Phi: Jurnal Pendidikan Fisika dan Terapan
Vol.13 No.1 (2027) 46-52
ISSN: 2460-4348, e-ISSN: 2549-7162
https://jurnal.ar-raniry.ac.id/index.php/jurnalphi/index

Article Type: *original research*

ESD-Based Project-Based Learning Enhances Science Literacy Among Senior High School

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RTICLE INFO

Article History:
Received: 25 May 2026
Revised: 04 July 2026
Accepted: 05 August 2026
Published: 23 August 2026

Keywords:
Project-based learning; Phyics education; Science literacy; Renewable energy;

ABSTRACT

This study investigated the effect of implementing Project-Based Learning (PjBL) integrated with Education for Sustainable Development (ESD) on the science literacy of Grade X students at MAS Syamsuddhuha. A quantitative quasi-experimental design with a nonequivalent control group was employed. The sample consisted of 50 students, divided into an experimental class (n=25) receiving PjBL-ESD and a control class (n=25) receiving conventional instruction. The experimental group engaged in a contextual project converting organic waste to biogas. Data were collected using a validated essay test based on the PISA science literacy framework, observation sheets, and interview guidelines. Quantitative data were analyzed using the Independent Samples t-test and Cohen's d, while qualitative data were analyzed descriptively. Results showed a significant improvement in the experimental group's posttest mean score (90.44) compared to the control group (74.00), with $p < 0.001$. The effect size was very large (Cohen's d =2.5). Observation and interview results indicated high-quality implementation and positive student responses, strengthening scientific attitudes and environmental sustainability awareness. The study concludes that PjBL-ESD effectively enhances science literacy by bridging theoretical concepts with real-world sustainability issues, even in schools with limited laboratory facilities. This model is recommended as a contextual and sustainable instructional strategy for renewable energy topics.

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1. INTRODUCTION

Efforts to improve the quality of education in Indonesia face serious challenges regarding students' low science literacy, as reflected in the PISA 2022 report, which indicates a longitudinal decline in achievement (OCDE, 2023). Science literacy is a crucial 21st-century competency that equips students with the ability to utilize scientific knowledge, identify questions, and draw evidence-based conclusions to understand natural phenomena (Falah, 2019). Furthermore, this competency enables students to critically evaluate the impacts of human activities on the environment and society (Muflikhah, 2023) . In a global context, science literacy serves as a fundamental indicator of educational quality and a basis for science-based decision-making in addressing environmental and health issues (Darmawan Harefa, 2023) Additionally, it prepares students to navigate complex technological challenges and make informed decisions in their daily lives (Rohmah & Lestari, 2024).

However, Indonesian students' science literacy achievements remain below the OECD average. This condition is influenced by the dominance of teacher-centered conventional instruction,

a lack of real-world contexts, and limited practical facilities such as physics laboratories (Fuadi et al., 2020). Preliminary identification at MAS Syamsuddhuha confirms that students' science literacy remains critically low. Diagnostic test results yielded an average score of only 37.08 out of 100, and a preliminary student questionnaire averaged 34 out of 100, categorizing their literacy in the low tier. Teacher interviews revealed that this condition is exacerbated by the complete absence of a physics laboratory, resulting in physics concepts—particularly those related to renewable energy—being understood only theoretically without direct experience linking concepts to everyday environmental issues (Hindun et al., 2024).

In the context of renewable energy, biogas derived from organic waste offers a practical solution to environmental and energy challenges (Rahmat, 2023). Furthermore, ESD serves as a lifelong learning process that equips students with critical thinking skills to address sustainability issues (Nurlailah & Hamdu, 2021). The integration of ESD principles into project-based activities has been proven to stimulate students' creative thinking in solving real-world environmental problems (Hidayati & Siswanto, 2020). The implementation of ESD is also highly urgent in the current curriculum to ensure that learning not only focuses on cognitive knowledge but also instills sustainable attitudes and skills (Vioreza et al., 2023).

