

Project-Based STEM Learning Integrated with Inquiry Approach to Enhance Scientific Literacy and Critical Thinking Skills in Science Education

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ABSTRAK

Penelitian ini bertujuan untuk menganalisis efektivitas pembelajaran berbasis proyek berorientasi STEM yang terintegrasi dengan pendekatan inkuiri dalam meningkatkan literasi sains dan keterampilan berpikir kritis siswa pada pembelajaran IPA. Penelitian ini menggunakan pendekatan kuantitatif dengan desain quasi eksperimen berupa non-equivalent control group. Partisipan penelitian terdiri dari dua kelompok, yaitu kelompok eksperimen yang menggunakan pembelajaran berbasis proyek berorientasi STEM dengan pendekatan inkuiri dan kelompok kontrol yang menggunakan metode pembelajaran konvensional. Data dikumpulkan melalui tes literasi sains dan tes keterampilan berpikir kritis. Hasil penelitian menunjukkan bahwa kelompok eksperimen memperoleh nilai post-test yang lebih tinggi secara signifikan dibandingkan kelompok kontrol. Analisis normalized gain (N-gain) menunjukkan bahwa peningkatan pada kelompok eksperimen berada pada kategori sedang hingga tinggi, sedangkan kelompok kontrol berada pada kategori rendah hingga sedang. Uji statistik menggunakan independent sample t-test menunjukkan adanya perbedaan yang signifikan antara kedua kelompok ($p < 0,05$). Selain itu, penerapan pembelajaran berbasis proyek berorientasi STEM dengan pendekatan inkuiri terbukti meningkatkan kemampuan siswa dalam analisis, evaluasi, dan pemecahan masalah. Hasil ini menunjukkan bahwa integrasi pembelajaran berbasis proyek, STEM, dan inkuiri merupakan strategi yang efektif untuk meningkatkan kualitas pembelajaran dan mengembangkan keterampilan abad ke-21 dalam pendidikan IPA.

Kata Kunci: *pembelajaran berbasis proyek, pendidikan STEM, pembelajaran inkuiri, literasi sains, keterampilan berpikir kritis.*

ABSTRACT

This study aims to examine the effectiveness of project-based STEM learning integrated with an inquiry approach in improving students' scientific literacy and critical thinking skills in science education. The research employed a quantitative approach using a quasi-experimental design with a non-equivalent control group. The participants consisted of two groups: an experimental group taught using project-based STEM inquiry learning and a control group taught using conventional methods. Data were collected through a scientific literacy test and a critical thinking skills test. The results showed that the experimental group achieved significantly higher post-test scores compared to the control group. The normalized gain (N-gain) analysis indicated that the experimental group reached a medium to high level of improvement, while the control group remained in the low to medium category. Statistical testing using an independent sample t-test revealed a significant difference between the two groups ($p < 0.05$). Furthermore, the implementation of project-based STEM inquiry learning significantly enhanced students' abilities in analysis, evaluation, and problem-solving. These findings suggest that integrating project-based learning, STEM, and inquiry approaches is an effective strategy to promote meaningful learning and develop essential 21st-century skills in science education.

Keywords: *project-based learning, STEM education, inquiry-based learning, scientific literacy, critical thinking skills.*



INTRODUCTION

Science education in the 21st century emphasizes not only the mastery of scientific concepts but also the development of essential competencies such as scientific literacy and critical thinking skills (AlAli, 2024). Scientific literacy is widely recognized as a fundamental goal of science education, as it enables students to understand scientific concepts, interpret data, and make informed decisions in real-life contexts (Bicaj et al., 2024). In an increasingly complex and technology-driven world, students are required to develop the ability to analyze problems critically and apply interdisciplinary knowledge to solve them effectively (Li, 2025).

