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(Research Article)

Development of RBL-STEM learning tools to improve students' combinatorial thinking skills in solving QRIS watermarking problems using local metric dimension

Ivana Gabriella [1,*], Dafik [2] and Arika Indah Kristiana [3]

[1] *Department of Postgraduate Mathematics Education, Faculty of Teacher Training and Education, University of Jember, Indonesia.*
[2] *Department of Mathematics, Faculty of Mathematics and Natural Science, University of Jember, Indonesia.*
[3] *Department of Postgraduate Mathematics Education, PUI-PT Combinatorics and Graphs, CGANT, Faculty of Teacher Training and Education, University of Jember, Indonesia.*

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Abstract

The advancement of digital technology highlights the importance of enhancing students' combinatorial thinking skills, particularly in addressing mathematical problems related to data security. One effective model that can be applied is Research-Based Learning (RBL) integrated with Science, Technology, Engineering, and Mathematics (STEM). This study aims to identify RBL-STEM activities, describe the development process of RBL-STEM learning tools, and analyze their effectiveness in improving students' combinatorial thinking skills in solving QRIS watermarking problems using the local metric dimension. The research employed a Research and Development (R&D) method based on the 4D model, consisting of Define, Design, Develop, and Disseminate stages. The developed products included the Student Task Design (RTM), Student Worksheet (LKM), and Learning Outcome Test (THB). The learning tools obtained a validity score of 93.61%, indicating very high validity. The trial, conducted with 36 students, demonstrated that the RBL-STEM tools were practical (95.25%) and effective (94%) in improving learning outcomes. Students showed positive responses and high engagement during learning. The post-test results revealed that 58% of students achieved a high level of combinatorial thinking, 36% were in the moderate category, and 6% were in the low category. Statistical analysis using the paired samples t-test (Sig. = 0.000 < 0.05) confirmed a significant improvement between pre-test and post-test scores. Therefore, the RBL-STEM learning tools are effective in enhancing students' combinatorial thinking and their ability to apply mathematical reasoning to QRIS digital watermarking problems.

Keywords: Combinatorial Thinking Skills; Research-Based Learning; STEM; Local Metric Dimension; QRIS Watermarking

1. Introduction

Twenty-first century education emphasizes the development of four core competencies, namely Critical Thinking, Creativity, Collaboration, and Communication (4C), as essential skills for preparing students to face global challenges. The 4C competencies play an important role in shaping higher education graduates who are adaptive, innovative, and ready to respond to the demands of the Society 5.0 era [1]. One of the educational approaches increasingly applied in the 21st century is STEM (Science, Technology, Engineering, and Mathematics), which has proven effective in developing 21st-century skills and scientific literacy among students [2]. STEM-based learning encourages students to integrate concepts from multiple disciplines, enabling them to understand and solve complex problems in everyday life. To enhance the effectiveness of STEM learning, the Research-Based Learning (RBL) model integrates research activities into the learning process, where research is defined as a systematic scientific process carried out by students to discover

* Corresponding author: Ivana Gabriella

and construct concepts through observation, data collection, analysis, and conclusion drawing. The syntax of RBL consists of orientation to research problems, formulation of hypotheses or research questions, data collection and analysis, conclusion drawing, and communication of research results [3]. The integration of RBL into STEM learning can create a deeper learning experience because students are directly involved in the scientific process. In addition, RBL-STEM increases students' motivation by allowing them to explore personally meaningful topics, fostering a sense of ownership and curiosity that leads to higher levels of engagement [4].

According to [5], one of the cognitive aspects emphasized in RBL-STEM is combinatorial thinking skills. Combinatorial thinking plays an important role in mathematics because it enables students to identify relationships, predict outcomes, and formulate systematic problem-solving strategies, such as analyzing patterns, listing possibilities, applying counting principles, and formulating efficient solutions based on problem structures [3]. RBL-STEM has been shown to improve combinatorial thinking skills by involving students in graph exploration, pattern recognition, and algorithm development, which significantly enhance their mathematical reasoning [6]. Based on these findings, the enhancement of combinatorial thinking through RBL-STEM encourages students to explore mathematical concepts, particularly those in graph theory.

