

# Development of STEAM-Based Learning with a Deep Learning Approach to Enhance Critical Thinking Skills on Circle Material

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## Abstract

This study aims to develop STEAM-based mathematics learning tools integrated with a deep learning approach to enhance junior high school students' critical thinking skills on circle material. The study employed the 4D development model consisting of Define, Design, Develop, and Disseminate stages. The developed products included a Module Implementation Plan (RPM), teaching materials, interactive learning media, Student Worksheets (LKM), and critical thinking assessment instruments. The novelty of this study lies in the systematic integration of STEAM principles and deep learning into all learning components specifically designed for circle material at the junior high school level. The validity of the tools was assessed by expert validators, while practicality was evaluated through observations of learning implementation, student activities, and student responses. Effectiveness was examined using the N-Gain test. The results showed that the developed tools were valid (mean score = 3.76), practical, and effective, with students demonstrating active participation, positive responses, and a moderate improvement in critical thinking skills (N-Gain = 0.60).

## Keywords

STEAM; deep learning; critical thinking skills; circle material; 4D development model

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## 1. INTRODUCTION

Education is one of the most vital aspects in preparing human resources capable of facing rapid technological developments and global changes (Dudin et al., 2016)(Malik, 2018). In the 21st century, the advancement of science and technology demands the world of education not only to focus on mastering subject matter, but also on developing skills needed in life (Pentury et al., 2023)(Wulandari, 2025)(Krittapakpokin et al., 2026). Students must not only memorize concepts and formulas; they must be able to think critically, creatively, communicate, collaborate, have good character, and practice citizenship in facing various problems (Bulkis et al., 2025)(Glaser, 1985). These skills are known as the 6C competencies (Critical Thinking, Creativity, Communication, Collaboration, Character, and Citizenship), which are the main competencies in 21st-century learning (Arianda et al., 2024)(Dong, 2022).



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One of the most important skills to develop is critical thinking. Critical thinking is the ability to analyze information, evaluate a problem, provide logical reasoning, and make appropriate decisions based on facts and evidence (Putri & Nurmalina, 2018). Mathematics is one of the subjects that plays an important role in training students' critical thinking skills (Lambertus, 2009). In the mathematics learning process, students are required to understand concepts, connect various information, determine solution strategies, and draw logical conclusions (Ben-Hur, 2006) (Niemi, 1996).

However, the critical thinking skills of Indonesian students remain relatively low. This is evidenced by the results of the Programme for International Student Assessment (PISA) (Katoningsih, 2020) (Esti et al., 2023), which shows that Indonesian students' ability to solve reasoning and problem-solving-based questions is still below the international average (Ependi et al., 2023) (Sholikah & Pertiwi, 2021). Most Indonesian students still have difficulty in understanding contextual questions, justifying their answers, and drawing conclusions from problems. Students tend to be accustomed to solving routine procedural problems, making it difficult for them when faced with problems requiring deeper reasoning (Nilyani et al., 2023).

Previous studies have shown that the STEAM approach has a positive impact on improving students' critical thinking skills and engagement in mathematics learning. For example, Jeranah et al. (2024) reported that STEAM integration improved students' mathematical critical thinking skills (Jeranah et al., 2024), while Pasca Emilidha et al. (2024) emphasized the role of STEAM in fostering higher-order thinking skills through contextual learning activities. In addition, research by Ichsan et al. (2024) demonstrated that deep learning approaches can enhance students' understanding and critical thinking by promoting meaningful and reflective learning experiences (Pasca Emilidha et al., 2024).

