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Development of GeoGebra in problem-based learning to enhance students' mathematical critical thinking skills

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Abstract

This study is motivated by students' low critical thinking skills, particularly in three-dimensional geometry. Moreover, the limited availability of effective interactive learning media impedes the development of these skills. Three-dimensional geometry requires a more engaging and interactive approach to enhance understanding. This study aims to develop GeoGebra-based learning media within the Problem-Based Learning model to enhance students' critical thinking skills in mathematics. The research method employed is Research and Development using the ADDIE design model. The study subjects consist of eighth-grade students. The research instruments include validation sheets, practicality questionnaires, and tests. The validation results indicate that the GeoGebra validation score is reaching 95.16% (highly valid). The practicality test showed an average score of 96.09% (highly practical). The obtained N-Gain score of 0.7655 (high category) indicates an improvement in students' critical thinking abilities. The findings of this study conclude that the use of GeoGebra in PBL-based learning is effective in enhancing students' mathematical critical thinking skills and can serve as an innovative alternative for teaching three-dimensional geometry. The findings of this study have positive implications for enhancing students' critical thinking skills through the integration of interactive learning tools such as GeoGebra, which can improve engagement and understanding in mathematics.

Keywords: critical thinking; GeoGebra; problem-based learning; three-dimensional geometry

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Introduction

Mathematical critical thinking ability is an essential cognitive competence required by students to solve real-world problems logically, systematically, and reflectively. In the context of junior high school mathematics learning, critical thinking involves the ability to interpret problems, analyze information, draw inferences, evaluate arguments, and explain solutions rationally (Masjudin, 2024; Padilah et al., 2025; Pratiwi et al., 2025). This competence forms the foundation for developing higher order thinking skills needed in the 21st century (Abrenica, 2025; Majaga et al., 2024). Learning activities that foster critical thinking encourage students not only to understand procedures but also to assess the validity of solutions, connect concepts, and articulate reasoning argumentatively. Therefore, critical thinking supports not only mathematical achievement but also the development of independence and reflective thinking skills that are essential in daily life (Nu'man, 2025; Sutama et al., 2022).

However, various studies indicate that junior high school students' mathematical critical thinking skills remain relatively low, particularly when confronted with non-routine problems. Many students struggle to translate contextual situations into appropriate mathematical models, especially in problems that require multi-step solutions (Ke et al., 2023). Rahman et al., (2021) revealed that the majority of high school students still lack adequate critical thinking skills due to conventional teaching methods that fail to engage students in higher-order thinking processes. Similarly, Noverianto et al., (2024) found that students' mathematical problem-solving abilities are still weak, with many demonstrating limited reasoning skills needed to solve complex problems. Furthermore, results from international assessments such as the Trends in International Mathematics and Science Study (TIMSS), which ranks Indonesia among the lowest-performing countries in terms of mathematics achievement. Indonesia ranked 46th out of 51 countries, with an average score of 397 points (Hidayat et al., 2023; Utomo, 2021). This trend is also supported by the findings of the Programme for International Student Assessment (PISA) consistently highlight significant deficiencies, with Indonesian students scoring significantly lower than their peers globally (Negara et al., 2022).

Indonesia's PISA mathematics results shows the average PISA 2022 scores across three domains: mathematics, science, and reading. Indonesia ranks 69th out of 81 countries, with a mathematics score of 366, far below countries like Singapore (575) and China (552). This indicates a general weakness in Indonesian students' mastery of mathematical concepts and reasoning. The distribution of students' abilities according to proficiency levels, For mathematics, 69.8% of Indonesian students are in Levels very low proficiency. Only 0.04% reach Level 5, and 0% are at Level 6, which represents the highest indicators of critical thinking and complex problem-solving (OECD, 2023). Critical thinking is closely related to high competency levels in international assessments like PISA. The low proportion of Indonesian students in Levels 4–6 reflects that the majority of students have yet to master critical mathematical thinking skills such as deep analysis, argument evaluation, and solution justification.

Several factors contribute to the low achievement of students' critical thinking, including teaching approaches that emphasize algorithm memorization without deep conceptual understanding (Cesaria et al., 2024), weak understanding of mathematical terminology due to language barriers (Otuma et al., 2022), and limited learning resources and technologies that support students' exploration (Rezat et al., 2021). Without problem-based or inquiry-based learning experiences, students tend to stagnate in developing analytical abilities and solution justification (Dairo et al., 2024; Shanley et al., 2025).

One of the relevant approaches to improve mathematical critical thinking is *Problem-Based Learning* (PBL). PBL focuses on contextual problem-based learning that challenges students to think analytically, collaborate, and express their reasoning openly (Suryawan et al., 2023; Susilo, 2022). Besides improving the ability to solve non-routine problems, PBL also strengthens students' metacognitive skills and self-reflection (Al Ayyubi et al., 2024; Murnaka et al., 2023). Through exploration and group discussions, PBL creates a learning atmosphere that systematically promotes the growth of critical thinking (Jahudin & Siew, 2023; Yanto et al., 2023).