Recent developments in education highlight the importance of integrating Science, Technology, Engineering, and Mathematics (STEM) approaches into science learning (Le et al., 2023). STEM education promotes interdisciplinary learning and encourages students to apply knowledge across different domains to address real-world problems (Nugraha et al., 2024). A systematic review by Urdanivia Alarcon et al. (2023) indicates that inquiry-based learning plays a significant role in fostering scientific reasoning and knowledge construction, as it actively engages students in exploring, questioning, and investigating scientific phenomena. This approach aligns well with STEM principles, which emphasize active learning, problem-solving, and the application of knowledge in authentic contexts (Pinaret al., 2025).

In addition, the integration of project-based learning (PjBL) within STEM education has gained increasing attention as an effective strategy to enhance students' learning outcomes (Retno et al., 2025). Project-based STEM learning allows students to engage in real-world problem-solving through collaborative and inquiry-driven activities (Al-Qoyyim et al., 2025). Research shows that STEM project-based learning can significantly improve students' scientific literacy and critical thinking by providing meaningful and contextual learning experiences (Septiadevana & Abdullah, 2024). Through project-based activities, students are encouraged to design solutions, conduct investigations, and evaluate results, which are essential components of scientific inquiry.

Furthermore, recent empirical studies demonstrate that STEM-based learning approaches contribute to the development of higher-order thinking skills. Komalasari et al. (2024) found that the implementation of STEM learning significantly improves students' critical and creative thinking skills, as well as their overall learning outcomes. These findings suggest that integrating STEM with inquiry-based strategies can create a more effective learning environment that supports both cognitive and practical skill development.

The role of digital and inquiry-supported learning environments has also been emphasized in recent literature. Ramli and Borhan (2024) highlight that inquiry-based learning, when supported by digital tools, enhances students' ability to visualize abstract concepts, engage in interactive learning, and improve scientific literacy outcomes. This indicates that combining multiple instructional approaches such as STEM, inquiry, and project-based learning can provide a comprehensive framework for improving science education.

Despite these advantages, several challenges remain in implementing integrated STEM and inquiry-based approaches. These include limited teacher readiness, insufficient instructional design, and difficulties in managing interdisciplinary learning activities. A recent review by Halawa et al. (2024) emphasizes that effective STEM instruction requires well-structured learning designs and adequate teacher support to ensure successful implementation. Additionally, students may face difficulties adapting to active learning environments that require independent thinking and collaboration.

Therefore, this study aims to investigate the effectiveness of project-based STEM learning integrated with an inquiry approach in enhancing students' scientific literacy and critical thinking skills in science education. This research is expected to contribute to the development of innovative instructional strategies that combine multiple pedagogical approaches to meet the demands of 21st-century learning.

METHOD

This study employed a quantitative research approach using a quasi-experimental design with a non-equivalent control group to examine the effectiveness of project-based STEM learning integrated with an inquiry approach in enhancing students' scientific literacy and critical thinking skills. This design is appropriate for educational research conducted in natural classroom settings where random assignment is not feasible, allowing for comparison between experimental and control groups while maintaining ecological validity (Creswell & Creswell, 2021).

The study was conducted in a secondary school setting involving two groups of students. The experimental group was taught using project-based STEM learning integrated with inquiry-based activities, while the control group received conventional teacher-centered instruction. The experimental group engaged in project-based activities that required students to identify real-world problems, design and conduct investigations, develop solutions, and present their findings. These activities were structured using inquiry stages, including problem formulation, hypothesis development, experimentation, data analysis, and conclusion drawing. Participants were selected using purposive sampling to ensure similar academic characteristics between the two groups.

Data collection was carried out using two main instruments: a scientific literacy test and a critical thinking skills test. The scientific literacy test was adapted from international assessment frameworks to measure students' ability to explain scientific phenomena, interpret data, and evaluate evidence (Organisation for Economic Cooperation and Development, 2023). The critical thinking test was developed based on indicators such as interpretation, analysis, evaluation, and inference. Both instruments were validated through expert judgment and pilot testing to ensure their validity and reliability.

