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THE IMPACT OF THE STEM LEARNING MODEL ON STUDENTS' SCIENCE PROCESS SKILLS AND CRITICAL THINKING SKILLS IN PHYSICS EDUCATION

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ABSTRACT

The development of science process skills and critical thinking skills is a crucial aspect of physics education, as these competencies are essential for preparing students to face the challenges of 21st-century learning and to solve scientific problems effectively. This issue highlights the need for further research on the effectiveness of implementing STEM-based learning models in enhancing students' higher-order thinking skills. This study aims to analyze the effect of the STEM learning model on students' science process skills and critical thinking skills in physics learning. The research employed a quantitative approach using a quasi-experimental method with a pretest–posttest control group design. Data were collected through tests and observation sheets designed to measure science process skills and critical thinking skills based on higher-order thinking indicators. The collected data were analyzed using descriptive statistics, independent samples t-test, and normalized gain (N-gain) analysis. The results indicate that the implementation of the STEM learning model significantly improves students' science process skills and critical thinking skills, as evidenced by the differences in posttest mean scores between the experimental and control groups and N-gain values in the medium to high categories. These findings suggest that STEM-based learning is effective in fostering higher-order thinking skills. This study provides a significant contribution to the development of physics education at both national and international levels through the implementation of innovative, student-centered, and interdisciplinary learning models that support the development of 21st-century skills. Furthermore, the findings are expected to serve as a reference for future research, particularly in the development of STEM-based learning models and the enhancement of higher-order thinking skills, as well as to encourage more in-depth and applicable subsequent studies.

Keywords: STEM Learning Model, Science Process Skills, Critical Thinking, Physics Education, Quasi Experiment.

INTRODUCTION

In the context of 21st-century education, physics learning is expected not only to enhance students' conceptual understanding but also to develop higher-order competencies, particularly science process skills and critical thinking. These competencies are essential for preparing students to address complex scientific and technological challenges at both national and global levels (Wahono et al., 2020; OECD, 2019; National Research Council, 2012). However, current practices in physics education indicate that classroom instruction remains predominantly teacher-centered and heavily focused on mathematical problem-solving, thereby limiting

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students' opportunities to actively engage in scientific inquiry (Utami et al., 2021; Hake, 1998). Consequently, students' science process skills and critical thinking abilities remain relatively low, particularly at the secondary school level. This issue has become increasingly urgent, as global educational frameworks emphasize inquiry-based, interdisciplinary, and problem-oriented learning approaches to foster scientific literacy and 21st-century competencies (OECD, 2019; Bybee, 2013).

From an analytical perspective, the limited development of these competencies is closely related to the instructional approaches applied in physics classrooms. Based on constructivist learning theory, as proposed by Piaget and further developed by Vygotsky (1978), meaningful learning occurs when students actively construct knowledge through interaction, experimentation, and problem-solving. Learning environments that do not engage students in essential scientific activities—such as observing, hypothesizing, experimenting, analyzing data, and drawing conclusions—are unlikely to promote the development of higher-order thinking skills. Therefore, innovative and student-centered learning models that integrate real-world contexts are critically needed to foster active engagement and analytical reasoning in physics learning (Firmansyah & Suhandi, 2021; Prince & Felder, 2006).

Previous studies have explored various innovative approaches in physics education, including inquiry-based learning, problem-based learning, and the use of interactive media. Sabaryati et al. (2022) reported that interactive and project-based learning media significantly improved students' motivation and conceptual understanding. Similarly, Zulkarnain et al. (2024) found that virtual laboratories effectively enhanced student engagement in physics learning. Other studies have also highlighted the effectiveness of active learning strategies in improving conceptual mastery and engagement (Freeman et al., 2014). However, most of these studies primarily focus on cognitive learning outcomes or conceptual understanding, while the combined impact on science process skills and critical thinking skills has not been comprehensively examined. Moreover, empirical research investigating the implementation of STEM (Science, Technology, Engineering, and Mathematics) learning models specifically in physics education contexts remains limited (Bybee, 2013; Ortiz-Revilla et al., 2022), indicating a clear research gap.

This study offers a novel contribution by examining the simultaneous effect of the STEM learning model on both science process skills and critical thinking skills in physics learning. Unlike previous studies that tend to examine these variables separately, this research integrates interdisciplinary STEM-based learning activities that encompass scientific inquiry, technological application, engineering design, and mathematical reasoning. The theoretical framework is grounded in constructivist learning theory and STEM education theory, which emphasize active learning, problem-solving, and the integration of knowledge across disciplines (Vygotsky, 1978; Bybee, 2013; Ortiz-Revilla et al., 2022). Through this integrated approach, the study aims to bridge the gap between theory and classroom practice while addressing the limitations identified in previous research.

