerPoint when learning Mathematics?"*
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please, elaborate further!")
18. "*In your opinion, is it importa nt to incorporate games in Mathematics learning, as Ms. Sury did?"*
(If the participant responded briefly, ask, "Why do you say so?" or request, "Please elaborate further!")