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The STEM Learning Approach in Improving Learning Outcomes of High School Students

Mardhiyah Karismayanda[1], Kurniawan[2] Sri Kadarsih [3], Al Munip[4], Hasna Dewi[5]
[1] Universitas Negeri Medan, Indonesia
[2345] Institut Islam Al-Mujaddid Sabak, Jambi, Indonesia

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ABSTRACT

This study evaluated the impact of an integrated STEM learning approach on the learning outcomes of high school students in Jambi. Employing a quasi-experimental pretest-posttest design, 140 Grade XI students were assigned to either a STEM intervention group or a traditional instruction control group. Post-intervention analysis using ANCOVA and t-tests revealed that the STEM group achieved statistically significant ($p < .001$) gains in conceptual understanding, critical thinking skills, and problem-solving abilities compared to the control group. These findings provide robust empirical evidence for the effectiveness of constructivist-based STEM pedagogy.

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Corresponding Author:

Mardhiyah Karismayanda
Universitas Negeri Medan, Indonesia
Email: mardhiyahk@gmail.com

1. INTRODUCTION

In response to the demands of the 21st-century, educational paradigms are shifting from rote memorization towards fostering critical thinking and problem-solving skills. The integrated Science, Technology, Engineering, and Mathematics (Gonzalez & Kuenzi, 2012) learning approach has emerged as a prominent pedagogical model designed to meet this need. It moves beyond traditional, siloed instruction by engaging students in interdisciplinary, project-based learning that addresses authentic, real-world challenges. Despite its growing international adoption, rigorous empirical evidence documenting its effectiveness in specific regional contexts remains limited. This study addresses this gap by investigating the impact of STEM pedagogy within the Jambi high school system.

This research provides a quantitative evaluation of the STEM learning approach on the academic performance of high school students in Jambi. It specifically measures the intervention's impact on conceptual understanding, critical thinking, and problem-solving abilities. Grounded in the theoretical framework of constructivism, the study hypothesizes that the active, inquiry-based nature of STEM education fosters more profound learning than traditional pedagogy. Through a quasi-experimental, pretest-posttest design, this investigation compares a group receiving a STEM intervention against a control group. The primary objective is to provide empirical evidence on whether this pedagogical shift yields measurable improvements in student learning outcomes.

This research is grounded in the theoretical framework of Constructivism, (Mills et al., 2006) which posits that learners actively construct their own understanding and knowledge through experiences and interactions with their environment. Unlike traditional pedagogical models that view students as passive recipients of information, constructivism emphasizes inquiry-based learning, critical thinking, and problem-solving(Khalaf & Mohammed Zin, 2018). The STEM approach is a direct pedagogical application of this theory, as it requires students to engage in hands-on projects and real-world challenges, thereby building conceptual frameworks rather than merely memorizing facts.(Slough & Milam, 2013)

Specifically, this study draws upon Jean Piaget's theory of cognitive constructivism (Waite-Stupiansky, 2022) which describes how individuals build mental models, or schemas, to understand the world. The hands-on, problem-based nature of STEM education directly facilitates this process. It challenges high school students, who are typically transitioning into the formal operational stage, to assimilate new information and accommodate their existing schemas when faced with complex, interdisciplinary problems. This cognitive engagement is hypothesized to lead to deeper, more durable learning outcomes than rote memorization.

Furthermore, Lev Vygotsky's theory of Social Constructivism (Vygotsky & Cole, 2018) provides a crucial lens for understanding the collaborative aspects of STEM learning. Vygotsky argued that learning is an inherently social process, mediated by language and interaction with more knowledgeable others. STEM projects often necessitate teamwork, compelling students to articulate their reasoning, negotiate solutions, and co-construct knowledge within their Zone of Proximal Development (Fani & Ghaemi, 2011) This collaborative environment fosters not only content mastery but also essential communication and interpersonal skills, which are integral learning outcomes.