One of the fundamental concepts in graph theory that has been widely studied is the metric dimension. Chartrand et al. define the metric dimension as the minimum cardinality of an ordered set of vertices capable of distinguishing every pair of distinct vertices in a graph based on their distance representations to that set [7]. As graph theory research evolved, this concept was later extended by Okamoto et al. into the local metric dimension, which is specifically used to distinguish pairs of adjacent vertices [8]. By focusing on relationships between neighboring vertices, the local metric dimension allows for more efficient and accurate identification of vertices within a graph. The development of the local metric dimension concept has broad implications, including its application in digital data security through watermarking technology. Watermarking is the process of embedding information into digital media to protect copyright, authenticity, and data ownership [9]. In the context of digital financial documents, particularly QRIS (Quick Response Code Indonesian Standard), which is a national QR-based payment standard developed by Bank Indonesia to unify various payment service providers and make transactions more practical, fast, and efficient [10], there remains a serious issue regarding the potential misuse of users' personal data, raising concerns about legal protection and digital security. Watermarking can be a solution to ensure the authenticity, integrity, and validity of QRIS, while protecting all parties involved from potential losses. However, implementing watermarking in QRIS presents its own challenge: the embedded information must not alter the original appearance of the QR code, as each visual element is sensitive to modification. Therefore, the local metric dimension in graph theory can be utilized to accurately identify adjacent points, supporting the application of watermarking for protecting QRIS without altering its structural or visual integrity.

The connection between graph theory and watermarking serves as the foundation for developing RBL-STEM learning tools focused on graph-based problem-solving. Makhfudloh et al. found that integrating the concept of rainbow antimagic coloring into RBL-STEM learning tools successfully enhanced students' computational thinking in solving graph-based digital watermarking problems [11]. However, research specifically linking RBL-STEM, combinatorial thinking skills, local metric dimension, and QRIS watermarking remains very limited. Therefore, this study, entitled "Development of RBL-STEM Learning Tools to Improve Students' Combinatorial Thinking Skills in Solving QRIS Watermarking Problems Using Local Metric Dimension," aims to fill this research gap. This study has theoretical significance in expanding the application of graph theory in mathematics education, and practical significance in supporting digital data security through research-based educational innovation.

2. Material and methods

2.1. RBL-STEM

RBL was first developed at Griffith University in 2008 and is grounded in the philosophy of constructivism, which emphasizes students' active roles in the learning process. In this context, educators are expected to present studies and findings that are relevant to the latest developments within their research groups [12]. RBL is a learning model that provides opportunities for students to learn and construct knowledge through research-oriented steps such as formulating research questions, designing methods, collecting and analyzing data, and drawing conclusions based on obtained findings [13]. By implementing RBL in the classroom, a specific learning atmosphere is created, where new concepts must align with the prior knowledge and skills possessed by students. In the era of the Fourth Industrial Revolution (Industry 4.0), the demand for graduates with strong technological literacy and creativity has become increasingly urgent. The STEM approach, which integrates Science, Technology, Engineering, and Mathematics, serves as a response to this need [14]. STEM emphasizes problem-solving through research-based and practice-oriented learning [15]. Moreover, the STEM approach encourages students to engage in hands-on activities, experiments, and real-world problem solving, thereby developing an understanding of how to apply scientific principles in everyday life [16]. Through STEM learning, students come to realize that mastery of mathematical and scientific concepts must be supported by technological proficiency and engineering design principles to plan, test, and refine a product or solution.

The integration of STEM and RBL has shown great potential in developing 21st-century skills among university students. According to [17], the RBL-STEM method is effective in enhancing information literacy, computational thinking, and technological literacy, as it guides students to analyze data, design solutions, and communicate research outcomes through technological products. In addition, RBL-STEM promotes cognitive activities that cultivate critical thinking skills and scientific creativity [18]. This study applies the RBL model integrated with the STEM approach to enhance students' combinatorial thinking skills in solving QRIS watermarking problems using the local metric dimension technique in graph theory. The integration of these elements provides a framework for connecting abstract mathematical reasoning with technological applications, thereby fostering analytical, research-oriented, and innovative capabilities in university mathematics education.

