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STEM implementation to enhance elementary students' critical thinking skills in science for PISA challenges

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ABSTRACT

This study investigates the effectiveness of STEM-based science learning in improving elementary students' critical thinking skills while addressing limitations in prior research designs. A quantitative approach with a one-group pretest–posttest design was employed to better capture learning gains. The participants were 30 fifth-grade students in Gorontalo City selected purposively based on academic characteristics. STEM instruction was implemented over four sessions using the 5E model. Data were collected through a validated and reliable critical thinking test, product assessment rubrics, and observation sheets. Data analysis included descriptive statistics, paired-sample t-tests, effect size calculation, and Pearson correlation tests. The results showed a significant improvement in students' critical thinking scores after the intervention ($p < 0.001$) with a moderate effect size. Positive correlations were found among test scores, product performance, and instructional implementation. However, the findings are limited by the small sample size and short intervention duration. Overall, STEM-based learning demonstrates potential in fostering critical thinking skills in elementary science learning contexts.

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Introduction

Science learning in elementary schools should not only focus on conceptual understanding but also emphasize the development of higher-order thinking skills that are essential for facing twenty-first-century challenges (Hidayat, 2020). One of the most critical competencies in this regard is critical thinking, which involves the ability to analyze information, evaluate arguments, draw inferences, and formulate evidence-based solutions (Nurhayati & Ahmad, 2021). In the context of science education, critical thinking is closely linked to scientific literacy, as students are required to interpret data, solve problems, and make reasoned decisions based on scientific evidence.

However, international assessments continue to highlight concerns regarding Indonesian students' performance in scientific literacy. The Programme for International Student Assessment (PISA) consistently reports that Indonesian students perform below the OECD average (Hardinata et al., 2023). This gap reflects not only limitations in content knowledge but also weaknesses in higher-order thinking skills, particularly critical thinking and problem-solving. Although these findings provide a global perspective, empirical evidence at the local level, including in elementary schools in Gorontalo City, remains limited and requires further investigation.

To address these challenges, innovative instructional approaches are needed to promote active learning and higher-order thinking. STEM (Science, Technology, Engineering, and Mathematics) education has emerged as a promising approach that integrates multiple disciplines into a cohesive learning experience (Setiawan & Kurniawan, 2021). Rather than focusing on isolated subject matter, STEM emphasizes contextual problem-solving, collaboration, and hands-on activities, which are expected to support the development of critical thinking skills.

Theoretically, STEM learning aligns with constructivist principles, where students actively construct knowledge through inquiry, exploration, and reflection. Through activities such as designing prototypes, testing solutions, and evaluating outcomes, students engage in processes that require analysis, evaluation, and reasoning (Handayani, 2020). These processes correspond directly to key indicators of critical thinking, suggesting that STEM has the potential to serve as an effective pedagogical approach in elementary science education.

Previous studies have reported positive effects of STEM-based learning on students' higher-order thinking skills. Research has shown that STEM can enhance critical thinking and problem-solving abilities across various educational levels (Dewi, 2020; Ridwan & Lestari, 2019; Saxton et al., 2014). In the context of elementary education, quasi-experimental studies have demonstrated significant improvements in students' abilities to analyze problems, evaluate solutions, and design innovative products (Fitriyani et al., 2020; Wahyuni, 2022). Similarly, classroom action research has indicated a consistent increase in critical thinking performance across learning cycles (Surya & Fadilah, 2021).

Despite these promising findings, several limitations can be identified in the existing literature. Most studies rely heavily on quasi-experimental designs with control groups, which, although methodologically robust, are often difficult to implement in elementary school settings due to limited parallel classes and institutional constraints (English & King, 2019; Kapp, 2012). Moreover, prior research tends to focus on general learning outcomes rather than explicitly measuring critical thinking skills as a distinct construct (Nugraha, 2022). In addition, few studies have critically examined the variability of results or potential contextual factors influencing STEM implementation.

Another important gap lies in the limited availability of studies that employ more practical research designs suited to real classroom conditions while maintaining acceptable levels of validity. Some recent studies have begun to explore alternative approaches, such as using benchmarks and triangulated instruments; however, these approaches remain underexplored and require further empirical validation (Arifin & Lestari, 2022). Furthermore, the explicit linkage between STEM learning outcomes and global benchmarks such as PISA has not been sufficiently analyzed in previous studies.