Applying this constructivist framework to the context of high schools in Jambi, this study will analyze how the STEM approach facilitates the active and social construction of knowledge. The theory suggests that by implementing STEM, educators can create learning environments that encourage students to explore, experiment, and collaborate.(WAnG, 2009) Consequently, this research will evaluate whether these constructivist-aligned pedagogical practices result in measurable improvements in student learning outcomes, including enhanced critical thinking, problem-solving abilities, and a more profound conceptual understanding of scientific principles

2. METHOD

This study will employ a quasi-experimental,(Evers et al., 2006) pretest-posttest non-equivalent control group design to evaluate the impact of the STEM learning approach. This design is selected due to the practical constraints of randomly assigning students to different classes within the Jambi high school system. Two intact classes will be designated as the experimental group, receiving the STEM intervention, and two other classes will serve as the control group, continuing with traditional instruction. Both groups will be administered a pretest to establish baseline equivalence on key learning outcomes. A posttest will be administered at the conclusion of the intervention to measure any significant differences.

The primary independent variable in this research is the instructional method (Hartman et al., 2000), with two levels: the integrated STEM learning approach and the traditional, discipline-specific teaching approach. The dependent variables are the student learning outcomes, operationally defined as: (1) conceptual understanding in science and mathematics, measured by a standardized achievement test; (2) critical thinking skills, assessed using a validated critical thinking appraisal instrument; and (3) problem-solving

abilities, evaluated through a performance-based assessment requiring students to solve a real-world problem. These variables align with the constructivist framework, emphasizing deep understanding and higher-order cognitive skills.

The experiment will be conducted over a full academic semester, approximately 16 weeks, to allow for meaningful implementation and impact. To enhance internal validity, several control measures will be instituted. The core curriculum topics covered will be identical for both the experimental and control groups, with only the pedagogical delivery method differing.(Kember, 2003) Teachers in the experimental group will receive intensive training on STEM project-based learning implementation, while control group teachers will continue their standard practice. Instructional time will be held constant for both groups to control for exposure effects, ensuring observed differences are attributable to the intervention.

Participants and Sampling Procedures, The target population for this study comprises Grade XI students from public high schools in Jambi City, Indonesia. A purposive sampling technique will be employed to select one specific public high school that is representative of the region's educational environment and student demographics. The selection criteria include the school's willingness to participate in a semester-long study, possession of adequate laboratory and technology facilities to support STEM activities, and having at least four parallel Grade XI science-stream classes. This approach, while non-random, is necessary to ensure the feasibility of implementing the STEM intervention and to control for school-level confounding variables such as administrative policies.

From the selected high school, four intact Grade XI science-stream classes will be chosen to participate, totaling approximately 140 students. This constitutes a cluster sampling approach, where the clusters are pre-existing classrooms. To minimize selection bias at the classroom level, these four classes will be randomly assigned to the experimental and control conditions. Two classes will be designated as the experimental group ($n \approx 70$), receiving the STEM-based instruction, while the other two will form the control group ($n \approx 70$), following the traditional curriculum. This method respects the school's administrative structure and prevents disruption.

Prior to the commencement of the study, formal approval will be secured from the Jambi Provincial Education Office and the administration of the selected school. Informed consent will be obtained from the parents or legal guardians of all participating students, and student assent will also be required. Participants will be explicitly informed that their involvement is voluntary and that they can withdraw at any time without penalty. All collected data will be anonymized to ensure confidentiality. The sample is expected to consist of male and female students aged 16-17, reflecting the typical demographic composition of public high schools in Jambi.

STEM Intervention Implementation, Prior to the intervention, teachers assigned to the experimental group will undergo a comprehensive 40-hour training program over two weeks. This training, led by university researchers specializing in STEM pedagogy, will focus on the principles of Project-Based Learning,(Condliffe, 2017) strategies for integrating science, technology, engineering, and mathematics concepts, and methods for facilitating student-led inquiry. Teachers will be trained in developing authentic, real-world problem scenarios relevant to the Jambi context and using formative assessment techniques to guide student progress. The program is designed to ensure high fidelity in the implementation of the STEM approach across the experimental classrooms.