Recent studies have increasingly highlighted the effectiveness of STEAM and deep learning-oriented mathematics instruction in promoting students' higher-order thinking skills. Research by Yakman (2008) emphasized that STEAM integration provides interdisciplinary learning experiences that foster critical and creative thinking (Yakman, 2008). Similarly, Quigley and Herro (2016) found that STEAM-based project learning enhances students' problem-solving abilities and engagement in authentic learning contexts (Quigley et al., 2017). Further, Henriksen (2017) argued that the integration of arts within STEM learning encourages creativity and flexible thinking, both of which are closely related to critical thinking skills (Henriksen, 2017). Studies conducted by Aguilera and Ortiz-Revilla (2021) demonstrated that STEAM education significantly improves students' reasoning and inquiry skills through collaborative activities (Aguilera & Ortiz-Revilla, 2021). Likewise, Perignat and Katz-Buonincontro (2019) reported that STEAM learning creates meaningful learning experiences that support the development of higher-order cognitive abilities (Perignat & Katz-Buonincontro, 2019). In the field of mathematics education, English (2016) emphasized that integrated STEM learning strengthens students' analytical and problem-solving skills through real-world applications (English, 2016). Moreover, Ge et al. (2016) showed that deep learning approaches encourage students to construct conceptual understanding and engage in reflective thinking processes (Ge et al., 2016). Biggs and Tang (2011) also argued that deep learning promotes meaningful learning by encouraging students to relate ideas, analyze evidence, and apply knowledge critically (Biggs & Tang, 2011). Additionally, Hmelo-Silver (2004) found that student-centered and inquiry-based learning environments significantly enhance critical thinking and self-directed learning skills (Hmelo-Silver, 2004). Finally, Bybee (2013) emphasized that integrated STEM and inquiry learning environments prepare students to think critically, solve complex problems, and apply knowledge in authentic situations (Bybee, 2013) (Xie et al., 2015). However, most previous studies have focused either on the implementation of STEAM learning or on the effectiveness of deep learning approaches separately. Research concerning the development of mathematics learning tools that systematically integrate STEAM with a deep learning approach is still limited. Moreover, previous studies generally examined these approaches in broad mathematics topics and have not specifically developed learning tools for circle material at the junior high school level.

Circle material is one of the geometry topics that is closely related to everyday life and requires students to connect concepts with contextual situations (Pirasa, 2016). Nevertheless, many students still experience difficulties in understanding circle concepts and solving contextual problems related to circle applications in real-life situations (Makkasau' et al., 2023). This indicates the need for innovative learning tools that facilitate meaningful and contextual learning experiences.

Therefore, this study fills the existing research gap by developing STEAM-based mathematics learning tools that systematically integrate a deep learning approach into circle material at the junior high school level. The novelty of this research lies in the integration of STEAM elements and deep learning principles into all components of the learning tools, including the RPM, teaching materials, learning media, LKM, and critical thinking assessment instruments, with the aim of enhancing students' critical thinking skills. Based on preliminary observations conducted in May at MTs Al-Falah, it was found that students still have difficulty in solving problems related to the circumference and area of a circle, and lack active involvement in learning processes that require deep understanding. This condition indicates the need for a learning innovation capable of encouraging students to be active, think critically, and understand concepts meaningfully.

One learning solution that can be used is STEAM-based learning. STEAM (Science, Technology, Engineering, Art, and Mathematics) is a learning approach that integrates five academic disciplines, helping to create contextual, creative, active, and meaningful learning (Pasca Emilidha et al., 2024). Through STEAM learning, students not only learn to understand mathematical concepts theoretically but also apply those concepts in solving real problems through various creative and collaborative activities (Jeranah et al., 2024). Furthermore, the use of a deep learning approach in instruction emphasizes profound and meaningful learning, so that students do not merely memorize information but understand concepts holistically (Safitri et al., 2025) (Kurniawan et al., 2022) (Ichsan et al., 2024).

Based on the above description, this study aims to develop STEAM-based learning tools with a deep learning approach that are valid, practical, and effective to enhance students' critical thinking skills on circle material at the junior high school level. The developed tools include RPM, teaching materials, learning media, LKM, and critical thinking assessment instruments using the 4D development model (Define, Design, Develop, Disseminate).

## 2. METHODS

### *Research Type and Design*

This study is a Research and Development (R&D) study aimed at producing STEAM-based learning tools with a deep learning approach to improve students' critical thinking skills on circle material. The development model used is the 4D model, consisting of four main stages: Define, Design, Develop, and Disseminate (Thiagarajan et al., 1974). The 4D model was chosen due to its systematic and flexible nature, providing a clear and structured workflow. This study not only produces teaching tools but also tests their validity, practicality, and effectiveness in the context of junior high school mathematics learning.