In response to these challenges, integrating the Project-Based Learning (PjBL) model with Education for Sustainable Development (ESD) offers a contextual and sustainable pedagogical framework. PjBL places students at the center of learning through the completion of authentic projects that encourage active knowledge construction (Aziz & Nurachadijat, 2023). Meanwhile, ESD serves as a value orientation that connects projects to environmental, social, and economic sustainability principles (Septiani, 2020). Operationally, this integration is realized through sustainability-focused problem formulation, collaborative investigation, and reflection on the ecological impact of developed solutions (Nihayati, 2018). This approach has proven effective in developing all three science literacy competencies outlined in the PISA framework: explaining phenomena, designing investigations, and interpreting data comprehensively (Andriyatno et al., 2024).

Although numerous studies have demonstrated the effectiveness of PjBL-ESD in improving science literacy, most have been conducted in educational settings with relatively adequate facilities and infrastructure (Kartini & Aljamaliah, 2024). Empirical studies specifically examining the implementation of this model in madrasah contexts with severe laboratory limitations remain highly limited. Furthermore, research that systematically integrates ESD principles into every stage of the PjBL syntax to address the gap in physics laboratory access, particularly through micro-scale renewable energy projects, has rarely been reported. The urgency of standardized science literacy assessment is also emphasized in recent physics education research, which highlights the importance of PISA framework-based instruments to accurately map student competencies prior to instructional intervention (Indasa et al., 2024)

Based on this background, this study aims to empirically investigate the effect of implementing an ESD-based Project-Based Learning model on the science literacy of class X students at MAS Syamsuddhuha. Through a contextual micro-scale biogas project derived from organic waste, this research seeks to fill an empirical gap regarding the implementation of meaningful, applicable, and sustainability-oriented physics instruction in resource-constrained schools.

2. METHODS

2.1. Research Design and Sample

This study employed a quantitative approach with a quasi-experimental Nonequivalent Control Group Design. This design was selected because the samples were not randomly assigned; however, both groups possessed relatively equivalent initial characteristics. An independent t-test on the pretest scores confirmed no significant difference between the groups ($p > 0.05$), and Levene's test confirmed homogeneous variances, establishing baseline equivalence. The population comprised all class X students at MAS Syamsuddhuha. Purposive sampling was used based on specific methodological considerations: balanced class size, instruction by the same physics teacher to

minimize instructional bias, and comparable weekly schedules. The sample consisted of class X Jenin as the experimental group (n=25) and class X Rafah as the control group (n=25).

Table 1. Research Design

Group	Pretest	Treatment	Posttest)
Experimental	O_1	X	O_2
Control	O_3	-	O_4

Note.
O_1 and O_3 = pretest
O_2 and O_4 = posttest
X = PjBL-ESD implementation
– = conventional instruction.

2.2. Procedure and Treatment

The treatment was delivered over 3 meetings (6 instructional hours) focusing on a contextual project converting organic waste into simple biogas. To accommodate the 6-hour timeframe, the biogas project was designed as a micro-scale experiment using sealed plastic bottles and balloons. This adaptation allowed students to observe gas volume changes and fermentation indicators within hours, rather than the weeks required for full-scale digesters. Meeting 1 focused on problem formulation and project planning. Meeting 2 involved the execution of the micro-biogas project and observation of gas volume changes and fermentation indicators. Meeting 3 centered on data analysis, presentation, and ESD reflection. The control group followed conventional lecture-based instruction without project intervention.

2.3. Instruments and Data Analysis

Data collection instruments included: (1) A 9-item essay test on science literacy aligned with the PISA framework. Content validity was established by one expert validator, followed by an empirical trial to students to assess item validity and reliabilityyielding a Cronbach's alpha of 0.846 (very high category); (2) a learning implementation observation sheet; and (3) a student interview guide.

Quantitative data were analyzed using pretest and posttest scores. Prerequisite tests (Shapiro-Wilk normality and Levene's homogeneity) were conducted, followed by the Independent Samples t-test for hypothesis testing and Cohen's d for effect size calculation. Qualitative data from observations and interviews were analyzed descriptively using thematic coding based on predefined indicators of scientific attitudes. Method triangulation was applied by cross-verifying interview transcripts with observation notes and project documentation to support the consistency of the qualitative findings.