2.2. Combinatorial Thinking Skills

Combinatorial thinking is one of the essential mathematical skills that enables learners to solve problems through the organization of ideas, principles, and mathematical structures based on their personal learning experiences [6]. This skill trains students to analyze a problem from multiple perspectives, select the most effective strategies, and develop accurate and logical solutions. According to [19], combinatorial thinking belongs to the category of higher-order thinking skills because it requires critical and creative reasoning to solve problems that have numerous possible solutions. Dafik et al. demonstrated that RBL-STEM learning tools are effective in improving students' combinatorial thinking skills, as they encourage active engagement in identifying relationships, constructing patterns, and formulating mathematical generalizations [20]. Various researchers have proposed diverse indicators of combinatorial thinking skills depending on the context and objectives of learning. These indicators generally emphasize the ability to identify patterns, generalize cases, construct algorithms, perform mathematical proofs, and apply concepts to new or open-ended problems. In the context of this study, combinatorial thinking serves as a foundation for connecting mathematical reasoning with real-world applications such as digital watermarking and data security.

2.3. Methods

The development process was conducted through the four stages of the 4D model: define, design, develop, and disseminate, as illustrated in Figure 1.

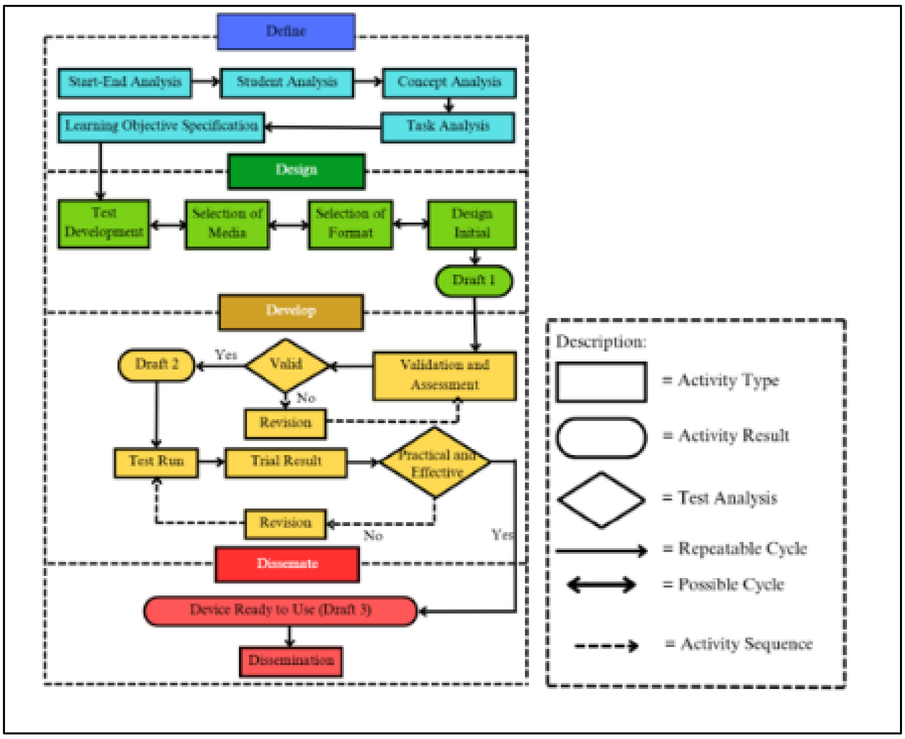

Figure 1 The flowchart of the 4D development model

The research procedure used in this study used Thiagarajan's development model, known as the 4D model. This model consists of the define, design, develop, and disseminate phases. A schematic diagram of the 4D model of learning device development is shown in Figure 1. Data collection techniques in this study were based on research instruments that included validation of learning devices, observation of learning implementation, data collection of learning outcomes, activity observation, and response questionnaires. In this study, data analysis was applied, namely quantitative data analysis using the SPSS application to perform statistical tests, namely paired sample t-test.

3. Results and discussion

3.1. RBL-STEAM Implementation

This RBL-STEM model requires students to be more active in learning through research. In the early stages of RBL syntax, problems arise from research groups that focus on open-ended issues. The researchers consider the problem of QRIS watermarking as shown in Figure 2.