### *Research Setting and Subjects*

This study was conducted at MTs Al-Falah, which has implemented the Merdeka Curriculum. Research subjects consisted of: (1) experts comprising content experts, media experts, and learning experts; (2) mathematics teachers involved in the implementation of the tools; and (3) Grade VIII junior high school students participating in the field trial to test the effectiveness of the tools on improving critical thinking skills.

### ***Development Procedure (4D Model)***

The Define stage aimed to establish and define the requirements for the development of learning tools. Activities included: (1) front-end analysis to identify fundamental problems in circle material learning; (2) learner analysis to understand students' characteristics, academic ability, and learning styles; (3) task analysis to identify critical thinking skills to be developed; (4) concept analysis to map the main concepts of circle material and their relevance to STEAM; and (5) formulation of specific and measurable instructional objectives.

The Design stage aimed to prepare a prototype of the learning tools. Activities included: (1) development of criterion-referenced tests to measure critical thinking skills; (2) selection of interactive digital learning media; (3) selection of tool formats supporting the integration of STEAM and deep learning; and (4) preparation of an initial design encompassing RPM, teaching materials, learning media, LKM, and assessment instruments.

The Develop stage aimed to produce learning tools revised based on expert feedback and trial data. Activities included: (1) expert appraisal by mathematics content experts, instructional technology experts, and STEAM education experts; and (2) developmental testing carried out in stages from limited trials to broader trials.

The Disseminate stage was the final stage aimed at disseminating the tested learning tools. Activities included validation testing in authentic settings, product packaging, and diffusion and adoption to a broader audience through socialization, scientific forums, and publication of research results.

### ***Research Instruments***

Instruments used in this study included: (1) a validation sheet with a Likert scale of 1–4 to measure tool validity; (2) an observation sheet for learning implementation and student activities; (3) student response questionnaires; (4) semi-structured interview guidelines with teachers; and (5) critical thinking test items consisting of three STEAM-based problems administered before and after tool implementation.

### ***Data Analysis Technique***

Validity analysis: The validity level was obtained from the assessment of two validators by calculating the mean score for all aspects on the validation sheet. An instrument was categorized as valid if the total mean score fell in the range  $3 \leq V_a \leq 4$ . Practicality analysis: Practicality data were obtained from analysis of field trial data including: (1) observation of learning tool implementation, with practical criteria if a minimum score of 3 (high category) was achieved; (2) student activity observation, effective if the percentage of student activity reached at least the good category for all sessions; and (3) student response, positive if at least 70% of students achieved the percentage on all aspects.

Effectiveness analysis was conducted using both descriptive and inferential statistical analyses. First, the N-Gain test was used to determine the magnitude of students' improvement in critical thinking skills before and after the implementation of the learning tools. The N-Gain values were categorized as high ( $\geq 0.70$ ), moderate ( $0.30 \leq \text{N-Gain} < 0.70$ ), and low ( $< 0.30$ ).

To examine whether there was a significant difference in critical thinking skills between the experimental and control groups, inferential statistical tests were conducted. The normality of the data was tested using the Shapiro–Wilk test, while the homogeneity of variances was examined using Levene's test. After the assumptions of normality and homogeneity were met, an independent samples t-test was performed to compare the posttest scores of the two groups. The significance level used in this study was  $\alpha = 0.05$ . The developed learning tools were considered effective if the N-Gain score was

at least in the moderate category and the results of the independent samples t-test indicated a statistically significant difference between the experimental and control groups ( $p < 0.05$ ).

### 3. FINDINGS AND DISCUSSIONS

#### Findings

##### *Results of the Define Stage*

In the Define stage, a front-end analysis was conducted through classroom observations, interviews with mathematics teachers, and an initial diagnostic test of students' critical thinking skills. The observations revealed that mathematics learning at MTs Al-Falah was still predominantly teacher-centered, causing students to be relatively passive during classroom activities. Interviews with the mathematics teacher indicated that the learning tools used, particularly the RPM and LKM, mainly focused on procedural exercises and had not yet integrated approaches that systematically promote critical thinking skills.

The results of the initial diagnostic test showed that students' critical thinking skills were still relatively low. Of the 32 Grade VIII students, 23 students (71.9%) had difficulties analyzing contextual problems related to circle material, 22 students (68.8%) were unable to provide logical explanations for their answers, and 24 students (75.0%) experienced difficulties in drawing conclusions based on mathematical evidence. These findings indicate that most students had not yet achieved the expected critical thinking indicators, particularly in analysis, explanation, and inference.

