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Sustainability-Oriented STEM-PjBL: Improving Students' Science Process Skills through Experimental Activities

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Abstract – *Science process skills (SPS) are essential competencies in physics education because they enable students to investigate scientific phenomena, apply concepts, and communicate evidence-based findings in real-world contexts. However, students often have difficulty formulating hypotheses, planning experiments, and systematically presenting observational results, indicating the need for instructional approaches that explicitly support scientific inquiry. This study aimed to examine the effect of sustainability-oriented STEM Project-Based Learning (STEM-PjBL) physics worksheets on high school students' SPS in renewable energy topics. A quantitative approach with a quasi-experimental pretest-posttest control group design was employed at SMAN 2 Banda Aceh during the 2023/2024 academic year. The sample consisted of 70 tenth-grade students selected through simple random sampling at the class level and divided into an experimental class (n = 35) and a control class (n = 35). The experimental class used sustainability-oriented STEM-PjBL worksheets that integrated the stages of the Engineering Design Process, while the control class used conventional PjBL worksheets. Data were collected using a 20-item SPS test and observation sheets, and then analyzed using normality and homogeneity tests, normalized gain scores, and an independent-samples t-test. The results showed that the experimental class achieved a higher N-gain score of 0.70 in the high category, compared with 0.63 in the medium category for the control class. The posttest difference was statistically significant (p = 0.030), and the experimental class showed higher gains across all SPS indicators, particularly in predicting and communicating. The novelty of this study lies in explicitly integrating sustainability principles into the Engineering Design Process and mapping them to integrated SPS indicators. These findings suggest that sustainability-oriented STEM-PjBL worksheets provide an evidence-based instructional model for strengthening scientific inquiry and contextual learning in physics education on renewable energy.*

Keywords: *engineering design; renewable energy; science process; STEM-PjBL; sustainability education.*

I. INTRODUCTION

Science process skills (SPS) constitute a fundamental component of science education because they enable students to acquire, construct, evaluate, and apply scientific knowledge through systematic inquiry. These skills include observing, classifying, predicting, asking questions, formulating hypotheses, planning investigations, using tools and materials, conducting experiments, applying concepts, and communicating scientific findings (Adam et al., 2022; Anggelina et al., 2025). In physics learning, SPS are particularly important because physics concepts are not only abstract and mathematical but also closely connected to observable phenomena, experimental procedures, and evidence-based reasoning. This need is also relevant to the Indonesian physics education context, where the representation of the nature of science in high school physics textbooks remains an important concern because students require learning experiences that reflect how scientific knowledge is constructed, tested, and communicated (Nurazmi & Bancong, 2025). Adam et al. (2022) emphasize that SPS involve mental, manual, and social skills required to develop scientific concepts, principles, laws, and theories. Therefore, strengthening SPS is essential for helping students move beyond the passive reception of scientific information toward active participation in scientific inquiry. In the context of twenty-first-century education, SPS are also closely associated with critical thinking, creativity, collaboration, and scientific communication, which are increasingly regarded as core competencies for preparing students to respond to complex social, technological, and environmental challenges (Fauziah, 2022; Juanta et al., 2023; Anggelina et al., 2025).

Recent literature has further highlighted the need to connect science learning with sustainability issues, particularly because contemporary scientific problems are increasingly interdisciplinary and situated within real-world contexts. This direction is consistent with recent developments in STEM and STEAM education, which show that interdisciplinary science learning has become an increasingly prominent global research trend from 2016 to 2025 (Jho et al., 2016; Nurazmi et al., 2025). Environmental degradation, climate change, energy insecurity, and waste accumulation require learners to understand scientific concepts while simultaneously considering their social and ecological implications. Sustainability education provides a meaningful framework for connecting scientific inquiry with authentic global and local problems, as environmental education can shape students' perceptions and awareness of sustainability issues (Boca & Saraçlı, 2019). Through sustainability-oriented science learning, students are encouraged to use scientific methods not merely to understand textbook concepts but also to analyze and propose solutions to environmental and societal issues (Agbor et al., 2025; Mngomezulu & Ramaila, 2025). This orientation is consistent with the broader agenda of Sustainable

Development Goal 4, which emphasizes inclusive, equitable, and quality education that supports lifelong learning and sustainable development (Ferguson et al., 2018; Işıkgöz & Öztunç, 2025). Accordingly, integrating sustainability into physics education is not an additional theme but a pedagogical necessity for making science learning more relevant, contextual, and socially meaningful.