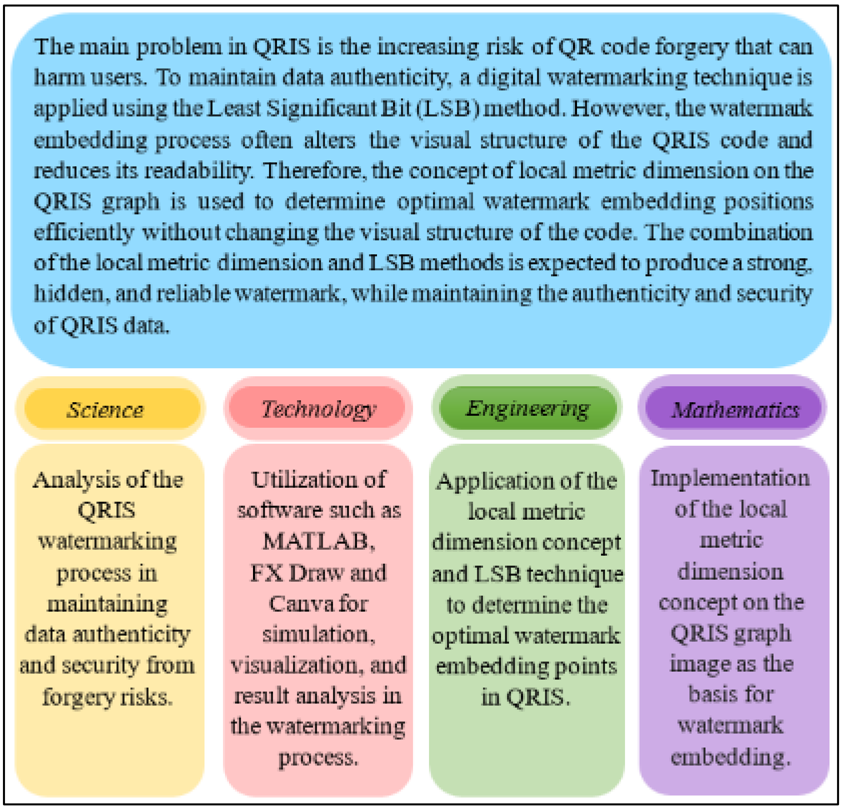

Figure 2 STEM elements of QRIS watermarking

This research aims to solve the problem of QRIS watermarking using the local metric dimension in graph theory through the RBL-STEM learning model. Therefore, the RBL-STEM model in this study has the following activity framework: (1) the first stage that students must carry out is to understand previous research related to digital watermarking and local metric dimension, (2) obtain innovations in the application of local metric dimension for securing QRIS data, (3) construct vertex representation functions and determine the local resolving set to find the local metric dimension value of the QRIS graph, (4) analyze data related to the watermark embedding process using the Least Significant Bit (LSB) technique and evaluate image quality through PSNR and SSIM, (5) generalize the obtained data by applying the method to other similar digital data problems, and (6) draw conclusions from the results by presenting findings related to solving QRIS watermarking problems using the concept of local metric dimension integrated within the RBL-STEM framework. The sequence of these activities and their relationship to the STEM domains are illustrated in **Figure 3**, which presents the RBL-STEM activity framework for solving QRIS watermarking problems using the local metric dimension.

