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Effectiveness of STEM-Based Project-Based Learning in Enhancing Senior High School Students' Scientific Literacy

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Abstract: The purpose of this study was to examine the effectiveness of the STEM (science, technology, engineering, and mathematics)-based Project-Based Learning (PjBL) model in improving senior high school students' scientific literacy. This study employed a quasi-experimental method with a pre-test and post-test nonequivalent control group design and was conducted at SMA Negeri 5 Padangsidimpuan. The research involved two classes consisting of 35 students each: an experimental class taught using STEM-based PjBL and a control class taught using conventional learning. Scientific literacy was measured using an essay test, while students' attitudes toward science were assessed through a questionnaire. The results of the independent samples t-test showed no significant difference in students' initial abilities (sig. = 0.064 > 0.05). However, the post-test results indicated a significant difference between the two groups (sig. = 0.000 < 0.05), with the experimental class achieving a higher mean score. In addition, students' attitudes toward science in the experimental class were categorized as good to very good. These findings indicate that STEM-based Project-Based Learning is effective in enhancing students' scientific literacy.

Keywords: Attitudes toward science; Project based learning; Quasi-experiment; Science literacy; STEM

Introduction

Education plays a strategic role in developing human resources capable of adapting to global scientific and technological advancements (Tusriyanto et al., 2024). However, international assessment results indicate that Indonesian students' science literacy remains relatively low. The Programme for International Student Assessment (PISA) 2022 reported Indonesia's science literacy score at 415, a decline from 436 in 2018, placing Indonesia 64th out of 81 participating countries. Similar trends were also identified in earlier PISA cycles, highlighting persistent challenges in students' scientific reasoning and application skills (OECD, 2022). Data from the UNESCO Institute for Statistics indicate that improvements in access to education have not been accompanied by proportional gains in science literacy aligned with global competency standards (Candrawati, 2023). These findings emphasize the urgent need to strengthen science instruction, particularly in Physics, to foster scientific reasoning, problem-solving abilities, and conceptual understanding (Pinar et al., 2025).

Observations at SMA Negeri 5 Padangsidimpuan reveal several instructional challenges that contribute to low science literacy achievement. Physics learning remains predominantly teacher-centered, with limited opportunities for students to actively construct knowledge or engage in higher-order problem-solving

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activities, a condition frequently reported in secondary science classrooms (Howell, 2024; Sasser, 2025). Traditional instructional approaches tend to emphasize procedural understanding rather than conceptual reasoning and application (Siregar, 2025). Innovative instructional models such as STEM-based Project-Based Learning (PjBL) have not been optimally implemented, despite substantial evidence of their effectiveness in promoting active learning and higher-order thinking skills (Nasution et al., 2024; Situmorang, 2025). Furthermore, assessment practices often fail to align with PISA-based scientific literacy indicators, resulting in students' difficulties in connecting abstract concepts to real-world phenomena and communicating scientific reasoning (Kastorff et al., 2026; Kizi, 2025).

A growing body of research demonstrates that Project-Based Learning and STEM integration significantly enhance students' conceptual understanding, motivation, and science literacy. Simanjuntak et al. (2023) reported that STEM-integrated learning improves students' ability to apply scientific concepts in authentic contexts. Similarly, Iryani et al. (2025) found that STEM-oriented PjBL strengthens conceptual mastery and scientific skills simultaneously. International studies also confirm that STEM-based PjBL enhances inquiry skills, collaboration, and problem-solving abilities (AlAli, 2024; Rasyid et al., 2023). Meta-analytical reviews further reveal that PjBL has a positive and significant effect on students' scientific reasoning and learning outcomes (Nurkanti et al., 2025; Zhang et al., 2024). However, most existing studies have not explicitly examined the integration of STEM-based PjBL within static fluid topics, nor evaluated science literacy using PISA-based indicators supported by both real mechanical projects and digital simulations (Pratama et al., 2025).

This study addresses this gap by integrating a STEM-based Project-Based Learning model with the construction of a mini hydraulic jack as a concrete representation of Pascal's Law, supported by PhET simulations to facilitate conceptual visualization and inquiry-based exploration (Bendu, 2024; Hartono et al., 2024; Muliyadi et al., 2023). Digital simulations have been shown to effectively enhance conceptual understanding when combined with hands-on experimentation (Munandar et al., 2024; Wahidin et al., 2025). The novelty of this study lies in the combined use of hands-on engineering projects and interactive digital simulations to comprehensively assess students' science literacy based on PISA indicators, an approach that remains limited in Physics education research (Kamilah et al., 2025; Zulkarnaen et al., 2025). Therefore, this study aims to analyze the effectiveness of STEM-based Project-Based Learning integrated with mini hydraulic jack construction and PhET simulations in improving senior high school students' science literacy on the static fluid topic.