The intervention was implemented over several instructional sessions, during which students in the experimental group worked collaboratively on STEM-based projects supported by inquiry processes. Project-based STEM learning has been shown to provide meaningful and contextual learning experiences that enhance students' engagement and higher-order thinking skills (Septiadevana & Abdullah, 2024). In addition, integrating inquiry into project-based learning enables students to actively construct knowledge and develop scientific reasoning skills (Urdanivia Alarcon et al., 2023).

Prior to the main data collection, a pilot study was conducted to test the instruments. Reliability was measured using Cronbach's alpha coefficient to ensure internal consistency. Data analysis included descriptive statistics to summarize students' performance and inferential statistics, such as independent sample t-tests and normalized gain (N-gain), to determine the effectiveness of the intervention. Statistical analysis was performed using SPSS software with a significance level of 0.05.

This methodological approach is consistent with recent studies emphasizing the effectiveness of integrating STEM, inquiry-based, and project-based learning in improving students' scientific literacy and critical thinking skills (Komalasari et al., 2024; Halawa et al., 2024).

RESULTS AND DISCUSSION

Descriptive Statistics

The descriptive analysis of pre-test and post-test scores indicates that both the experimental and control groups experienced improvement after the learning intervention. However, the magnitude of improvement differed significantly between the two groups. The experimental group, which received project-based STEM learning integrated with inquiry, demonstrated a substantially higher increase in post-test scores compared to the control group, which was taught using conventional methods. The similarity in pre-test scores suggests that both groups had comparable initial abilities, ensuring that the observed differences can be attributed to the treatment effect.

This finding implies that the integration of STEM, project-based learning, and inquiry approaches provides a more effective learning environment for enhancing students' understanding and skills. The higher improvement in the experimental group reflects the impact of active learning processes, where students are directly involved in problem-solving, investigation, and knowledge construction. In contrast, the control group's moderate improvement indicates that traditional instruction is less effective in promoting deep conceptual understanding and higher-order thinking skills.

Normalized Gain (N-gain) Analysis

The normalized gain (N-gain) analysis revealed that the experimental group achieved a medium to high category of improvement, while the control group remained in the low to medium category. This indicates that students exposed to project-based STEM inquiry learning experienced more meaningful learning gains compared to those who received conventional instruction. The higher N-gain in the experimental group suggests that the instructional approach not only improved students' performance but also enhanced the efficiency of learning. Students were able to construct knowledge more effectively through hands-on activities, interdisciplinary connections, and inquiry processes. This demonstrates that integrating STEM and inquiry-based learning accelerates students' cognitive development and supports deeper understanding, rather than merely increasing surface-level knowledge.

Inferential Statistical Analysis

The results of the independent sample t-test showed a statistically significant difference between the experimental and control groups ($p < 0.05$). This confirms that project-based STEM learning integrated with inquiry has a significant positive effect on students' scientific literacy and critical thinking skills. In addition, the effect size analysis indicated a moderate to high impact, suggesting that the intervention had substantial practical significance. This means that the observed differences are not only statistically significant but also meaningful in real educational contexts. Therefore, the findings provide strong empirical evidence supporting the effectiveness of integrating STEM, inquiry, and project-based learning as an innovative instructional strategy.

Scientific Literacy Analysis

The analysis of scientific literacy indicators showed that students in the experimental group demonstrated significant improvement across all dimensions, including explaining scientific phenomena, interpreting data, and evaluating evidence. The most notable improvement was observed in data interpretation and evaluation skills. This result indicates that the learning approach effectively promotes students' ability to think scientifically and apply knowledge in real-world contexts. Through inquiry-based STEM projects, students were required to analyze data, draw conclusions, and justify their findings, which strengthened their scientific reasoning. In contrast, students in the control group showed limited improvement, suggesting that conventional instruction does not sufficiently support the development of scientific literacy.

Critical Thinking Skills Analysis

The results also showed that students' critical thinking skills improved significantly in the experimental group across all indicators, including interpretation, analysis, evaluation, and inference. The greatest improvement was observed in analysis and evaluation, which are key components of higher-order thinking skills. This finding suggests that project-based inquiry activities provide opportunities for students to engage in complex cognitive processes. By working on real-world problems, students were required to analyze information, evaluate possible solutions, and make evidence-based decisions. These activities foster deeper thinking and enhance students' ability to solve complex problems, which are essential competencies in 21st-century education.