Nevertheless, the effectiveness of PBL may decline without adequate instructional media. The absence of visual aids and technology can hinder students' engagement in problem exploration and reduce the quality of reflection expected from (Tawfik et al., 2021; Tucker et al., 2024). Without digital support, students' discussion and collaboration opportunities become limited, especially when teachers lack the skills to facilitate PBL optimally in technology-constrained contexts (Lee, 2022; Saleh et al., 2022).

In this context, GeoGebra is a dynamic visual tool with strong potential to support PBL. GeoGebra enables students to visualize, manipulate variables, and explore concepts interactively and in real time (Baye et al., 2021; Ziatdinov & Valles, 2022). Its graphic, algebraic, and modeling features allow students to observe patterns, formulate conjectures, and verify solutions independently an essential process in developing critical thinking (Amalia et al., 2023; Handayani et al., 2022; Muslim et al., 2023). The use of GeoGebra also extends PBL implementation across various mathematical topics in contextual settings (Fauzi et al., 2025; Seftiana et al., 2024).

Preliminary observations at SMP Negeri 13 Mataram show that mathematics teachers have made efforts to apply the PBL approach in teaching. Teachers use contextual problems to initiate discussions and guide students to discover concepts through inquiry and collaboration. However, the implementation of PBL remains conventional, lacking interactive technology-based learning media. There has been no effort to develop or use GeoGebra as a supporting tool in PBL. Teachers do not yet have instructional materials that integrate GeoGebra into the PBL framework. As a result, students have not experienced learning that utilizes the visual and manipulative strengths of GeoGebra to facilitate conceptual understanding and critical reasoning.

Previous studies have demonstrated the effectiveness of integrating PBL with GeoGebra in mathematics instruction. Anzani & Juandi, (2022) showed that GeoGebra-assisted PBL significantly improved students' mathematical abilities Purbaningrum & Mahmudi, (2024) found that GeoGebra's interactive features positively impacted students' mathematical literacy and learning motivation. Similarly, Hadi et al., (2024) and (Samosir & Salayan, 2023) confirmed that PBL supported by GeoGebra enhances students' communication and problem-solving skills.

However, most of these studies focus only on general learning outcomes or specific skills and have not explicitly developed instructional materials that integrate GeoGebra within the PBL syntax to enhance mathematical critical thinking, particularly in geometry topics relevant to the real needs of State Junior High School 13 Mataram.

Based on the above, this study aims to develop GeoGebra as a tool within the *Problem-Based Learning* (PBL) model to improve students' mathematical critical thinking, particularly in solid geometry. GeoGebra, with its ability to dynamically manipulate three-dimensional geometric objects, will be used as an interactive and engaging learning medium. Its use within the PBL framework is expected to help students visualize complex geometric concepts, thereby enriching their understanding and enhancing their critical thinking skills. Through this approach, students will not only engage in problem-solving but also actively explore and construct their own knowledge, which is the core of the PBL model.

This research is expected to contribute significantly to the development of mathematics education in Indonesia and support improved mathematics learning quality through the integration of technology with an emphasis on students' critical thinking skills.

Methods

This study is a type of Research and Development aimed at producing a mathematics learning device based on Problem-Based Learning (PBL) supported by GeoGebra media to enhance students' mathematical critical thinking skills. The development model used in this study is ADDIE. The ADDIE model is a widely used framework for instructional design and interactive learning media development, known for its flexibility in making iterative revisions throughout the process (Adeoye et al., 2024; Widiana, 2022). This systematic approach allows for the design of adaptive, structured instructional materials that meet the diverse needs of students (Ainullah et al., 2023; Aydın, 2020; Σπατιώτη et al., 2023).

The ADDIE model consists of five main stages: Analysis, Design, Development, Implementation, and Evaluation. The flow diagram of this research is presented in Figure 1 below.

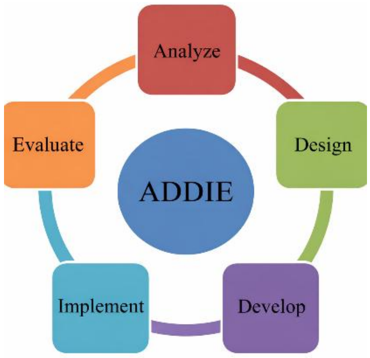


Figure 1. Research flowchart of the ADDIE model development cycle

Below is a detailed explanation of each stage in the ADDIE model used in this study.

Analysis stage

In this stage, an analysis is conducted on the needs of the students, the material to be taught, and the characteristics of the students. The first step is to identify the problems faced by students in learning three-dimensional geometry, specifically related to the difficulties in visualizing three-dimensional geometric objects. In this study, the analysis also includes a review of the available learning resources and the technologies that can be used to enhance students' understanding of the material. This stage is crucial to ensure that the product being developed aligns with the real needs of students and the learning objectives (Lailiyah & Marlena, 2024; Sadewi & Kamaludin, 2023).

Design stage

This stage involves the design of the GeoGebra development to be used in the study. In this research stage, GeoGebra is designed in accordance with the needs of the Lesson Plan, Student Worksheets, and Critical Thinking Ability Tests. The design of GeoGebra also considers the practicality and effectiveness of the product. Therefore, GeoGebra is chosen as an interactive learning media that allows students to draw and manipulate three-dimensional geometric objects, making it easier for them to understand abstract concepts. The product design also includes determining the appropriate learning steps aligned with the PBL model, where students will actively engage in collaborative problem-solving processes.