Method

This study employed a quantitative approach using a quasi-experimental nonequivalent control group design (Creswell et al., 2011; Pamungkas, 2021). Two intact classes were involved: an experimental group receiving STEM-based Project-Based Learning (STEM-PBL) and a control group taught through conventional instruction. A pre-test and post-test were administered to examine changes in students' scientific literacy. The research was conducted at SMA Negeri 5 Padangsidimpuan during the 2024/2025 academic year and involved a total of 70 eleventh-grade students. Purposive sampling was applied, with Class XI-2 assigned as the experimental group (35 students) and Class XI-1 as the control group (35 students). This clarification addresses previous discrepancies in sample size reporting.

The research procedure comprised three stages: preparation, implementation, and evaluation. The preparation stage included the development of STEM-PBL learning materials, the construction of a miniature hydraulic jack project, and instrument validation. During the implementation stage, the experimental group engaged in STEM-PBL activities supported by PhET simulations, while the control group received conventional instruction; both groups completed a pre-test prior to the intervention. The evaluation stage involved administering the post-test followed by data analysis.

Research instruments consisted of ten essay-type scientific literacy items developed according to the PISA framework (OECD, 2023). Instrument validity and reliability were examined using item–total correlation and Cronbach's Alpha (Pallant, 2011). Scientific attitudes were measured using a Likert-scale questionnaire focusing on key indicators, namely curiosity, critical thinking, and responsibility in scientific activities. Data analysis employed descriptive percentage analysis, Levene's test for homogeneity, and independent samples t-tests to examine differences between groups (Ewid et al., 2020).

Result and Discussion

Students' Initial Scientific Literacy Ability (Pre-test)

Students' initial scientific literacy was measured using a pre-test to ensure the equivalence of the experimental and control classes prior to treatment. As presented in Table 1, the experimental class obtained a mean score of 59.51, while the control class achieved a mean score of 54.69. Both classes shared the same

minimum score (40), and the difference in maximum scores was not substantial. The detailed results are presented in Table 1.

Table 1. Descriptive Statistics of Pre-test Scores in the Experimental and Control Classes

Class	N	Min	Max	Mean	Std. Deviation
Experimental	35	40	87	59.51	11.680
Control	35	40	75	54.69	9.719

Statistical analysis confirmed that both groups were equivalent at baseline. The homogeneity test indicated homogeneous variances (Sig. = 0.517 > 0.05), and the independent samples t-test showed no significant difference between the two classes (Sig. = 0.064 > 0.05). These results indicate that the experimental and control classes had comparable initial scientific literacy abilities, ensuring that differences found in the post-test could be attributed to the instructional treatment rather than pre-existing conditions (Fraenkel et al., 1990; Sugiyono, 2019).

Improvement of Students' Scientific Literacy after PJBL-STEM Implementation (Post-test)

After the implementation of the STEM-based Project Based Learning (PJBL-STEM) model, students' scientific literacy showed a substantial improvement. As shown in Table 2, the experimental class achieved a mean post-test score of 82.23, while the control class obtained a mean score of 66.26, with a mean difference of 15.97 points. The detailed results are presented in Table 2.

Table 2. Descriptive Statistics of Post-test Scores for the Experimental and Control Classes

Class	N	Min	Max	Mean	Std. Deviation
Experimental	35	77	91	82.23	3.020
Control	35	59	73	66.26	3.175

The homogeneity test confirmed equal variances (Sig. = 1.000), and the independent samples t-test revealed a statistically significant difference between the two groups (Sig. = 0.000 < 0.05). These findings demonstrate that PJBL-STEM was significantly more effective than conventional instruction in enhancing students' scientific literacy.

The superior performance of the experimental class can be attributed to the authentic learning experiences embedded in the PJBL-STEM model. Through the hydraulic jack project, students applied Pascal's Law and static fluid concepts within an engineering design process, allowing them to connect theoretical knowledge with real-world applications. This finding supports previous studies indicating that project-based and STEM-integrated learning promotes deeper conceptual understanding and scientific reasoning (Bell, 2010; Nurhidayah et al., 2021). Additionally, the use of PhET simulations supported students' conceptual visualization, helping them develop more accurate mental models of physics concepts (Qureshi et al., 2025).