Based on the above discussion, three main research gaps can be identified. First, there is a need for studies that specifically examine critical thinking skills in elementary science learning rather than general academic achievement (Li & Tsai, 2021). Second, there is a lack of research that employs practical and context-sensitive designs without control groups while still ensuring data validity through benchmarks and triangulation. Third, there is limited research that explicitly connects STEM-based learning outcomes to global challenges such as PISA, particularly within the Indonesian context.

Therefore, this study aims to analyze the effectiveness of STEM-based science learning in improving the critical thinking skills of fifth-grade elementary students in Gorontalo City. The study employs a simplified experimental approach supported by benchmark comparison and validated instruments to provide a more contextually feasible yet methodologically transparent alternative. By addressing both theoretical and practical gaps, this research is expected to contribute to the development of STEM pedagogy and offer insights for improving scientific literacy in elementary education.

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Method

This study employed a quantitative approach using a one-group pretest–posttest design to measure changes in students' critical thinking skills before and after STEM-based instruction. Although no control group was included due to the limited number of parallel classes, internal validity was strengthened through baseline measurement (pretest), standardized instruments, and triangulation of multiple data sources.

The participants were 30 fifth-grade students from an elementary school in Gorontalo City. A purposive sampling technique was applied by considering students' prior science achievement to ensure relatively homogeneous academic ability, as indicated by their previous semester scores (mean = 72.15, SD = 5.32). All participants were officially approved by the school administration.

The intervention was conducted over four instructional sessions (2 × 35 minutes per session) on the topic "Energy and Its Transformations." STEM-based learning was implemented using the 5E instructional model (Engage, Explore, Engineer, Explain, and Evaluate). In the Engage phase, students were introduced to real-life problems related to energy use. During Explore and Engineer phases, students conducted simple investigations and designed prototypes (e.g., energy transformation models). In the Explain phase, students presented and justified their findings, while in the Evaluate phase, both formative and summative assessments were conducted.

Data were collected using three instruments. First, a critical thinking test consisting of 15 items (combining multiple-choice reasoning and constructed responses) was developed based on four indicators: analysis, evaluation, inference, and problem solving. The instrument was validated by three experts in science education, and reliability testing yielded a Cronbach's Alpha coefficient of 0.82, indicating high reliability. Second, a performance assessment rubric was used to evaluate student products, covering design analysis, functionality, creativity, and scientific argumentation. Third, an observation sheet was completed by two trained observers to assess the fidelity of STEM implementation; inter-rater agreement reached 0.87, indicating strong consistency.

Data analysis included descriptive statistics (mean, median, standard deviation) and paired-sample t-tests to compare pretest and posttest scores. Effect size was calculated using Cohen's d to determine the magnitude of improvement. Prior to inferential analysis, assumptions of normality were tested using the Shapiro–Wilk test. Pearson correlation analysis was conducted to examine relationships among critical thinking scores, product performance, and implementation fidelity. Additionally, item analysis was performed to evaluate instrument quality based on difficulty index and discrimination power.

To enhance the robustness of findings, data from test results, product assessments, and classroom observations were triangulated. However, it is acknowledged that the absence of a control group and the relatively short duration of the intervention may limit the generalizability of the results.

Results and Discussions

Descriptive Statistics

Based on the results of the science critical thinking test administered to 30 fifth- grade students after participating in STEM-based learning, the mean score obtained was 76.83 with a standard deviation of 7.21. The highest score achieved by students was 90, while the lowest was 65. The score distribution shows that 23 students (76.7%) scored above the benchmark of 70, whereas 7 students (23.3%) fell below the standard. This indicates that the majority of students were able to achieve the expected level of critical thinking skills.

Table 1. Critical Thinking Skills Test Results

Statistic	Value
Number of Students	30
Minimum Score	65
Maximum Score	90
Mean (M)	76.83
Median	77.00
Standard Deviation	7.21

One-Sample t-Test

To determine whether the students' mean critical thinking score differed significantly from the benchmark value (70), a one-sample t-test was conducted. The results showed $t = 5.14$ with $p < 0.001$. Thus, it can be concluded that the students' mean critical thinking score was significantly higher than the benchmark of 70.