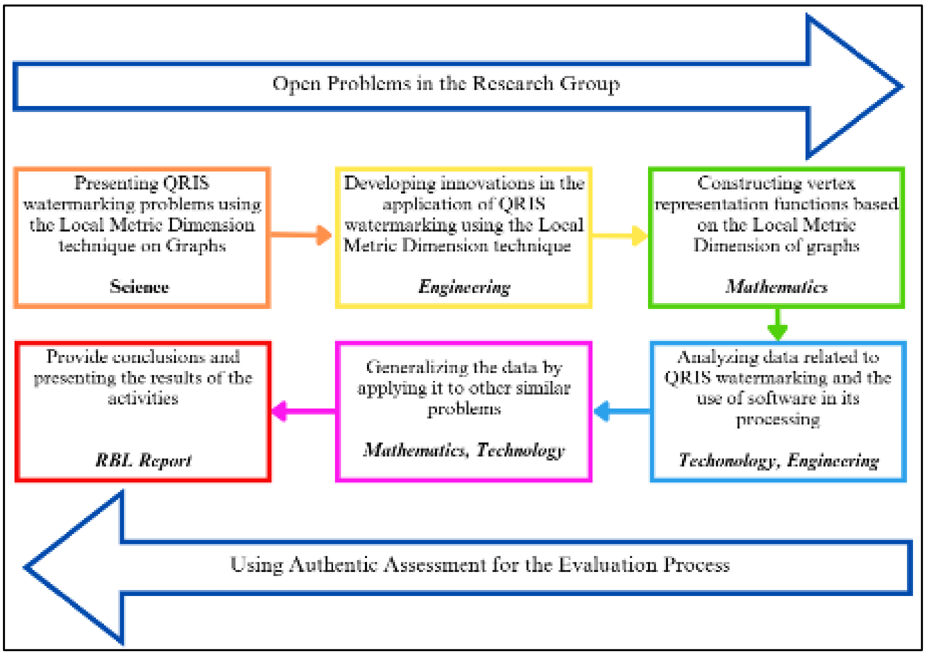

Figure 3 RBL-STEM Activity Framework for the Local Metric Dimension Problem

3.2. Validity, Practicality, and Effectiveness of RBL-STEAM Tools

The first stage of the 4D model is the Define phase, which aims to identify and determine the learning needs by analyzing the objectives and scope of the material to be developed. This stage is divided into four sub-stages, namely beginning–end analysis, learner analysis, concept analysis, and task analysis. The beginning–end analysis was carried out to identify students' difficulties in learning, particularly in understanding the concept of local metric dimension and its application in solving QRIS watermarking problems, which serves as the foundation for developing appropriate learning tools. The learner analysis was conducted to obtain data on the characteristics of undergraduate students of Mathematics Education at the University of Jember, including their prior knowledge, motivation, and learning preferences. The concept analysis aimed to identify, detail, and systematically organize the key concepts related to graph theory, local metric dimension, and digital watermarking, which would be introduced through the RBL-STEM learning model. Finally, the task analysis was intended to determine the essential skills and learning outcomes expected in accordance with the mathematics education curriculum, particularly focusing on students' combinatorial thinking skills in accordance with the expected final skill.

The second stage, Design, aims to plan and construct the learning devices to be used, resulting in an initial prototype of the developed materials. At this stage, the design of the RBL-STEM learning tools was carried out to determine their potential in improving students' combinatorial thinking skills through the concept of local metric dimension applied to QRIS watermarking problems. The design phase consists of four main steps: test preparation, media selection, format selection, and initial planning. The test preparation in this study involved creating descriptive assessment items that integrated STEM elements and were related to the concepts of local metric dimension, graph representation, and the use of watermarking techniques for data authenticity in QRIS. The media selection process included the use of PowerPoint as a presentation medium for delivering material related to graph theory and digital watermarking, as well as the development of RBL-STEM-based learning modules containing indicators of combinatorial thinking. The selected research format applied the RBL model integrated with the STEM approach, with structured stages serving as the learning framework. The initial design encompassed all learning tools required for the study, including the Student Task Design (RTM), Student Worksheet (LKM), and Learning Outcome Test (THB). The visualization of the developed learning materials is presented in Figure 4.