In addition, several common errors were identified in students' solutions to circle problems. For example, students were generally able to memorize the formulas for circumference and area of a circle; however, many of them failed to determine which formula should be applied in contextual situations. Some students also substituted numerical values directly into formulas without first interpreting the information given in the problem. These errors indicate that students tended to rely on procedural understanding rather than conceptual understanding and critical reasoning.

Task analysis identified six critical thinking indicators as the main targets of the developed learning tools, namely interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 1990). Furthermore, concept analysis produced a concept map of circle material covering circle elements, circumference, area, arc length, sector area, and the relationship between central and inscribed angles, all of which were linked to STEAM contexts. These analytical results served as the foundation for formulating specific, measurable, and critical-thinking-oriented learning objectives.

##### *Results of the Design Stage*

Based on the results of the Define stage, a prototype of STEAM-based learning tools with a deep learning approach was designed. The developed learning tools consisted of five main components: RPM, teaching materials, interactive learning media, LKM, and critical thinking assessment instruments.

The RPM was designed according to the principles of STEAM and deep learning and consisted of several components, including learning objectives, learning outcomes, learning materials, learning activities, assessment techniques, and reflection activities. The learning syntax included: (1) problem orientation through contextual situations related to circles, (2) exploration of concepts using STEAM activities, (3) investigation and problem solving, (4) presentation and discussion of solutions, and (5) reflection to encourage meaningful and reflective learning.

The teaching materials were presented in multimedia format and contained explanations of circle concepts integrated with real-life contexts. The materials were enriched with illustrations, QR codes linked to digital resources, and contextual examples involving science, technology, engineering, art, and

mathematics. Students were encouraged to explore circle applications through activities such as designing circular parks, analyzing circular motion, and creating geometric art patterns.

Interactive learning media were developed using GeoGebra and integrated into an e-learning platform. The media provided several features, including dynamic visualization of circle elements, interactive simulations of circumference and area, exploration of central and inscribed angles, and practice activities accompanied by immediate feedback. These features allowed students to manipulate objects directly and observe changes in geometric relationships dynamically.

The LKM (Student Worksheets) were designed based on STEAM activities and consisted of four stages: problem orientation, exploration, investigation, and contextual application. In the Science component, students investigated circular motion phenomena; in Technology, they explored circle concepts using GeoGebra; in Engineering, they designed objects with circular structures; in Art, they created mandala patterns; and in Mathematics, they solved contextual problems involving circle concepts.

The critical thinking assessment instruments consisted of STEAM-based essay questions developed according to six critical thinking indicators proposed by Facione (1990), namely interpretation, analysis, evaluation, inference, explanation, and self-regulation. The tests were prepared in two equivalent forms (pretest and posttest) with different contexts but the same cognitive level to measure students' improvement in critical thinking skills (Facione, 1990).

Each component of the developed learning tools was designed to integrate at least one STEAM element and one deep learning principle, such as meaningful learning, active and collaborative learning, and reflective learning (Fullan & Langworthy, 2014).

### Results of the Develop Stage

Expert validation was conducted by two validators consisting of a mathematics content expert and a learning tools expert. Assessment used a validation sheet with a Likert scale of 1–4. The validation results of all learning tool components are presented in Table 1.

**Table 1.** Validation Results of Learning Tools

No.	Component	Validator 1	Validator 2	Mean (Va)	Category
1	RPM	3.72	3.81	3.77	Valid
2	Teaching Materials	3.65	3.78	3.72	Valid
3	Learning Media	3.80	3.84	3.82	Valid
4	LKM	3.68	3.75	3.72	Valid
5	Assessment Instrument	3.75	3.82	3.79	Valid
	<b>Total Mean</b>	<b>3.72</b>	<b>3.80</b>	<b>3.76</b>	<b>Valid</b>

Expert validation was conducted by two validators consisting of a mathematics content expert and a learning tools expert. The mathematics content expert evaluated the accuracy, completeness, and suitability of the circle material and its integration with STEAM concepts, while the learning tools expert assessed the instructional design, learning syntax, media usability, and the integration of deep learning principles into the developed tools.