Table 2. One-Sample t-Test Results

Parameter	Value
Benchmark (μ_0)	70
Mean (M)	76.83
t-value	5.14
p-value	< 0.001
Conclusion	Significant

Correlation Analysis

Pearson correlation analysis was conducted to examine the relationships among critical thinking test scores, product rubric scores, and the implementation fidelity of STEM learning. The results showed that critical thinking test scores had a significant positive correlation with product rubric scores ($r = 0.62$, $p < 0.01$) and with STEM implementation fidelity ($r = 0.54$, $p < 0.01$). These findings indicate that the better the implementation of STEM learning, the higher the critical thinking skills demonstrated by students, both in their test performance and in the products they produced.

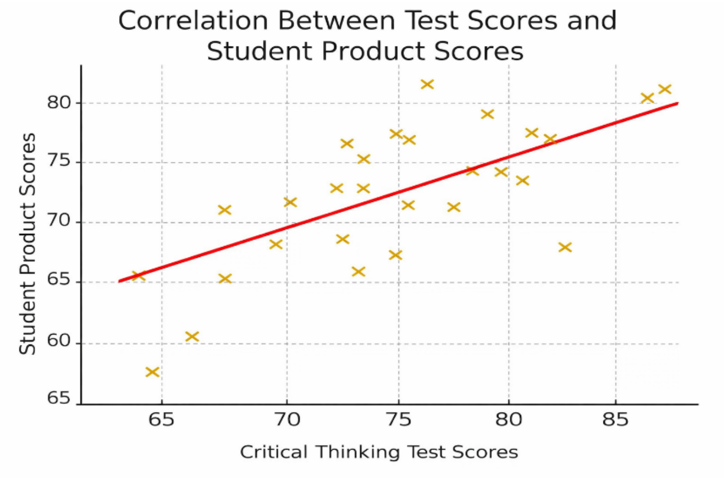

Figure 1. Correlation Between Critical Thinking Test Scores and Student Product Performance

Item Analysis

The item analysis revealed that of the 12 test items administered, 10 items fell into the medium difficulty category (0.30–0.70), while 2 items were categorized as easy (>0.70). In terms of discrimination index, 11 items demonstrated good discrimination (>0.30), whereas 1 item was categorized as fair. These findings indicate that the critical thinking test instrument used in this study possesses adequate quality for measuring students' skills.

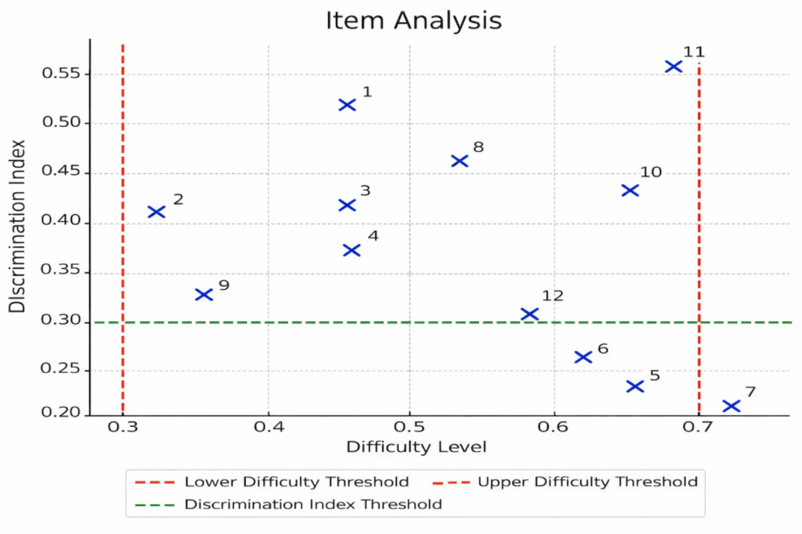

Figure 2. Item Analysis Based on Difficulty Level and Discrimination Index

Interpretation

Overall, the findings indicate that STEM-based science learning is effective in enhancing elementary students' critical thinking skills. This is evidenced by the mean score that significantly exceeded the benchmark, as well as the consistency between test results, product performance, and implementation fidelity. Therefore, the STEM approach can be considered a relevant strategy for addressing Indonesia's low scientific literacy performance at the global level, as reflected in PISA assessments.