Development stage

In the development stage, the designed learning devices are tested and validated by experts to ensure the product’s feasibility. This development process involves two types of test subjects: product evaluators and target product subjects.

The product evaluators consist of two groups. Media and content experts, two lecturers from *Universitas Pendidikan Mandalika* who specialize in learning media and mathematics content. They are responsible for assessing the quality and practicality of using GeoGebra in PBL-based learning. The content expert evaluates the appropriateness of the material and the ability of the learning devices to support the development of students’ critical thinking skills.

The target product subjects are 30 eighth-grade students from State Junior High School 13 Mataram. These students serve as the primary subjects to assess the effectiveness and practicality of the developed learning product. Students will use PBL-based learning devices with the help of GeoGebra, and their learning outcomes will be measured through critical thinking ability tests. The indicators of students' critical thinking skills measured in this study are shown in Table 1.

Table 1. Operational definitions of critical thinking indicators

No	Indicator	Operational Definition
1	Interpretation	The ability to understand, clarify, and explain the given information clearly and accurately. This involves identifying the meaning of data or arguments, linking it to prior knowledge, and understanding the

No	Indicator	Operational Definition
		underlying context. Interpretation includes a deep understanding of data, whether in the form of text, numbers, or graphs.
2	Analysis	The ability to break down complex information or arguments into smaller components to identify relationships, patterns, or structures. This process involves careful observation of the elements that form a problem or situation and understanding how these elements interact. Analysis focuses on the ability to look deeper and question the various components of the given information.
3	Evaluation	The ability to assess or judge the quality or value of an argument, solution, or information based on relevant criteria. Evaluation includes the ability to consider the available evidence, the reliability of sources, and the suitability of the solution to the problem at hand. This process leads to decision-making based on evidence, logical reasoning, and consideration of various available alternatives.
4	Inference	The ability to draw logical conclusions or make predictions based on the available information or evidence. Inference involves both deductive and inductive reasoning to take appropriate steps and generate possible answers or solutions based on limited data. This ability allows individuals to move beyond the information directly provided and conclude things that are not explicitly stated in the available material.

Implementation stage

The implementation stage involves applying the developed PBL-based learning devices in classroom activities. In this stage, the validated GeoGebra will be applied in the PBL model for teaching three-dimensional geometry. Students will be given the opportunity to manipulate three-dimensional geometric objects using GeoGebra, while working in groups to solve contextual problems relevant to real life.

During the implementation stage, the teacher acts as a facilitator who guides students through the problem-solving process, provides feedback, and encourages students to think critically at every stage of problem-solving. This implementation will also be monitored to assess how the learning device contributes to enhancing students' critical thinking skills and their interest in mathematics.

Evaluation stage

Evaluation is conducted at two levels: product evaluation and learning process evaluation. In the product evaluation stage, the validity of the learning device is assessed based on feedback from media and content experts. This evaluation process aims to determine the extent to which the developed device meets the standards of feasibility, practicality, and effectiveness in supporting learning. This evaluation is important to ensure that the media and learning tools remain relevant, effective, and have a real impact in the educational context (Choi et al., 2022; Harwyandani & Suyono, 2023).

In addition, evaluation is also carried out on the effectiveness of the GeoGebra-integrated learning device in improving students' critical thinking skills. For this purpose, the instruments used in this study are validation sheets, practicality questionnaires for both teachers and students, and validated critical thinking ability tests. The results of the practicality questionnaire will provide information on how easy the learning device is to implement by teachers and students, while the critical thinking ability test will provide data on the improvement of students' critical thinking skills after using the learning device.

This study uses a pretest-posttest one-group design to measure changes in students' critical thinking skills before and after the implementation of problem-based learning with GeoGebra. This design allows for assessing the effectiveness of the intervention in enhancing students' understanding and engagement in three-dimensional geometry. The instruments used to collect data include: (1) Validation Sheets: Used to assess the quality of the learning devices based on feedback from media and content experts. (2) Practicality Questionnaire: Used to measure how practical GeoGebra is in its application in the classroom, completed by both teachers and students. (3) Critical Thinking Ability Test: This test is used to measure the improvement in students' critical thinking skills after using the PBL-based learning devices supported by GeoGebra. The validity and reliability of the instrument in this study were determined through expert agreement. The critical thinking test was validated and its reliability tested by a panel of experts in mathematics education. Their feedback ensured that the test had relevance, clarity, and consistency aligned with the research objectives, providing strong evidence of its validity and reliability.

The collected data will be analyzed using descriptive quantitative techniques. Data from the validation sheets will be analyzed to determine the feasibility of the GeoGebra media based on the average scores provided by the validators. The assessment data will then be calculated using the percentage formula:

$$Validity\ persentage\ (\%) = \frac{Total\ scor\ obtined}{Maximum\ possible\ scor}\ x\ 100\% \quad (1)$$

The results of these calculations are interpreted into validity categories in Table 2 below.