The assessment employed a validation sheet using a four-point Likert scale ranging from 1 (very poor) to 4 (very good). The validation results of all learning tool components are presented in Table 2.

Based on Table 2, all learning tool components obtained validity scores within the range of  $3 \leq Va \leq 4$  and were therefore categorized as valid. The learning media obtained the highest validity score ( $Va = 3.82$ ), indicating that the developed interactive media effectively supported students' understanding

of circle concepts. Meanwhile, the teaching materials and LKM obtained a validity score of  $V_a = 3.72$ , which was also categorized as valid. The total mean validity score of all developed learning tools was  $V_a = 3.76$ .

The validators provided several suggestions for improvement, including refining the wording of assessment items, adjusting STEAM contexts to suit students' cognitive development levels, improving the clarity of instructions in the LKM, and adding more detailed guidelines for using the learning media. All suggestions were incorporated into the revised version of the learning tools before the field trial stage.

### Field Trial Results

Observation of learning tool implementation was conducted by an observer at each session during implementation. The results of the observation are presented in Table 2.

**Table 2.** Observation Results of Learning Tool Implementation

Session	Aspects Observed	Score	Category
1	Introduction, core activities, closing	3.52	High
2	Introduction, core activities, closing	3.64	High
3	Introduction, core activities, closing	3.71	High
4	Introduction, core activities, closing	3.78	High
<b>Mean</b>		<b>3.66</b>	<b>High</b>

Based on Table 3, the mean implementation score over four sessions was 3.66, categorized as high (score  $\geq 3$ ). This indicates that the teacher was able to conduct learning according to the STEAM-based RPM with the deep learning approach. The increasing score from session one to session four indicates that the teacher became progressively more familiar with the developed approach.

**Table 3.** Student Activity Observation Results

Session	Relevant Activity Percentage (%)	Category
1	72.4	Good
2	78.6	Good
3	83.2	Very Good
4	86.5	Very Good
<b>Mean</b>	<b>80.2</b>	<b>Good</b>

Based on Table 3, the mean percentage of student relevant activity over four sessions was 80.2%, categorized as good. Student activity showed consistent improvement from session one to four, indicating that students became increasingly active and engaged in STEAM-based learning with the deep learning approach. This aligns with the principle of active learning in deep learning pedagogy that emphasizes active student involvement in knowledge construction (Fullan & Langworthy, 2014).

**Table 4.** Student Response Summary

Aspect	Positive Response (%)	Category
Appearance and ease of use	85.7	Very Positive
Clarity of materials and instructions	82.1	Positive
Attractiveness of learning activities	88.4	Very Positive
Involvement of STEAM elements	79.6	Positive

Aspect	Positive Response (%)	Category
Usefulness of tools	84.3	Positive
<b>Mean</b>	<b>84.0</b>	<b>Positive</b>

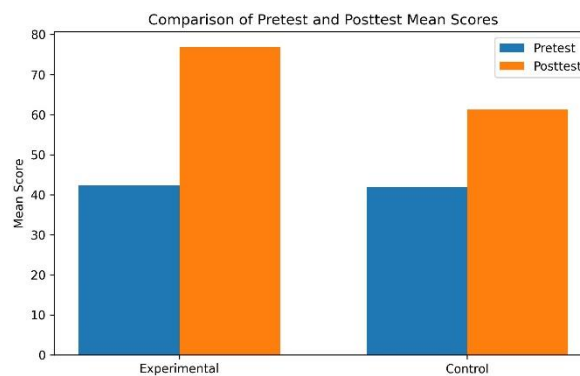
Based on Table 4, the mean positive student response was 84.0%, exceeding the minimum threshold of 70%. All evaluation aspects obtained a percentage  $\geq 70\%$ , so the learning tools met the practicality criteria. The attractiveness of learning activities obtained the highest percentage (88.4%), indicating that the integration of STEAM activities in the learning tools successfully attracted students' interest and enthusiasm.

**Effectiveness Analysis Results**

The critical thinking test was administered before (pretest) and after (posttest) the implementation of learning tools to both the experimental and control classes. A summary of pretest and posttest results is presented in Table 5.