3. RESULT AND DISCUSSION

3.1 Descriptive Statistics and Prerequisite Tests

Descriptive analysis revealed that the pretest mean scores for the experimental and control groups were 24.11 and 22.78, respectively, indicating comparable initial performance. Post-treatment, the experimental group's posttest mean increased to 90.44, while the control group reached 74.00. Prerequisite assumptions were met, with Shapiro-Wilk significance values above 0.05 and Levene's test significance of 0.248, allowing the use of parametric hypothesis testing.

3.2 Hypothesis Testing and Effect Size

The Independent Samples t-test yielded a two-tailed significance value of 0.000 ($p < 0.001$), leading to the rejection of H_0 and acceptance of H_a. The mean difference of 16.44 points indicates that the experimental group achieved a significantly higher science literacy score than the control group. This result provides statistical evidence that the learning treatment was associated with a substantial difference in posttest science literacy between the two groups.

Table 2. Independent Samples t-Test Results

Variable	t-value	df	Sig. (2-tailed)	Mean Difference
Science Literacy	8.838	48	0.000	16.440

The effect size analysis complements the significance test by showing the magnitude of the difference between groups. A Cohen's d value of 2.5 indicates a very large effect according (Sawilowsky, 2009). Thus, the difference in posttest science literacy was not only statistically significant but also substantial in practical magnitude

Table 3. Effect Size Calculation (Cohen's d)

Component	Value
Mean Experimental Group	90.44
Mean Control Group	74.00
Pooled Standard Deviation	6.577
Cohen's d	2.5
Category	Very Large

Table 3 shows that the experimental group had a posttest mean of 90.44 compared with 74.00 in the control group. With a pooled standard deviation of 6.577, the resulting Cohen's d of 2.5 falls in the very large category. This magnitude indicates that the observed difference between the two groups was substantial, not merely a consequence of statistical significance.

3.3 Indicator-Level Analysis

Analysis based on the PISA indicators showed comprehensive improvement in the experimental group. Interpreting data and scientific evidence (Indicator 3) experienced the highest improvement, supported by direct gas volume recording.

Table 4. Mean Scores of Science Literacy Indicators (Posttest)

Science Literacy Indicator	Experimental Mean	Control Mean
Explaining phenomena scientifically	90.33	76.67
Evaluating and designing scientific enquiry	86.00	77.00
Interpreting data and evidence scientifically	91.50	71.50

Table 4 indicates that the experimental group obtained higher mean scores than the control group on all three PISA science literacy indicators. The highest experimental-group mean was found for interpreting data and evidence scientifically (91.50), followed by explaining phenomena scientifically (90.33) and evaluating and designing scientific enquiry (86.00). This pattern is consistent with the project activities that required students to observe, record, interpret, and communicate evidence from the biogas project.

3.4 Qualitative Findings

Observation results recorded a 100% implementation rate (Very Good category). All PjBL syntax stages were executed systematically. Student interviews were conducted with five purposively selected students. The transcripts were coded thematically, and method triangulation was applied by cross-verifying interview data with observation notes. The analysis revealed positive responses and strengthened scientific attitudes. For example, one student stated, "Making biogas from market waste made me realize that physics is not just formulas; it is about solving real environmental problems." Minor technical constraints, such as tool leaks, served as reflective moments that strengthened a growth mindset.