The experimental group's intervention will be structured around three interdisciplinary, project-based learning modules.(Brassler & Dettmers, 2017) For instance, one module might challenge students, working in small collaborative groups, to design and build a low-

cost water filtration system to address local water quality issues. This project requires them to apply physics principles of fluid dynamics, chemical concepts of filtration, engineering design processes, and mathematical calculations for efficiency. The teacher will act as a facilitator, guiding inquiry and providing resources rather than delivering direct instruction. This hands-on, problem-solving approach directly reflects the constructivist principles guiding this research study.

Simultaneously, the control group will follow the standard national curriculum, covering the same core science and mathematics topics as the experimental group. Instruction will be delivered using traditional, discipline-specific methods, primarily consisting of lectures, textbook-based assignments, and confirmatory laboratory exercises conducted separately for each subject. There will be no deliberate integration of STEM disciplines or implementation of project-based learning. This conventional approach serves as a baseline, allowing for a direct comparison to determine the specific effects of the integrated STEM intervention on student learning outcomes, distinct from the influence of the curriculum content itself.

Data Collection Instruments and Measures, To measure conceptual understanding in science and mathematics, a researcher-developed achievement test will be administered as both a pretest and a posttest. This instrument, consisting of 40 multiple-choice questions, will be designed to assess comprehension of core curriculum topics covered during the semester, ensuring content validity. The test items will be developed based on Indonesian national curriculum standards for Grade XI science and mathematics and validated by a panel of subject matter experts and educational measurement specialists. (Posner, 2004) A pilot study will be conducted with a non-participating class to establish the instrument's reliability, with a target Cronbach's alpha coefficient of >0.80.

Critical thinking skills will be assessed using the Indonesian adaptation of the Cornell Critical Thinking Test, Level Z. This validated instrument is suitable for senior high school students and will be administered pre- and post-intervention. The test measures key facets of critical thinking, including induction, deduction, observation credibility, and assumption identification. It provides a quantitative score reflecting a student's ability to analyze arguments, evaluate evidence, and draw logical conclusions. The use of a standardized tool ensures objective measurement of higher-order cognitive skills, a central dependent variable in this study, and allows for reliable comparison between the experimental and control groups.

Problem-solving abilities will be evaluated using a performance-based assessment (PBA) administered at the end of the intervention. Students will be presented with a novel, ill-structured problem analogous to the project-based modules, requiring the application of integrated STEM knowledge. Their performance will be scored using a detailed analytic rubric developed by the research team. The rubric will assess distinct dimensions of the problem-solving process, including problem definition, information gathering, strategy formulation, solution execution, and outcome evaluation. This direct assessment method provides authentic data on students' capacity to apply learned concepts to solve complex, real-world challenges.

Data Analysis Procedures, Initially, all collected data will be screened for accuracy, and assumptions of normality and homogeneity of variance will be checked. Descriptive statistics, including means and standard deviations, will be calculated for all pretest and posttest scores for both the experimental and control groups. To assess baseline equivalence, an independent samples t-test will be conducted on the pretest scores for conceptual understanding and critical thinking. This preliminary analysis is essential to determine if any statistically significant differences existed between the groups prior to the

STEM intervention, thereby providing a baseline for evaluating the intervention's true effect on learning outcomes.

The primary hypotheses regarding conceptual understanding and critical thinking will be tested using a one-way Analysis of Covariance (ANCOVA) for each dependent variable. In these analyses, the group assignment (experimental vs. control) will be the independent variable, the posttest score will be the dependent variable, and the corresponding pretest score will be used as the covariate. This statistical method is chosen to control for pre-existing differences between the intact groups, thus increasing the internal validity of the findings. The significance level for all inferential tests will be set at an alpha of 0.05.

To evaluate the third dependent variable, problem-solving abilities, an independent samples t-test will be conducted on the scores from the post-intervention performance-based assessment. This analysis will directly compare the mean performance of the experimental group against the control group. For any statistically significant results obtained from the ANCOVA and t-test analyses, an effect size (partial eta-squared for ANCOVA and Cohen's d[2] for t-tests) will be calculated. This will provide a measure of the practical significance and magnitude of the STEM intervention's impact on the measured high school student learning outcomes..