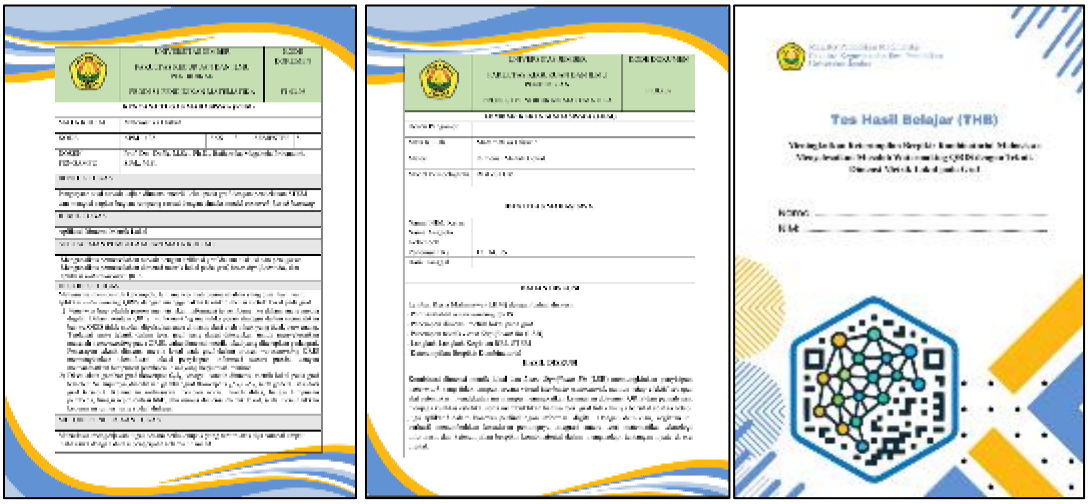

Figure 4 Initial Design of RTM, LKM, THB

The third stage is the development stage, which consists of four steps: validity testing, device trials, practicality testing, and effectiveness testing. Each learning tool produced in this stage was validated by experts and revised according to their recommendations. After the devices were declared valid, they were tested in the Discrete Mathematics course, Class E, Mathematics Education Study Program, University of Jember. Based on the evaluation and suggestions from two validators, revisions and improvements were made to the developed learning tools. The evaluation results from both validators indicated that the devices were feasible for use with minor revisions. Based on the recapitulation of the validation results of the RBL-STEM learning tools and instruments presented in Table 1, the average validation score was 3.75 with a percentage of 93.61%. According to the validity criteria, the developed learning tools met the requirement for validity since the score was within the range 3.25 ≤ Va < 4. Therefore, the RBL-STEM learning tools are considered valid and suitable for implementation in further stages of development.

Table 1 Recap of RBL-STEM Device Validation

Validation Result	**Average Score**	**Percentage**
Learning Device	3.80	94.95%
Student Activity Observation Sheet	3.75	93.75%
RBL-STEM Implementation Sheet	3.61	90.33%
Student Response Questionnaire	3.82	95.42%
Overall average score	3.75	93.61%

The revised and validated learning tools were then tested on students to determine their practicality and effectiveness. The trial was conducted in a class of 36 students from the Discrete Mathematics course, Mathematics Education Study Program, University of Jember, and was supervised by eight observers who were postgraduate students of Mathematics Education, FKIP, University of Jember. Observations and student performance assessments were used to evaluate the practicality and effectiveness of the developed RBL-STEM learning tools.

The practicality test consisted of two indicators: the analysis of learning implementation in the classroom and the analysis of student response questionnaires. The observation of learning implementation was carried out using the RBL-STEM implementation observation sheet, evaluated by the eight observers during classroom activities. The average score of the overall learning implementation observation was 3.81, with a percentage of 95.25%. According to the practicality criteria, the developed learning device meets the very high practicality category because it achieved a score within the range of 90% ≤ SR ≤ 100%.

Table 2 Observation Results of RBL-STEAM Model Implementation

Assessed Aspects	**Avarage Score**	**Percentage**
RBL-STEAM syntax	3.79	94.75%
Social system	3.75	93.75%
Reaction and management principles	3.9	97.5%
Overall average score	3.81	95.25%

Based on students' responses in the questionnaire, the overall average percentage of positive responses was 96.87%, indicating that the learning device was well-received and easy to use. From the analysis of these two practicality indicators—learning implementation and student responses—it can be concluded that the developed RBL-STEM learning tools are practical and suitable for implementation in mathematics learning activities.

Table 3 Summary of Data from Student Response Questionnaire Results

Assessed Aspects	**Percentage**
Enjoyment of the learning component	100%
Learning components are new	97.22%
Students are interested in learning	97.22%
Students clearly understand the language used	95.83%
Students understand the meaning of each problem presented	87.50%
Students are attracted by the appearance	100%
Students enjoy discussing with group members	100%
Students' combinatorial thinking skills feel trained	97.22%
Overall average score	96.87%

The effectiveness test of the developed learning tools consisted of two indicators, namely the analysis of student learning outcomes and the analysis of student activity observations. Student learning outcomes were obtained through a post-test administered on Friday, November 7, 2025, involving 36 students as research subjects. Based on the post-test results, it was found that 34 students (94%) achieved scores above the minimum completeness criterion, indicating that learning was classically complete.

Student activities were observed throughout the learning process, including the introduction, core, and closing activities. The analysis of student activity was based on the student activity observation sheets assessed by eight observers. As presented in Table 3, the overall average score of student activity observation was 3.85, with a percentage of 96.25%. In addition, the observers' comments were predominantly positive, indicating that the developed RBL-STEM learning tools facilitated active and engaging learning experiences without requiring substantial revisions. According to the effectiveness criteria, the developed learning tools meet the very effective category since the obtained score fulfills the range of $90\% \leq P \leq 100\%$. Therefore, the RBL-STEM learning tools for improving combinatorial thinking in solving QRIS watermarking problems using the local metric dimension can be declared effective for classroom implementation.