Table 2. Validity criteria for learning media GeoGebra (Adaptation from Masjudin et al., 2025)

Interval Percentage	Validity Criteria
80% < Score ≤ 100%	Very valid
60% < Score ≤ 80%	Valid
40% < Score≤ 60%	Fairly valid
20% < Score ≤ 40%	Less valid
0% < Score ≤ 20%	Not Valid at All

The practicality data of the GeoGebra media is obtained from the average responses of the teachers and students after the implementation of the device in the classroom. Practicality is measured based on the ease of use of the media, clarity of instructions, suitability of the implementation time, and its benefits to the learning process. The data is analyzed by calculating the average percentage score of the responses, which is then categorized into five levels in Table 3 below.

Table 3. Practicality criteria for GeoGebra (Adaptation from Masjudin et al., 2025)

Percentage	Practically Criteria
80%< Score ≤100%	Very practical
60%< Score ≤80%	Practical
40%< Score≤60%	Fairly Practical
20%< Score ≤40%	Less Practical
0%< Score ≤20%	Not Practical at all

In addition to the quantitative data, the results of teacher interviews are also analyzed descriptively to strengthen the practicality assessment, particularly in identifying the challenges and advantages of the developed learning device.

The data from the students' mathematical critical thinking ability tests is analyzed to determine the improvement in students' abilities after using the developed learning devices. This analysis is conducted to evaluate the effectiveness of the GeoGebra media using the following N-Gain formula.

$$N - \text{Gain} = \frac{Posttest\ Scor - Pretest\ Scor}{Ideal\ Scor - Pretest\ Scor} \quad (2)$$

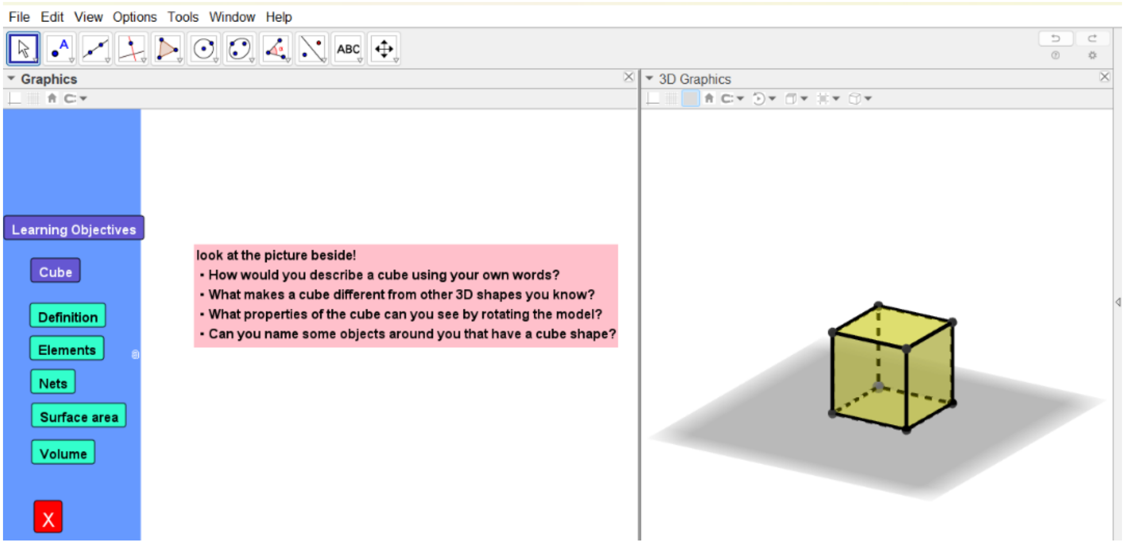
To assess the category of the N-Gain score improvement, one can refer to the normalized Gain criteria in Table 4.

Table 4. Criteria for N-Gain (g) categorization

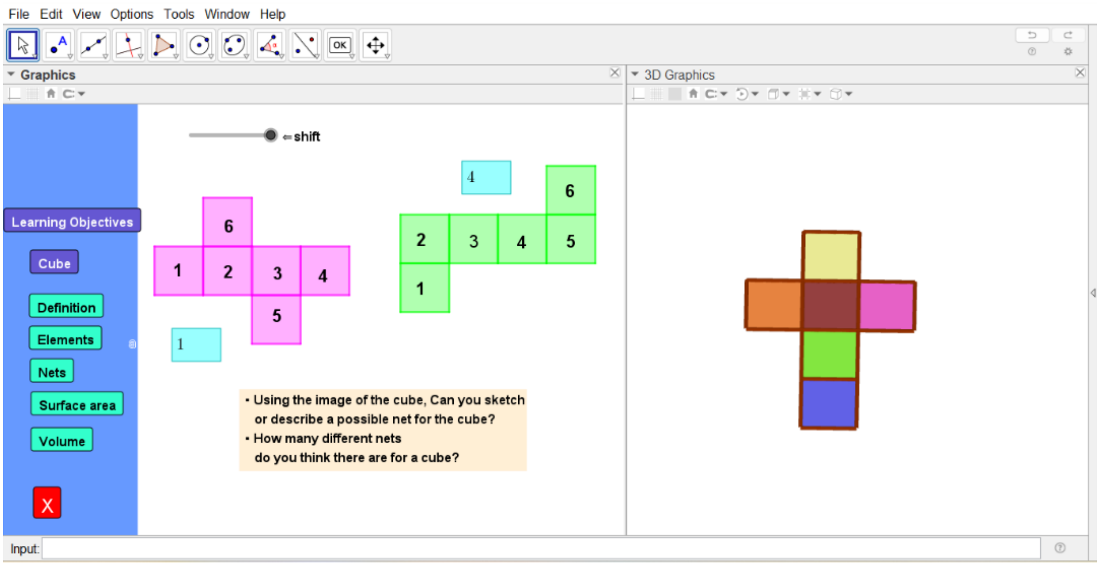
Scor Interval	Category
$0.7 \leq g$	High
$0.3 \leq g < 0.7$	Medium
$g < 0.3$	Low
$g=0$	No increase has occurred
$-1.00 \leq g < 0.00$	A decrease has occurred