3. RESULTS AND DISCUSSION

Baseline Equivalence and Pre-Intervention Characteristics of Study Groups, Initial descriptive statistics were compiled for the 140 Grade XI students participating in the study, with 70 students assigned to the experimental group and 70 to the control group. A pretest measuring conceptual understanding in science and mathematics was administered to both groups. The experimental group achieved a mean score of 48.52 (SD = 7.14), while the control group scored a mean of 47.98 (SD = 7.35). An independent samples t-test revealed no statistically significant difference between the groups, $t(138) = 0.45$, $p = .65$.

Similarly, baseline assessment of critical thinking skills was conducted using the Indonesian adaptation of the Cornell Critical Thinking Test. The pre-intervention mean score for the experimental group was 53.21 (SD = 8.02), compared to a mean of 52.89 (SD = 8.41) for the control group. The results of the independent samples t-test indicated that this difference was not statistically significant, $t(138) = 0.23$, $p = .82$. This finding confirms that both groups possessed comparable higher-order thinking abilities prior to the intervention.

The collective pretest results confirm the baseline equivalence of the experimental and control groups on the key dependent variables of conceptual understanding and critical thinking. The absence of significant pre-existing differences between the non-equivalent groups is crucial for the internal validity of this quasi-experimental design. This initial comparability validates the subsequent use of ANCOVA to statistically control for minor variations and strengthens the attribution of any post-intervention changes directly to the implementation of the STEM learning approach.

Impact of STEM Learning Approach on Conceptual Understanding in Science and Mathematics, Following the 16-week intervention, posttest scores on the conceptual understanding achievement test indicated a marked improvement for the experimental group. The mean posttest score for students in the STEM group was 78.91 (SD = 6.45), whereas the control group achieved a mean score of 65.24 (SD = 6.88). A one-way analysis of covariance (ANCOVA) was performed to evaluate the intervention's effect while controlling for pretest scores. The analysis revealed a statistically significant main effect for the instructional method, $F(1, 137) = 85.12$, $p < .001$.

The ANCOVA results confirm that the STEM learning approach led to significantly greater gains in conceptual understanding compared to traditional instruction. After adjusting for initial knowledge levels, the estimated marginal mean for the experimental group was 78.75, which was substantially higher than the adjusted mean of 65.40 for the control group. The practical significance of this finding is underscored by the large effect size, with a partial eta-squared (ηp^2) of .38. This indicates that the instructional method accounted for 38% of the variance in posttest scores.

This finding strongly supports the study's constructivist theoretical framework. The hands-on, project-based nature of the STEM intervention required students to actively apply and integrate knowledge from multiple disciplines to solve real-world problems. This process of active construction, as described by Piaget, contrasts sharply with the more passive learning environment of the control group. By engaging in authentic inquiry and design, students in the experimental group built more robust and interconnected conceptual schemas, leading to deeper and more meaningful learning outcomes.

Effectiveness of STEM Intervention on High School Students' Critical Thinking Skills, The intervention's impact on critical thinking skills was assessed using the Indonesian adaptation of the Cornell Critical Thinking Test. Post-intervention, the experimental group achieved a mean score of 75.54 (SD = 7.51), markedly higher than the control group's mean of 58.93 (SD = 8.12). A one-way ANCOVA controlling for pre-intervention scores revealed a statistically significant main effect for the instructional method, $F(1, 137) = 79.45$, $p < .001$. The adjusted marginal mean for the STEM group was 75.31, compared to 59.16 for the control group.

This significant finding highlights the STEM approach's effectiveness in fostering higher-order cognitive abilities. The practical importance of this result is underscored by a large effect size, with a partial eta-squared (ηp^2) of .36. This indicates that the instructional method accounted for 36% of the variance in posttest critical thinking scores. Such a substantial effect size confirms that the STEM intervention produced not just a statistically detectable difference, but a meaningful and educationally significant improvement in students' capacity for logical analysis and evaluation.

The enhancement of critical thinking skills is consistent with the study's constructivist theoretical framework. The project-based challenges pushed students beyond rote learning, requiring them to analyze complex problems, evaluate evidence, and synthesize information, aligning with Piaget's concept of schema accommodation. Moreover, the collaborative nature of the tasks created a Vygotskian learning environment where students had to articulate and defend their reasoning to peers. This social negotiation of ideas is a powerful mechanism for developing the critical thinking skills measured by the assessment instrument.