Table 4 Recapitulation of Student Activity Observation Results

Assessed Aspects	**Average Score**	**Percentage**
Introduction	4	100%
Core Activities	3.79	94.75%
Closing	3.75	93.75%
Overall average score	**3.85**	**96.25%**

The final stage is the Deployment stage, which involves implementing the developed learning tools on a broader scale, such as in other classes or study programs with similar courses that have not been previously tested. The purpose of this stage is to determine whether the developed RBL-STEM learning tools function effectively in various learning contexts and maintain their quality and consistency across different groups of students.

3.3. Improvement of Combinatorial Thinking Skills

This section presents the improvement in students' combinatorial thinking skills after the implementation of the RBL-STEM learning tools. The improvement was analyzed based on the results of the Learning Outcomes Test (THB), which was administered before and after the learning intervention. The analysis focused on four indicators of computational thinking, namely decomposition, pattern recognition, abstraction, and algorithmic thinking. The distribution of students' pre-test and post-test scores is presented in Figure 5, while Figure 6 illustrates the percentage levels of students' combinatorial thinking improvement after the implementation of RBL-STEM learning activities.

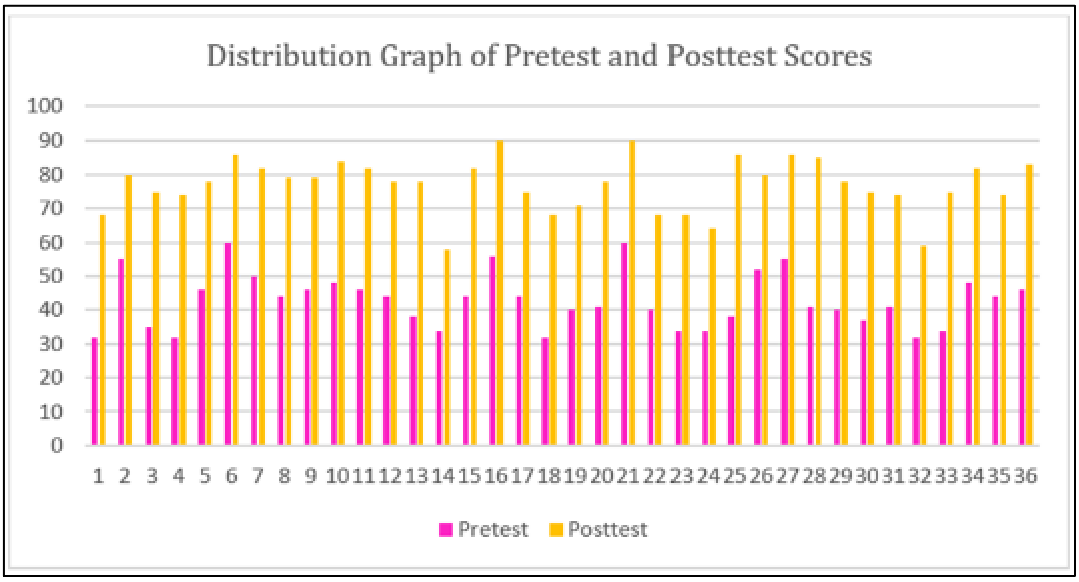

Figure 5 Graph of Distribution of Pretest and Posttest Scores

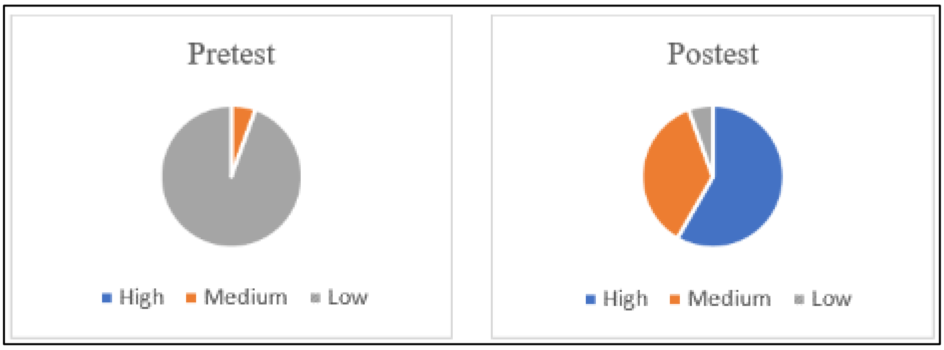

Figure 6 Percentage of Students' Combinatorial Thinking Skills Level

Based on the classification results, during the pre-test, 94% of students were categorized as having a low level of combinatorial thinking skills, while 6% were in the moderate category. After the implementation of the learning process and the post-test, 58% of students reached a high level of combinatorial thinking, 36% were in the moderate category, and 6% remained in the low category. These results indicate a significant improvement in students' combinatorial thinking skills after participating in the RBL-STEM learning activities focused on solving QRIS watermarking problems using the local metric dimension. In addition, a normality test was conducted as a prerequisite for the paired samples t-test to determine whether the data were normally distributed. The statistical test was performed using the SPSS software, and the results confirmed the improvement in students' combinatorial thinking skills after the implementation of the RBL-STEM learning tools.