From a pedagogical perspective, these results suggest that PJBL-STEM effectively facilitates higher-order thinking skills, problem-solving abilities, and meaningful learning experiences, which are essential components of scientific literacy (Kassymova et al., 2020).

Students' Scientific Attitudes

The analysis of scientific attitudes indicates that PJBL-STEM learning positively influenced students' affective dimensions. The results of students' scientific attitudes in the experimental class are presented in Table 3.

Table 3. Students' Scientific Attitudes in the Experimental Class

Indicator of Scientific Attitude	Percentage	Category
Interest in Science	77%	Good
Understanding of Scientific Approach	81%	Very Good
Environmental Awareness	76%	Good

As shown in Table 3, students' interest in science reached 77% (good category), understanding of scientific approaches achieved 81% (very good category), and awareness of environmental issues reached 76% (good category). These findings indicate that project-based STEM learning supports the development of students' curiosity, inquiry skills, and awareness of the relevance of science in real-life contexts.

The positive development of scientific attitudes can be attributed to students' active involvement in investigative and contextual learning activities, such as designing and testing the hydraulic jack. Through these activities, students engaged in inquiry processes and applied scientific concepts to authentic problems, which enhanced their scientific attitudes. These results are consistent with previous studies reporting that STEM-based project learning improves students' scientific attitudes and their ability to connect scientific concepts with societal and environmental issues (Ayuso et al., 2022; Kiazai et al., 2020).

Pedagogical Implications

The findings of this study indicate that the PJBL-STEM model is an effective instructional approach for science education, particularly in improving students' scientific literacy and scientific attitudes. By integrating scientific concepts with engineering design, technology, and inquiry-based activities, PJBL-STEM supports

meaningful learning and the development of higher-order thinking skills. For science teachers, this model offers a practical alternative to conventional instruction by promoting contextual learning and real-world problem solving, which are essential for strengthening scientific literacy in 21st-century science education.

Instrument Testing and Data Feasibility

The research instruments were tested for validity and reliability to ensure the appropriateness of the data used in the analysis. The validity test results for the 10 items of the scientific literacy test indicated that all items were valid, as shown by r-calculated values greater than the r-table value (0.235) and significance values below 0.05. The scientific attitude questionnaire consisted of 11 items, with 10 items categorized as valid and one item categorized as invalid because its r-calculated value was lower than the r-table value (0.334).

Reliability testing indicated that the test instruments demonstrated very high internal consistency, with Cronbach's Alpha values of 0.984 for the pre-test and 0.871 for the post-test, classifying both as highly reliable. A summary of the reliability results is presented in Table 4.

Table 4. Pre-test and Post-test Reliability Categories

Test Type	Cronbach's Alpha	Category
Pre-test	0.984	Very Reliable
Post-test	0.871	Very Reliable

Reliability testing of the questionnaire yielded a Cronbach's Alpha value of 0.736, indicating that the instrument is reliable and suitable for measuring students' scientific attitudes.

Table 5. Questionnaire Reliability

Instrument	Cronbach's Alpha	Category
Questionnaire	0,736	Reliable

Reliability testing using Cronbach's Alpha indicated that the test instruments fell into the "very reliable" category, with $\alpha = 0.984$ for the pre-test and $\alpha = 0.871$ for the post-test. The questionnaire instrument was also deemed reliable, with $\alpha = 0.736$, reflecting good internal consistency. Based on these results, all research instruments can be considered suitable for use, as they meet both validity and reliability criteria. This ensures that the data obtained are accurate and trustworthy for further analysis.

Conclusion

The study conducted at SMA Negeri 5 Padangsidimpuan demonstrated that the STEM-based Project Based Learning (PJBL-STEM) model effectively enhances students' scientific literacy, as evidenced by the significant difference in post-test scores between the experimental and control classes (82.23 vs. 66.26; p = 0.000). The hydraulic jack project, integrated with PhET simulations, provided a contextual learning experience that strengthened students' understanding of static fluid concepts and scientific skills. Scientific attitudes also improved across indicators of interest in science, understanding of the scientific approach, and environmental awareness, reaching good to very good categories. The research instruments were validated and reliable, ensuring that the data obtained were trustworthy. Overall, PJBL-STEM proved relevant and effective for Physics learning in improving both students' competencies and scientific attitudes.

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