Results

In this section, the research results are presented in a clear and detailed manner. Research results can be presented based on research results at each stage of research or research results that answer each problem formulation or others as long as the results of the research that have been carried out are visible. Research results should be supported by empirical evidence. This study aims to produce valid, practical, and effective GeoGebra learning media within a Problem-Based Learning (PBL) framework to enhance students' critical thinking skills, specifically in the topic of three-dimensional geometry. The resulting GeoGebra learning media can be seen in Figure 2 below.



(a)



(b)

Figure 2. Display of GeoGebra learning media product (a) Definition of a cube; (b) Net of a cube.

Based on Figure 2, it can be seen that the mathematics material created for the media is the topic of three-dimensional geometry, which is one of the important topics in mathematics education at the junior high school level. The GeoGebra learning media developed covers the topic of cubes, designed to help students understand three-dimensional concepts interactively. This media includes the definition of a cube, explaining its shape and properties, as well as the elements that make up a cube, such as faces, edges, and angles. Additionally, it introduces the cube's nets, demonstrating how the cube's parts can be arranged in a flat shape. Finally, cube-related problems are presented to test students' understanding of the concepts learned, allowing them to explore the material practically and visually with the help of GeoGebra.

The GeoGebra media is complemented with Student Worksheets to highlight the Problem-Based Learning (PBL) approach. GeoGebra serves as an interactive tool for visualizing and exploring mathematical concepts, while the Student Worksheets guides students through problem-solving processes, encouraging collaborative learning and critical thinking. The integration of GeoGebra allows students to manipulate mathematical models and visualize solutions, while the Student Worksheets fosters inquiry and reflection, key components of PBL. This combination supports the development of students' critical thinking skills, enabling them to analyze, evaluate, and justify their reasoning in solving real-world mathematical problems. The resulting product of GeoGebra is then tested for its validity, practicality, and effectiveness.

Results of learning device validation test

The validation process in this study involved assessments by media and content experts. The results showed that all learning instruments, including the Lesson Plan, Student Worksheets, GeoGebra Media, Teacher & Student Response Questionnaires, and Test Sheets, received highly satisfactory scores. Table 5 below presents the details of the validation results for the learning devices and research instruments.

Table 5. Result of validation of GeoGebra media

Product	Average Score	Max Score	Percentage	Criteria
GeoGebra Learning Media	59	62	95.16%	Very Valid

Based on Table 5, it is obtained that the validation results of the GeoGebra media is very valid for implementation and use in PBL-based mathematics learning, particularly in the topic of three-dimensional geometry. GeoGebra received a score of 59 out of a maximum score of 62, with a validity percentage of 95.16%, which falls into the "Highly Valid" category. This validity indicates that GeoGebra meets high feasibility criteria in supporting interactive learning processes and is suitable for use in the implementation stage.

Results of GeoGebra media practicality test

The practicality test was conducted to assess the extent to which GeoGebra can be applied in learning and accepted by both teachers and students. The results are as Table 6 below.

Table 6. Data of product practicality test results

No	Responden	Average Score Obtained	Max Score	Percentage	Criteria
1	Teacher	62	64	96.88%	Very practical
2	Student	61	64	95.31%	Very practical
	Average	61.5	64	96.09%	Very practical

Based on Table 6, the practicality test results show a very high level of acceptance from both parties. The teachers gave an average score of 96.88%, and the students gave a score of 95.31% in evaluating the practicality of using GeoGebra. Overall, the average practicality score reached 96.09%, which falls into the "Highly Practical" category.

Results of GeoGebra media effectiveness test

The effectiveness was measured using the N-Gain formula, which assesses the improvement in students' critical thinking ability after using the problem-based learning device integrated with GeoGebra. The N-Gain test results were analyzed using SPSS. The analysis results are presented in Table 7.

Table 7. N-Gain test results

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
N-Gain_Score	30	.44	1.00	.7655	.14360
N-Gain_Percent	30	44.44	100.00	76.5497	14.35969
Valid N (listwise)	30				

The N-Gain test results show a significant improvement in students' critical thinking abilities, with an average N-Gain score of 0.7655 and an average N-Gain percentage of 76.5%. This result indicates that the GeoGebra learning media in Problem-Based Learning is in the high category and effective in improving students' mathematical thinking skills.