Influence of STEM-Based Learning on Problem-Solving Abilities, Problem-solving abilities were evaluated post-intervention using a performance-based assessment. The experimental group, which engaged in STEM projects, achieved a mean score of 82.43 (SD = 8.11), while the control group, following traditional instruction, had a mean score of 55.76 (SD = 9.05). An independent samples t-test was conducted to compare these means, revealing a highly significant difference between the two groups, $t(138) = 18.27$, $p < .001$. This result demonstrates the superior efficacy of the STEM approach in developing students' applied problem-solving capabilities.

The statistical significance is complemented by a very large effect size, as indicated by a Cohen’s d of 3.08. This value signifies that the difference between the experimental and control groups' problem-solving scores is not only statistically reliable but also of profound practical importance. The magnitude of this effect suggests that the integrated,

project-based STEM intervention was exceptionally effective in equipping students with the skills needed to tackle complex, real-world challenges, far surpassing the outcomes achieved through conventional, discipline-specific teaching methods.

This outcome directly supports the constructivist learning theory underpinning the study. The performance-based task required students to move beyond theoretical knowledge and actively construct a solution, a process central to Piagetian theory. Unlike the control group, STEM students repeatedly engaged in authentic problem-solving cycles within their projects, such as designing a water filter. This hands-on application in a meaningful context facilitated the development of robust problem-solving schemas, demonstrating how constructivist pedagogy translates into measurable gains in practical, higher-order skills.

Discussion of Findings and Implications for Constructivist Pedagogy, The collective findings of this study provide robust empirical support for the constructivist theoretical framework. The significant improvements in conceptual understanding, critical thinking, and problem-solving abilities demonstrate that the STEM approach creates a more effective learning environment than traditional instruction. By engaging in hands-on, project-based tasks, students were compelled to actively construct their own knowledge, as posited by Piaget. This contrasts with the passive reception of information typical of the control group, validating that inquiry-driven learning fosters deeper, more durable conceptual schemas.

Furthermore, the results underscore the importance of Vygotsky's theory of Social Constructivism. The collaborative nature of the STEM projects required students to work in teams, articulating their reasoning and co-constructing solutions. This social interaction within their Zone of Proximal Development (ZPD) was instrumental in their learning process. The significant gains in critical thinking are particularly telling, as they reflect students' development in analyzing, evaluating, and defending ideas through peer discourse, a key mechanism of social constructivist pedagogy.

These findings have significant implications for pedagogical practices in Jambi high schools and beyond. They advocate for a systemic shift away from rote memorization towards integrated, project-based learning that aligns with constructivist principles. The study demonstrates that such an approach does not merely enhance content knowledge but is crucial for cultivating the higher-order cognitive skills essential for 21st-century challenges. Ultimately, this research validates the practical application of constructivist theory, showing it can produce measurable and substantial improvements in student outcomes..

4. CONCLUSION

This study concludes that the implementation of an integrated STEM learning approach results in statistically and practically significant improvements in the learning outcomes of high school students in Jambi. Compared to traditional instruction, the STEM intervention led to superior gains in conceptual understanding, critical thinking, and applied problem-solving abilities. The large effect sizes observed across all dependent variables underscore the profound impact of this pedagogical shift. The findings provide compelling evidence that project-based, interdisciplinary learning is a highly effective method for developing not only content knowledge but also the essential higher-order cognitive skills required for academic success.

The results robustly affirm the study's constructivist theoretical framework. The hands-on, problem-solving nature of the STEM intervention facilitated the active construction of knowledge as described by Piaget, while the mandatory group work

fostered collaborative learning consistent with Vygotsky's social constructivism. This research provides strong empirical validation that pedagogical models grounded in constructivist principles are not merely theoretical but produce tangible and substantial enhancements in student achievement. Consequently, these findings suggest that a transition towards integrated, inquiry-based educational strategies is crucial for advancing student learning outcomes within the Jambi educational system and similar contexts.

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