The findings of this study indicate that students' critical thinking scores showed improvement after participating in STEM-based science learning, as reflected in the difference between pretest and posttest results. However, this improvement should be interpreted cautiously, considering the absence of a control group and the relatively short duration of the intervention. While the mean score exceeded the benchmark, this alone does not fully confirm the effectiveness of the STEM approach, but rather suggests its potential contribution to enhancing students' higher-order thinking skills.

The improvement observed in students' performance can be partially explained by the characteristics of STEM learning, which emphasize active engagement, problem-solving, and integration of multiple disciplines. During the learning process, students were involved in activities such as exploring real-life problems, designing prototypes, and presenting their findings. These activities are theoretically aligned with key indicators of critical thinking, including analysis, evaluation, and reasoning (Rahmawati & Susilo, 2019; Wang et al., 2024). However, the present study did not directly measure which specific components of STEM contributed most significantly to the observed improvement, indicating a need for more detailed process-oriented analysis.

The correlation results revealed positive relationships among critical thinking test scores, product performance, and implementation fidelity. This suggests that better implementation of STEM learning may be associated with higher student performance. Nevertheless, these relationships should not be interpreted as causal, as other variables such as students' prior knowledge, motivation, or teacher facilitation skills may also have influenced the outcomes. Further studies are needed to examine these potential contributing factors more comprehensively.

In comparison with previous studies, the findings are generally consistent with research indicating that STEM learning can support the development of higher-order thinking skills (Dewi, 2020; Fitriyani et al., 2020; Wahyuni, 2022). However, unlike most prior studies that employed quasi-experimental designs with control groups, this study used a simplified design to accommodate real classroom conditions (English & King, 2019; Kapp, 2012). While this approach increases practical feasibility, it also introduces limitations in terms of internal validity, which must be acknowledged when interpreting the results.

Another important finding is that not all students achieved scores above the benchmark, indicating variability in learning outcomes. This suggests that STEM-based instruction may not equally benefit all students, possibly due to differences in initial ability, engagement levels, or learning preferences. Unfortunately, this study did not explore these differences in depth, which represents a limitation and an opportunity for future research.

The relevance of these findings to broader contexts, such as Indonesia's performance in PISA, should also be interpreted with caution. Although STEM learning shows potential in fostering critical thinking skills, the direct impact on large-scale assessments like PISA cannot be concluded from this study alone. Instead, the results may be viewed as preliminary evidence supporting the role of classroom-level interventions in addressing broader educational challenges (Hardinata et al., 2023).

From a practical perspective, this study suggests that STEM-based learning can be implemented in elementary classrooms using structured models such as the 5E framework. However, teachers need adequate preparation, clear instructional design, and appropriate assessment tools to ensure effective implementation. Without these supports, the potential benefits of STEM may not be fully realized.

Several limitations should be acknowledged. First, the use of a one-group pretest–posttest design limits the ability to establish causal relationships. Second, the sample size was relatively small and drawn from a single school, which restricts generalizability. Third, the intervention duration was limited to four sessions, which may not be sufficient to produce long-term changes in critical thinking skills.

Future research is recommended to employ more rigorous experimental designs, include larger and more diverse samples, and extend the duration of intervention. In addition, qualitative data such as classroom interactions and student reflections could provide deeper insights into how STEM learning influences critical thinking processes.

Overall, while the findings indicate that STEM-based science learning has potential to support the development of critical thinking skills in elementary students, the results should be interpreted as exploratory rather than conclusive, and further research is needed to confirm and extend these findings.

Conclusions

This study demonstrates that STEM-based science learning has a positive impact on elementary students' Based on the findings, this study concludes that STEM-based science learning has the potential to improve elementary students' critical thinking skills, as indicated by the increase in posttest scores and supported by performance and implementation data; however, these results should be interpreted cautiously due to the limitations of the research design, and further studies with more rigorous methods are needed to confirm its effectiveness.

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