Table 5 Normality Test Results

Tests of Normality						
	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.
THB Pretest	0.098	36	0.200*	0.942	36	0.060
THB Posttest	0.134	36	0.098	0.956	36	0.165

Based on the results of the data normality test in Table 5, it shows that the pretest and posttest scores are normally distributed because the significance value (Sig.) is > 0.05. Next, a paired samples t-test is performed as shown in Table 6.

Table 6 Paired Sample Statistics

Paired Samples Statistics					
		Mean	**N**	**Std. Deviation**	**Std. Error Mean**
Pair 1	THB Pretest	42.8611	36	8.02194	1.33699
	THB Posttest	77.0000	36	7.77909	1.29652

The test results presented in Table 6 show that the average post-test score was higher than the pre-test score, indicating a significant improvement in students' learning outcomes after the implementation of the RBL-STEM learning tools. The average pre-test score was 42.86, which increased to 77.00 on the post-test. This increase demonstrates a substantial enhancement in students' combinatorial thinking skills after participating in RBL-STEM learning activities involving QRIS watermarking problems using the local metric dimension. Furthermore, the total number of data entries in both the pre-test and post-test was 36, corresponding to the total number of participating students.

Table 7 Paired Sample Correlations

Paired Samples Correlations				
		N	**Correlation**	**Sig.**
Pair 1	THB Pretest & THB Posttest	36	0.768	0.000

The test results presented in Table 7, with a total of 36 data points, show that the correlation value between the pre-test and post-test scores is 0.768 > 0.05. This indicates that there is a strong and significant correlation between the two sets of scores, meaning that students who performed well in the pre-test also tended to achieve higher results in the post-test. These findings suggest that the implementation of the RBL-STEM learning tools contributed to a consistent and measurable improvement in students' combinatorial thinking skills in solving QRIS watermarking problems using the local metric dimension.

Table 8 Paired Sample Test

Paired Samples Test									
		Paired Differences					**t**	**df**	**Sig. (2-tailed)**
		Mean	**Std. Deviation**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
					Lower	**Upper**			
Pair 1	THB Pretest - THB Posttest	-34.138	5.383	0.897	-35.960	-32.317	-38.050	35	0.000

The test results presented in Table 8 show that the probability value or Sig. (2-tailed) is 0.000 < 0.05. This indicates a statistically significant difference between the pre-test and post-test scores. Therefore, it can be concluded that there is a significant improvement in students' combinatorial thinking skills after learning with the RBL-STEM learning tools. These findings confirm that the implementation of RBL-STEM effectively enhances students' ability to analyze, construct, and apply mathematical reasoning in solving QRIS watermarking problems using the local metric dimension.

4. Conclusion

Based on the results of the research conducted on the development of RBL-STEM learning tools to improve students' combinatorial thinking skills, the developed learning tools meet the criteria of validity, practicality, and effectiveness. Quantitative analysis was carried out through the processing of pre-test and post-test data using normality tests and paired samples t-tests. The results of the normality test showed that both pre-test and post-test scores were normally distributed because the significance value (Sig.) was greater than 0.05. Furthermore, the results of the paired samples t-test indicated that the Sig. (2-tailed) value was 0.000 < 0.05, meaning that there was a significant difference between students' scores before and after learning using the RBL-STEM learning tools. These findings demonstrate a significant improvement in students' combinatorial thinking abilities after participating in the RBL-STEM-based learning activities involving QRIS watermarking problems with the local metric dimension. The outcomes of this research can serve as a valuable reference for further development of RBL-STEM learning tools aimed at enhancing mathematical reasoning and higher-order thinking skills in the field of mathematics education.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

Statement of ethical approval

This research was approved by the Research Ethics Committee of Universitas Jember.

Statement of informed consent

All participants gave their informed consent before participating in this study.

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