Discussion

This study aims to develop a GeoGebra learning tool to support Problem-Based Learning (PBL) with the goal of enhancing students' critical thinking skills in mathematics, specifically in the topic of spatial geometry. The results of the study show that the developed GeoGebra learning tool is highly valid, practical, and effective in improving students' mathematical critical thinking skills.

The validity of the GeoGebra tool also received a high score (95.16%), indicating that aspects such as design, language, visual appeal, and alignment with lesson plans and worksheets have been met. This tool effectively facilitates the achievement of learning objectives, particularly in helping students understand spatial concepts and the relationships between the elements of geometric figures.

Based on the practicality test, both teachers and students rated the GeoGebra tool as highly practical, with an average score of 96.09%. This result shows that GeoGebra is easy to use, easy to integrate into the learning process, and relevant to the steps of the PBL model. The practicality of this tool can be explained through several indicators: (1) ease of access and use; (2) alignment with learning objectives and content; (3) visual appeal; (4) clarity of language and usage instructions; and (5) support for active learning.

From the teacher's perspective, the practicality of GeoGebra is reflected in its ability to save preparation time and provide high flexibility in learning. Teachers can quickly prepare interactive geometry models according to the topic being taught. Meanwhile, from the students' perspective, the practicality is seen in how easily they can understand instructions, interact directly with 3D objects, and explore concepts independently. The effectiveness test shows a significant improvement in students' critical thinking skills after using the PBL-based learning tool integrated with GeoGebra. The average N-Gain score of 0.7655 (high category) indicates that the integration of this model with GeoGebra successfully enhanced students' mathematical critical thinking skills. The improvement in students' critical thinking skills can also be seen in Figure 3.

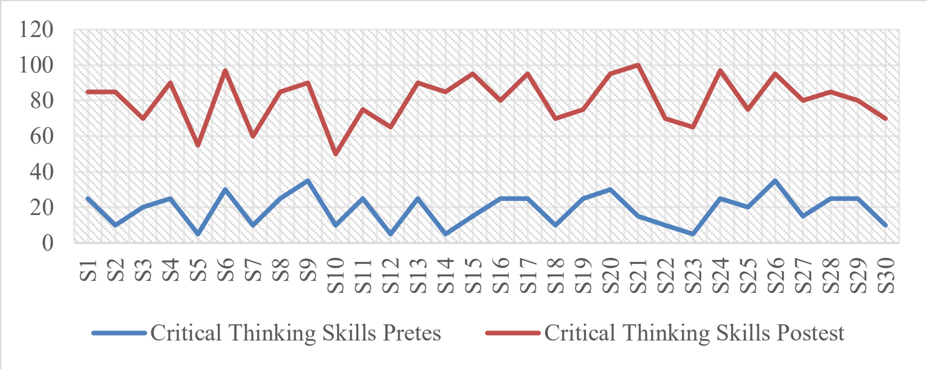


Figure 3. Improvement in students' mathematical critical thinking skills from pretest to posttest

Based on the diagram in Figure 3, it shows a comparison of students' critical thinking skills between the pretest (blue line) and posttest (red line). It is clear that almost all students experienced significant improvement in the posttest, with most students who had low scores on the pretest showing considerable progress. This indicates the effectiveness of the learning process and the GeoGebra media in enhancing students' critical thinking skills. The achievement of students' critical thinking skills based on the evaluation results of the four critical thinking indicators can be seen in Figure 4.

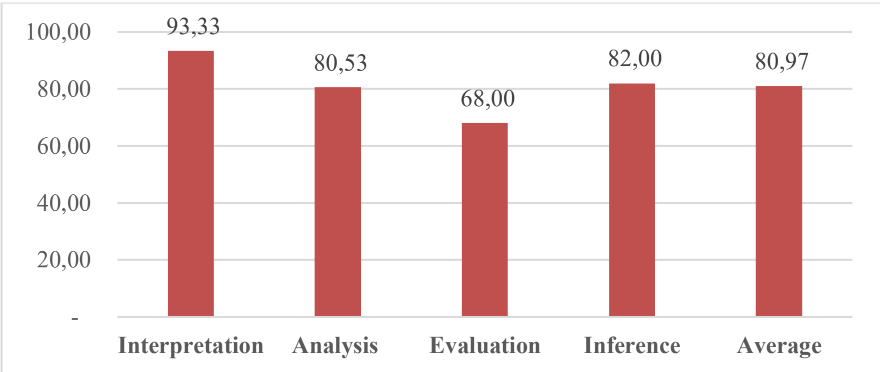


Figure 4. Students' mathematical critical thinking skills achievement

Figure 4 shows the achievement of each critical thinking skill indicator, including interpretation, analysis, evaluation, and inference. From the evaluation results, the interpretation indicator achieved the highest score of 93.33, indicating that students are proficient in understanding information. Meanwhile, evaluation had the lowest achievement at 68.00, suggesting that students tend to struggle in assessing and evaluating the presented arguments. Overall, the average student achievement is 80.97, reflecting a good level of critical thinking skill achievement.