**Table 5.** Pretest and Posttest Results of Critical Thinking Skills

Class	N	Mean Pretest	Mean Posttest	Gain
Experimental	32	42.31	76.84	34.53
Control	32	41.87	61.25	19.38



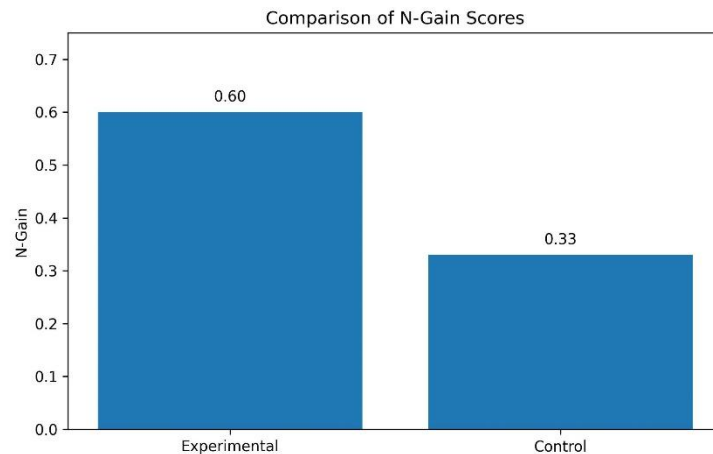
**Figure 1.** Comparison of Pretest and Posttest Mean Scores of Critical Thinking Skills in the Experimental and Control Classes

Based on Table 5, the mean posttest score of the experimental class (76.84) was higher than that of the control class (61.25). The gain score of the experimental class (34.53) was also greater than that of the control class (19.38). This indicates that the implementation of STEAM-based learning tools with the deep learning approach had a greater impact on improving students' critical thinking skills.

The N-Gain test was conducted to determine the magnitude of improvement in critical thinking skills before and after treatment. Results are presented in Table 6.

**Table 6.** N-Gain Test Results of Critical Thinking Skills

Class	Mean N-Gain	Category
Experimental	0.60	Moderate
Control	0.33	Moderate



**Figure 2.** Comparison of N-Gain Scores of Critical Thinking Skills between the Experimental and Control Classes.

Based on Table 7, the mean N-Gain of the experimental class was 0.60 (moderate category), while the control class obtained an N-Gain of 0.33 (also moderate). However, the N-Gain of the experimental class (0.60) was significantly higher than that of the control class (0.33). Both classes met the minimum effective criteria ( $N\text{-Gain} \geq 0.3$ ); however, the STEAM-based learning tools with the deep learning approach yielded a significantly greater improvement, indicating the effectiveness of the developed tools in improving students' critical thinking skills on circle material.

## Discussion

The findings of this study indicate that the STEAM-based learning tools integrated with a deep learning approach are capable of promoting students' critical thinking skills through meaningful, contextual, and student-centered learning experiences. The results are consistent with previous studies showing that STEAM learning facilitates higher-order thinking skills and encourages active student engagement in mathematics learning. Pasca Emilidha et al. (2024) reported that STEAM integration supports students in solving contextual problems and developing critical thinking through interdisciplinary learning activities (Pasca Emilidha et al., 2024). Likewise, Jeranah et al. (2024) found that STEAM-based mathematics learning significantly improves students' critical thinking skills. However, these previous studies mainly focused on the implementation of STEAM learning strategies and did not specifically develop learning tools that systematically integrate STEAM with a deep learning approach (Jeranah et al., 2024).

The novelty of this study lies in the development of a comprehensive set of mathematics learning tools that integrates STEAM principles and deep learning into all learning components, including the RPM, teaching materials, GeoGebra-based learning media, LKM, and critical thinking assessment instruments. Unlike previous studies that investigated STEAM or deep learning separately, this study combines both approaches within a unified instructional design specifically developed for circle material at the junior high school level. Therefore, this research fills the gap in mathematics education research, particularly in the development of learning tools that integrate STEAM and deep learning systematically to improve critical thinking skills.

The effectiveness of the developed learning tools can be explained from the perspective of constructivist theory. Constructivism emphasizes that students actively construct knowledge through interaction with their environment and learning experiences. In this study, students were encouraged to investigate contextual problems, explore circle concepts using GeoGebra, discuss alternative solutions collaboratively, and reflect on their learning experiences. Such activities enabled students to develop conceptual understanding actively rather than merely receiving information from teachers. This finding is consistent with Hobri et al. (2021), who stated that contextual mathematics learning that emphasizes active knowledge construction can significantly improve students' reasoning and critical

thinking abilities (Hobri et al., 2021).