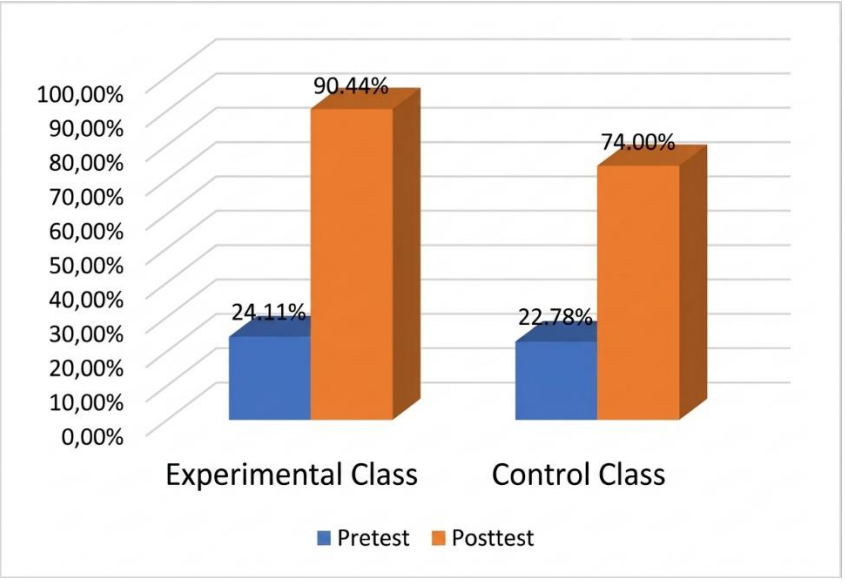


Figure 1. Comparison of Pretest and Posttest Mean Scores

4. DISCUSSION

The findings confirm that integrating PjBL with ESD not only yields statistical significance but also carries strong practical implications for enhancing science literacy. The very large effect size (d = 2.5) aligns with (Vilmala et al., 2025) and (Andriyatno et al., 2024), who assert that project-based approaches addressing sustainability issues can simultaneously integrate conceptual knowledge, procedural skills, and epistemic understanding.

The highest improvement in Indicator 3 (interpreting data) occurred because the micro scale biogas project required students to conduct direct observations, record empirical variables (gas volume in balloons), and analyze anaerobic fermentation patterns. This inquiry-based activity trained students to draw conclusions based on real evidence rather than assumptions (Purnamasari et al., 2024). Indicator 1 (explaining phenomena) also developed rapidly through collaborative discussions and presentations, where students connected the concept of chemical energy conversion to renewable energy alternatives (Laela et al., 2024).

A critical methodological consideration in this study was the management of time. A common critique of biogas projects is the time required for anaerobic fermentation, which typically takes weeks. However, in this study, the project was adapted to a micro-scale using sealed plastic bottles and balloons filled with market waste. This modification allowed students to observe gas volume changes and fermentation indicators within the 6-hour instructional timeframe, bypassing the need for a full-scale digester while maintaining authentic scientific inquiry. This addresses the common critique that biogas projects require weeks of fermentation (Kougias & Angelidaki, 2018). The simple tool modifications allowed the school to bypass the absence of a formal physics laboratory while still providing authentic, hands-on scientific experiences.

Furthermore, the qualitative data revealed that the ESD integration successfully instilled environmental awareness (Sari, 2023). Students did not just learn about renewable energy theoretically they actively engaged in waste reduction and sustainable problem-solving, reflecting the core values of ESD (Clarisa et al., 2020). The learning process not only improved science literacy scores but also instilled strong character values. This aligns with the findings that PjBL significantly strengthens student character, learning motivation, and collaborative skills through structured and meaningful project activities (Dewi et al., 2022).

5. CONCLUSION

This study concludes that the implementation of the ESD-based Project-Based Learning model significantly and substantially enhances the science literacy of high school students. The integration of PjBL and ESD transforms conventional, theory-heavy physics learning into a meaningful, context-

specific experience that fosters critical reasoning, data interpretation, and environmental sustainability awareness.

Contributions: Theoretically, this study enriches the literature on PjBL-ESD integration in resource-constrained contexts. Pedagogically, it provides a proven micro-scale project syntax that teachers can apply without relying on advanced laboratory facilities. Contextually, it offers an inclusive learning model tailored for madrasah and rural schools facing infrastructure limitations.

Limitations and Future Research: This study acknowledges certain limitations, including the use of a quasi-experimental design without random sampling, a relatively short intervention duration (6 hours), the use of simple measurement tools, and a primary focus on cognitive literacy. Future research should consider expanding the sample size, applying a true experimental design, integrating digital measurement sensors for more precise data, and examining affective variables such as long-term sustainability awareness and learning motivation.

ACKNOWLEDGEMENTS

The author expresses gratitude to the thesis supervisors, the administration of MAS Syamsuddhuha, and all class X students who actively participated in this study. The support and facilities provided during data collection were invaluable to the completion of this research.

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