Accordingly, this study focuses on analyzing the effect of the STEM learning model on students' science process skills and critical thinking skills in physics learning. The primary objective is to determine whether the implementation of the STEM learning model leads to a significant improvement in these competencies compared to conventional learning approaches. The findings of this study are expected to contribute both theoretically and practically to the advancement of physics education, particularly in developing innovative, student-centered, and interdisciplinary learning strategies that align with the demands of 21st-century education.

RESEARCH METHOD

This study employed a quantitative approach using a quasi-experimental method. The quantitative approach was selected due to its capability to examine relationships among variables and test hypotheses through numerical data and objective statistical analysis, as suggested by Isnawan (2022). The quasi-experimental method was utilized to determine the effect of the STEM learning model on students' science process skills and critical thinking skills in physics learning. This method was chosen based on the need to identify causal relationships between independent and dependent variables within a real classroom setting while maintaining controlled conditions.

The research design applied in this study was a quasi-experimental design in the form of a pretest–posttest control group design. This design aimed to examine the improvement in students' science process skills and critical thinking skills following the implementation of the STEM learning model. It was selected because it is appropriate for studies requiring comparisons between experimental and control groups without full randomization, as explained by Campbell and Stanley (1963) (Stanley, 1966). In this design, both groups were administered a pretest prior to the intervention and a posttest after the intervention to measure the effectiveness of the treatment. The schematic representation of the research design is presented in Figure 1.

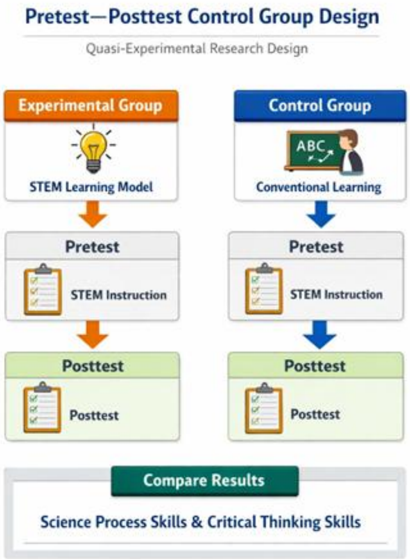

Figure 1. Reseach Design

The participants in this study consisted of approximately 70 tenth-grade senior high school students, divided into two classes. The sampling technique employed was non-probability sampling, specifically purposive sampling, following the procedures described by Sugiyono (2017) (Santoso & Yuzarion, 2021). This technique was selected based on the consideration of relatively similar academic abilities and learning conditions across the classes. One class was assigned as the experimental group, which received the STEM learning model, while the other class served as the control group, which was taught using a conventional learning model.

The research instruments used for data collection included tests and observation sheets. The test instrument consisted of multiple-choice and essay questions designed to measure students' science process skills and critical thinking skills based on higher-order thinking skills (HOTS) indicators. The instruments were validated by experts in physics education to ensure content validity. Reliability testing was conducted using Cronbach's Alpha, with a coefficient value greater than 0.70, indicating that the instrument was reliable. Data collection techniques included the administration of pretests and posttests, as well as classroom observations during the implementation of the STEM learning model.

The collected data were analyzed using both descriptive and inferential statistical techniques. Descriptive analysis was conducted to calculate the mean, standard deviation, and percentage of students' scores. Inferential analysis was performed using the independent samples t-test to determine the significance of differences between the experimental and control groups, following the procedures described by Sladekova et al. (2026). In addition, the normalized gain (N-gain) test was employed to measure the level of improvement in students' skills after the intervention. All data analyses were carried out using IBM SPSS Statistics software.

RESULTS AND DISCUSSION

This section presents the research findings obtained from the implementation of the STEM learning model in the experimental class and compares them with the conventional learning approach in the control class. Data were collected through pre-test and post-test instruments to measure students' science process skills and critical thinking skills. Subsequently, the findings were analyzed statistically and interpreted comprehensively by referring to relevant learning theories and prior empirical studies in physics education. Thus, the results not only demonstrate the effectiveness of the model but also highlight the novelty of this study within the broader body of scientific literature.

The results indicate a significant improvement in students' performance following the implementation of the STEM learning model. In the experimental group, the mean pre-test score of 62.10 increased to 83.75 in the post-test, reflecting a gain of 21.65 points. In contrast, the control group showed a smaller improvement, with scores increasing from 61.25 to 72.40, resulting in a gain of 11.15 points. This difference suggests that the STEM learning model is more effective in enhancing students' learning outcomes than conventional teaching methods. Moreover, notable improvements were observed in science process skill indicators, including the ability to formulate hypotheses, design experiments, and interpret data. Similarly, students in the experimental group demonstrated superior performance in critical thinking components, particularly in analysis, evaluation, and reasoning, indicating that STEM-based learning fosters deeper and more integrated cognitive engagement.