According to the results of the study, the developed GeoGebra learning media is validated as highly valid, practical, and effective in improving students' mathematical critical thinking skills. This is because the research findings demonstrate that the integration of GeoGebra into learning is effective in enhancing students' critical thinking skills. GeoGebra, a dynamic mathematics software, plays an important role in improving students' critical thinking skills by facilitating the development of key critical thinking indicators such as interpretation, analysis, evaluation, and inference. These cognitive skills are essential for students to approach mathematical problems in a systematic and creative manner. The visual features and immediate feedback from GeoGebra are very helpful in the process of conjecturing, exploring, and validating solutions, which are core aspects of critical thinking (Aparı et al., 2022; Samura & Darhim, 2023). Using GeoGebra, students can directly observe the effect of changes in variables on their mathematical representations, which encourages them to reflect and refine their problem-solving strategies. A study by Demiray et al., (2023) emphasized that GeoGebra facilitates investigative learning and allows students to test hypotheses through visual experiments. Therefore, integrating GeoGebra into PBL not only enhances conceptual understanding but also strengthens critical thinking skills by providing a constructive, reflective, and evidence-based learning environment.

GeoGebra plays a significant role in enhancing students' critical thinking skills by providing a learning environment that supports the exploration, analysis, and evaluation of mathematical concepts. The dynamic visualization features of GeoGebra allow students to engage more deeply with mathematical ideas, thereby encouraging deeper exploration of various concepts. When students manipulate mathematical objects, they can develop a better conceptual understanding and interpret various representations of these concepts more effectively (Canonigo, 2024; Yerizon et al., 2023).

In the analysis phase, GeoGebra facilitates collaborative work where students can analyze problems systematically. This collaboration creates a shared inquiry environment where students can assess and compare various solutions, which in turn enhances their analytical skills. Through discussion and collective reflection, students can explore different ways to solve problems, enriching their thinking process (Barçin & Yenmez, 2023; Ishartono et al., 2022).

Furthermore, GeoGebra supports evaluative thinking by allowing students to assess the accuracy of their results and the strategies used to achieve them. This iterative process strengthens their ability to critique and refine their mathematical reasoning. Students can evaluate whether their solutions are consistent with the theory they have learned and whether there are more efficient ways to solve problems, which is critical in developing their critical thinking skills (Birgin & Yazıcı, 2021; Muslim et al., 2023).

Through these interactive experiences, students not only strengthen their technical skills but also develop higher order thinking skills needed for effective problem-solving. GeoGebra acts as a bridge between abstract mathematical theory and more tangible understanding, encouraging a hands-on approach that is crucial for developing advanced critical thinking capabilities in mathematics (Dahal et al., 2022; Sebsibe & Abdella, 2025).

Overall, the findings of this study indicate that GeoGebra not only improves students' technical understanding in mathematics but also enriches their critical thinking skills. Through exploration and evaluation facilitated by GeoGebra, students can develop deeper and more reflective thinking skills, which are essential for solving more complex mathematical problems.

Moreover, the findings of this study also suggest that the combination of PBL and GeoGebra creates a strong synergy in improving the quality of mathematics education. PBL provides a pedagogical framework that emphasizes problem-based, collaborative, and reflective learning, while GeoGebra provides an interactive visual media that supports the exploration of abstract concepts.

In the Student Orientation to the Problem stage, GeoGebra plays a very important role in attracting students' attention and engagement through dynamic visualizations. By using GeoGebra, teachers can introduce complex mathematical problems in a clearer and more engaging way. The graphic visualizations allow students to see and understand mathematical objects that were previously abstract, such as three-dimensional geometric shapes. This not only clarifies the problem to be solved but also motivates students to explore further, which in turn enhances their intrinsic motivation to solve the problem (Amalia et al., 2023; Warsitasari & Rofiki, 2023).

In the Organizing Students for Learning stage, GeoGebra supports students in organizing themselves both individually and in groups. The collaborative features of GeoGebra allow students to work together in solving mathematical problems. They can share and analyze solutions in real-time, enhancing interaction and discussion among students. In the context of PBL, this stage is crucial because it enables students to help each other and validate their understanding, strengthening their mathematical communication skills. This aligns with findings from Sihombing et al., (2025) and Yerizon et al., (2022), which show that the use of GeoGebra supports more effective collaborative learning.

In the Investigation stage, GeoGebra functions as an investigative tool, enabling students to manipulate variables and observe the results. Students can change parameters, such as length, width, and height on geometric objects, and observe the changes directly. Thus, GeoGebra encourages students to develop a deeper understanding of mathematical concepts through hands-on experimentation and hypothesis testing. Findings by Harianto & Wawan Sudatha, (2024) and Awaji et al., (2025) highlight that GeoGebra deepens students' understanding by giving them the opportunity to interact directly with mathematical objects and explore solutions.

Next, in the Develop Work Outcomes stage, GeoGebra is highly effective in helping students develop and present their work. After completing their investigation, GeoGebra allows them to visualize their findings in a clearer and more engaging way. Students can use graphic representations and animations to explain the solutions they have found, clarifying their understanding and allowing them to present their work more systematically. As explained by Rokan et al., (2023), the ability to present results visually through GeoGebra helps clarify students' mathematical reasoning and enhances their communication skills.