Furthermore, the findings support experiential learning theory, which argues that learning becomes more meaningful when students acquire knowledge through direct experience. The STEAM activities designed in this study provided opportunities for students to explore circle concepts from multiple perspectives, including science through circular motion phenomena, technology through GeoGebra exploration, engineering through designing circular objects, art through mandala creation, and mathematics through formal problem solving. These authentic learning experiences enabled students to connect mathematical concepts with real-life situations. This result is in line with Quigley et al. (2017), who emphasized that STEAM creates meaningful interdisciplinary learning experiences and strengthens students' engagement in mathematics learning (Quigley et al., 2017).

The improvement in students' critical thinking skills can also be explained through inquiry learning and deep learning principles. During the learning process, students were encouraged to ask questions, formulate hypotheses, investigate problems, analyze information, evaluate alternative solutions, and draw conclusions independently. Such inquiry-oriented activities trained students to engage in higher-order thinking processes, particularly analysis and evaluation. This finding supports Munir et al. (2023), who reported that inquiry-based learning activities effectively improve students' analytical and evaluative thinking skills. In addition, Ichsan et al. (2024) emphasized that deep learning promotes meaningful understanding, reflective thinking, and the ability to transfer knowledge to new situations, which are essential dimensions of critical thinking (Ichsan et al., 2024).

The increase in critical thinking skills was particularly evident in the indicators of analysis and explanation. Students became more capable of identifying relevant information from contextual problems, relating circle concepts to real-life situations, and providing logical explanations for their answers. This improvement occurred because the developed learning tools consistently required students to investigate problems, discuss ideas collaboratively, and reflect on their learning experiences. Compared with conventional learning, which often emphasizes procedural exercises, the STEAM-based learning tools with a deep learning approach provided broader opportunities for students to develop conceptual understanding and critical reasoning skills.

Compared with previous studies, this research contributes a new perspective by demonstrating that the integration of STEAM and deep learning is not only effective at the conceptual level but can also be operationalized through systematically developed learning tools. While previous studies generally examined the effectiveness of STEAM learning models or deep learning approaches independently, there is still limited research focusing on the development of mathematics learning tools that integrate both approaches specifically for circle material at the junior high school level. Therefore, the present study offers an important contribution to mathematics education by providing validated, practical, and effective learning tools that promote critical thinking through contextual, interdisciplinary, and meaningful learning experiences.

Despite these positive findings, several limitations should be acknowledged. First, the implementation of the developed learning tools depends on technological facilities, particularly internet access and GeoGebra applications, which may not be equally available across schools. Second, STEAM-based learning integrated with a deep learning approach requires longer instructional time because students need opportunities for exploration, investigation, collaboration, and reflection. Future studies may expand the implementation to other mathematics topics and educational levels to examine the broader applicability of the developed learning tools.

#### 4. CONCLUSION

Based on the results of the research and discussion, it can be concluded that the STEAM-based learning tools with a deep learning approach to enhance the critical thinking skills of junior high school

students on circle material, developed using the 4D model, are declared: (1) Valid, with a mean  $V_a = 3.76$  in the range  $3 \leq V_a \leq 4$  for all tool components (RPM, teaching materials, learning media, LKM, and assessment instruments); (2) Practical, as demonstrated by a mean implementation score of 3.66 (high category), a student activity percentage of 80.2% (good category), and a positive student response percentage of 84.0%, exceeding the minimum threshold of 70%; and (3) Effective, as demonstrated by the mean N-Gain of the experimental class of 0.60 (moderate category), which is significantly higher than the control class (0.33). Thus, the developed learning tools are capable of significantly improving the critical thinking skills of junior high school students on circle material.

This study recommends that the STEAM-based learning tools with a deep learning approach that have been developed can be used more broadly in junior high school mathematics learning, especially in geometry. Further research can be conducted to extend implementation to other topics and to strengthen the digitalization aspects of learning media (Firmansyah et al., 2022; Fatahillah et al., 2023).

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