Furthermore, the results of inferential statistical analysis using the independent samples t-test revealed a significance value of 0.002 ($p < 0.05$), indicating a statistically significant difference between the learning outcomes of the experimental and control groups. Therefore, the research hypothesis stating that the STEM learning model has a significant effect on students' science process skills and critical thinking skills is accepted. This finding not only reinforces previous empirical evidence but also provides additional validation that the STEM approach is effective both descriptively and statistically in enhancing higher-order thinking skills.

From a theoretical perspective, the improvement in science process skills can be attributed to the inquiry-based nature of STEM learning, where students actively engage in scientific investigation. In addition, the enhancement of critical thinking skills is closely related to problem-solving activities embedded within STEM learning, which require students to analyze information, evaluate alternative solutions, and make logical decisions. Therefore, these findings are consistent with constructivist theory, which emphasizes that knowledge is constructed through direct experience, and they further support the implementation of student-centered learning approaches in contemporary physics education.

Moreover, the findings of this study are consistent with previous research demonstrating the effectiveness of STEM-based learning in improving higher-order thinking skills and student engagement. For instance, Sari et al. (2020) reported that inquiry-based STEM approaches effectively enhance students' science process skills. Similarly, Fadhilah et al. (2021) found that STEM integration in physics learning improves critical thinking and problem-solving abilities. In addition, Thahir et al. (2020) showed significant improvements in learning outcomes through the application of STEM models compared to conventional methods. However, other studies, such as Kurniawan (2019), reported less optimal results due to limited instructional time and insufficient teacher readiness in implementing STEM approaches.

Despite these similarities, this study offers a distinct contribution by integrating the measurement of science process skills and critical thinking skills simultaneously within a structured experimental design, as well as employing N-gain analysis to categorize the level of improvement more comprehensively. Furthermore, the STEM learning implementation in this study was systematically designed with a strong emphasis on integrated inquiry and problem-solving activities, resulting in moderate to high levels of improvement. Therefore, this study not only corroborates previous findings but also extends the existing literature by demonstrating the effectiveness of STEM learning in developing two essential 21st-century competencies concurrently within the context of physics education.

This study provides significant contributions both theoretically and practically to the advancement of physics education. Theoretically, the findings enrich the literature on the effectiveness of STEM learning in simultaneously enhancing science process skills and critical thinking skills. Practically, the study offers guidance for teachers in designing contextual and student-centered learning activities that integrate science, technology, engineering, and mathematics. In addition, the findings can serve as a foundation for curriculum development and the innovation of instructional strategies aimed at strengthening 21st-century competencies.

Nevertheless, this study has several limitations. The sample size was relatively small and confined to a single school context, which may limit the generalizability of the findings. Additionally, the relatively short duration of the intervention may not fully capture the long-term effects of STEM learning implementation. Therefore, future research is recommended to involve larger and more diverse samples across different educational levels and to employ longitudinal designs to examine the sustainability of students' skill development. Furthermore, the integration of digital technologies, such as virtual laboratories and interactive simulations, should be explored to further enhance the effectiveness of STEM learning in physics education.

CONCLUSION

Based on the findings of this study on the implementation of the STEM learning model in physics education, it can be concluded that the research objectives were successfully achieved. This study aimed to examine the effect of the STEM learning model on students' science process skills and critical thinking skills, and the results demonstrate that the application of this model has a positive and statistically significant impact on both competencies. The findings reveal that the STEM learning model significantly enhances students' science process skills and critical thinking abilities, as evidenced by the increase in mean scores from pre-test to post-test and supported by a significance level of $p < 0.05$. Moreover, students exposed to the STEM approach exhibited greater improvement compared to those engaged in conventional instruction, confirming the effectiveness of the model in fostering key scientific competencies such as hypothesis formulation, experimental design, data analysis, and logical reasoning.

Furthermore, this study provides a meaningful contribution to the advancement of STEM-based instructional models in physics education, particularly in strengthening students' science process and critical thinking skills as essential components of 21st-century competencies. From a theoretical perspective, the findings reinforce the effectiveness of interdisciplinary and student-centered learning approaches in enhancing the quality of physics instruction. From a practical standpoint, the results offer valuable guidance for educators in designing innovative learning strategies that promote active student engagement and the development of higher-order thinking skills. Therefore, the implications of this study extend beyond conceptual understanding and can be effectively applied in real classroom practices.

In addition, the findings offer strategic contributions to the enhancement of physics education at both national and international levels. At the national level, this study supports the development of innovative instructional strategies, the strengthening of curriculum implementation, and the design of learning media aligned with contemporary educational demands. At the international level, the study enriches the global body of knowledge on the effectiveness of STEM-based learning and promotes the advancement of interdisciplinary approaches aimed at fostering critical thinking and scientific skills. Nevertheless, this study is limited by a relatively small sample size and a restricted research context, which may affect the generalizability of the findings. Therefore, future research is recommended to involve larger and more diverse samples, incorporate additional variables such as motivation, creativity, and collaborative skills, and integrate digital technologies such as virtual laboratories and artificial intelligence within longitudinal research designs to comprehensively examine long-term impacts.

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