In the Analysis and Evaluation stage, GeoGebra supports reflective activities, enabling students to assess their problem-solving process and relate their findings to the existing theoretical framework. Students can evaluate whether the solutions they found are correct and how they can improve the process. This feature also allows students to revisit the steps they have taken and analyze the effectiveness of the strategies used. Saepuloh et al., (2021) and Wardani et al., (2022) state that this reflection phase strengthens students' metacognitive abilities, which is important in problem-based learning and in enhancing critical thinking.

Integrating GeoGebra into the PBL framework has proven to be highly effective in supporting every step of the learning process. GeoGebra offers students the opportunity to not only understand mathematical concepts more clearly but also improve their critical thinking and problem-solving skills. By supporting every phase of PBL—from problem exploration to result evaluation—GeoGebra helps create a more interactive, collaborative, and reflective learning environment, which is essential in developing higher-order thinking skills needed in the 21st century (Fang et al., 2023; Lingefjärd & Ghosh, 2022).

Although the research findings show that GeoGebra is valid, practical, and effective in improving students' critical thinking skills, its implementation faces several challenges related to time constraints and computer equipment. Teachers often report limited time available for planning and integrating GeoGebra into the curriculum, as the Problem-Based Learning (PBL) method requires longer exploration times (Fernandez & Condori, 2023). Additionally, limitations in technological facilities, such as computer equipment and uneven internet access, hinder students from fully accessing and using GeoGebra. Furthermore, a lack of training materials and supporting staff exacerbates the implementation of GeoGebra, particularly in schools with limited funding. These time and resource limitations hinder the optimal use of GeoGebra, despite its great potential to improve students' mathematical understanding (Fernandez & Condori, 2023). This issue needs to be addressed by teachers when implementing GeoGebra-assisted Problem-Based Learning.

The research findings have significant implications for mathematics learning in schools. First, the study strengthens the urgency of using digital media such as GeoGebra as an integral part of problem-based learning strategies. This media serves not only as a visual aid but also as a mathematical exploration platform that encourages active student engagement and enhances the quality of learning. Second, the success of GeoGebra-assisted PBL emphasizes the importance of the teacher's role as a facilitator. In the context of PBL, the teacher is no longer the center of information but acts as a guide who helps students navigate the thinking process, conduct investigations, and reflect on their learning outcomes. Third, these results provide a foundation for the development of a more adaptive mathematics curriculum that aligns with technological advancements and 21st-century skill requirements. Mathematics learning should no longer focus solely on mastering formulas but should emphasize the development of critical thinking, problem-solving, collaboration, and digital literacy skills.

Conclusion

GeoGebra learning media in Problem-Based Learning (PBL) has been proven to be valid, practical, and effective in enhancing students' mathematical critical thinking skills. GeoGebra plays a significant role in improving students' mathematical critical thinking skills, particularly through the Problem-Based Learning (PBL) approach. The use of GeoGebra in mathematics education is able to optimize students' skills in four aspects of critical thinking: interpretation, analysis, evaluation, and inference.

This study has several important implications for the development of mathematics education, especially in the context of using technology media to enhance students' critical thinking skills. (1) The results of this study indicate that the use of GeoGebra in Problem-Based Learning (PBL) can be an effective alternative to improving students' mathematical critical thinking skills. Therefore, educators are encouraged to integrate GeoGebra media into their teaching processes, both in secondary education and higher education, to create a more interactive and technology-based learning environment. (2) This study also contributes to the development of the PBL learning model that utilizes technology, thereby enriching student-centered learning approaches. (3) Furthermore, this research provides insights for the development of a curriculum that is more focused on technology and 21st-century skills, where the mastery of technology in mathematics education becomes an inseparable aspect. It is hoped that the findings of this study can serve as a foundation for further development in using GeoGebra as a learning media in various educational contexts.

This study has several limitations. First, the sample used was limited to one class, so the results may not be generalized to other educational levels. Additionally, limited access to technological resources, such as hardware, in schools may reduce the effectiveness of using GeoGebra. Furthermore, the teacher's ability to operate GeoGebra also affects the success of the learning implementation. Some teachers may not yet be familiar with using this technology, which could hinder the optimal use of the learning media. Therefore, further research is needed to explore the impact of these limitations and to optimize the use of GeoGebra in broader educational contexts.

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Declarations

Conflicts of Interest	:	The authors declare no conflict of interest.
Generative AI Statement	:	AI Used for Limited, Non-Substantive Support: Generative AI tools, such as Grammarly and ChatGPT, were employed solely for language editing and minor phrasing enhancements. All conceptualization, analysis, and scholarly content were independently developed and verified by the authors.
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Author Contributions : **Ade Kurniawan:** Played a key role as the developer of the GeoGebra learning media, which is central to this research. **Masjudin:** Designing the Problem-Based Learning (PBL) device integrated with GeoGebra. **Yuntawati:** acted as the research design architect, covering the methodology and overall structure of the study. **Eliska Juliangkary:** played an important role in communication and documentation, ensuring the smooth flow of information and the preparation of comprehensive documentation. **Reny Amalia Permata:** focused on analyzing the data obtained from this research and providing in-depth interpretation of the results. **Syahrir:** responsible for developing the evaluation instruments used to measure the effectiveness of GeoGebra in the learning process. **Ahmad Muzaki:** compiled the research report and wrote the publication manuscript summarizing the research findings for publication.

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