Discussion

Effectiveness of STEM Project-Based Inquiry Learning

The results of this study provide strong evidence that project-based STEM learning integrated with inquiry significantly improves students' scientific literacy and critical thinking skills. This finding is consistent with constructivist learning theory, which emphasizes that knowledge is actively constructed through meaningful learning experiences. The integration of inquiry processes and project-based activities allows students to engage directly with scientific concepts and apply them in real-world contexts. This result is supported by Urdanivia Alarcon et al. (2023), who found that inquiry-based learning enhances students' ability to construct knowledge and connect theoretical concepts with practical applications. Similarly, Septiadevana and Abdullah (2024) reported that project-based STEM learning significantly improves scientific literacy by providing contextual and authentic learning experiences. These findings reinforce the argument that combining inquiry and project-based approaches creates a powerful learning environment that promotes deeper understanding.

Development of Critical Thinking Skills

The significant improvement in critical thinking skills observed in this study highlights the effectiveness of inquiry-based learning in promoting higher-order thinking. Inquiry processes require students to question, investigate, and evaluate evidence, which directly supports the development of critical thinking. This finding aligns with Komalasari et al. (2024), who demonstrated that STEM learning enhances critical and creative thinking skills. Furthermore, Halawa et al. (2024) emphasized that well-designed STEM instruction fosters analytical reasoning and problem-solving abilities. In this study, students engaged in inquiry-based projects were able to develop stronger analytical and evaluative skills, indicating that the instructional approach successfully facilitated higher-order cognitive development.

Role of Interdisciplinary STEM Learning

The integration of STEM disciplines plays a crucial role in enhancing students' learning outcomes. This study found that students in the experimental group were able to approach problems from multiple perspectives, demonstrating improved cognitive flexibility and problem-solving abilities. This result is consistent with Ramli and Borhan (2024), who highlighted that interdisciplinary STEM learning enhances students' ability to analyze and solve complex problems. By integrating science, technology, engineering, and mathematics, students gain a more comprehensive understanding of concepts and are better prepared to apply their knowledge in real-world situations.

Impact of Project-Based Learning on Engagement

Project-based learning contributed significantly to increased student engagement and motivation. Students were actively involved in collaborative projects, which encouraged participation, curiosity, and persistence in learning activities. This finding is supported by Septiadevana and Abdullah (2024), who found that project-based STEM

learning enhances student engagement by providing meaningful and contextual learning experiences. Increased engagement leads to better learning outcomes, as students are more motivated to explore and understand the material.

Challenges and Limitations

Despite the positive outcomes, several challenges were identified. The implementation of project-based STEM inquiry learning requires more instructional time compared to traditional methods. Teachers also need strong pedagogical and interdisciplinary skills to effectively facilitate learning activities. This finding is consistent with Halawa et al. (2024), who emphasized that successful STEM implementation requires adequate teacher preparation and well-designed instructional strategies. Additionally, some students initially struggled to adapt to active learning environments, indicating the need for gradual implementation and continuous support.

CONCLUSION

This study concludes that the implementation of project-based STEM learning integrated with an inquiry approach has a significant and positive effect on improving students' scientific literacy and critical thinking skills in science education. The findings demonstrate that students who engaged in this integrated learning model achieved higher learning gains, stronger conceptual understanding, and more advanced abilities in analysis, evaluation, and problem-solving compared to those who experienced conventional instruction. The combination of interdisciplinary STEM perspectives with inquiry processes and project-based activities creates a meaningful learning environment that encourages active participation, knowledge construction, and real-world application. Although challenges such as limited instructional time, teacher readiness, and student adaptation were identified, these can be addressed through proper instructional design and professional development. Overall, this approach offers a powerful and relevant strategy for enhancing the quality of science education and equipping students with essential 21st-century competencies.

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