Despite the importance of SPS, preliminary observations at SMAN 2 Banda Aceh indicated that many students still had difficulty formulating hypotheses, planning experiments, and systematically communicating observation results. These difficulties suggest that students' engagement with scientific inquiry remains limited, particularly when learning activities do not provide sufficient opportunities to design investigations, manipulate variables, collect data, interpret evidence, and present findings coherently. Such conditions are problematic because SPS cannot be adequately developed through teacher-centered explanation or routine problem-solving alone. Students require structured learning experiences that enable them to engage directly with scientific problems, make predictions, design experiments, test ideas, and revise their understanding based on evidence. Previous studies have shown that inquiry-based and guided inquiry learning can improve students' SPS and support more active engagement in scientific investigation (Rafiah et al., 2018; Hikmah et al., 2021). In this regard, the low level of SPS observed in the school context reflects a broader instructional issue: science learning needs to be designed to explicitly train inquiry processes rather than merely deliver conceptual content.

To address this problem, a learning approach is required that integrates conceptual understanding, hands-on experimentation, collaborative problem solving, and real-world application. STEM-based Project-Based Learning (STEM-PjBL) has been widely discussed as a promising pedagogical approach because it combines science, technology, engineering, and mathematics within project-oriented learning activities. The STEM approach enables students to understand scientific concepts through technological applications, engineering design, and mathematical reasoning, while PjBL provides a structured learning environment in which students investigate problems and produce tangible outcomes. STEM integration also encourages teachers and students to connect scientific concepts with technological, engineering, and mathematical practices in classroom learning (Wang, 2012; Jho et al., 2016). Within this framework, students are not positioned as passive recipients of information but as active problem solvers who must identify needs, develop ideas, test solutions, and communicate results. Previous studies have shown that STEM-oriented and project-based learning environments can support students' scientific reasoning, problem-solving abilities, and engagement in inquiry-based activities (Li et al., 2020; Wahono et al., 2020; Nawangsari et al., 2026). Therefore, STEM-PjBL is theoretically well-suited to improving SPS because its learning stages closely align with the processes used in scientific investigation.

More specifically, the Engineering Design Process (EDP) provides a systematic structure that can strengthen the implementation of STEM-PjBL. The EDP stages, namely ask, imagine, plan, create, test, and improve, guide students through a sequence of activities that are strongly aligned with SPS indicators. In the ask stage, students identify problems and formulate questions; in the imagine stage, they generate ideas and make predictions; in the plan stage, they determine variables and design investigations; in the create and test stages, they use tools, conduct experiments, and collect data; and in the improve stage, they apply concepts, evaluate results, refine solutions, and communicate findings. When sustainability issues are embedded in each of these stages, students are also encouraged to consider resource efficiency, environmental impact, and the relevance of renewable energy. This integration allows students to practice scientific inquiry while developing awareness of how scientific knowledge can be used to address sustainability challenges. Studies on STEM-PjBL and sustainability-oriented science learning indicate that authentic, contextual, and design-based activities can enhance students' engagement and support higher-order scientific competencies (Sari et al., 2020; Fiteriani et al., 2021; Zizka et al., 2021; Ridha et al., 2022).

The present study is situated within this body of literature and also addresses several remaining gaps. Although previous studies have reported the effectiveness of STEM-PjBL in improving students' scientific skills, the integration of sustainability principles across all stages of learning remains relatively limited. This gap is also important when viewed within broader trends in physics education research, where innovative instructional strategies, student competencies, and learning environments remain central topics in reputable international publications (Nurazmi & Bancong, 2024). Many STEM-PjBL studies emphasize the technical construction of products or the general implementation of project-based learning, but they do not explicitly connect each stage of learning to sustainability-oriented decision-making. In addition, the EDP stages are often used as a design procedure without being systematically mapped onto specific SPS indicators. As a result, the relationship between engineering design activities and the development of SPS is not always made explicit. Furthermore, research on physics worksheets that integrate sustainability-oriented STEM-PjBL, renewable energy contexts, EDP stages, and all ten integrated SPS indicators remains limited, particularly in high school physics learning. This gap indicates the need for a worksheet model that not only guides students through project activities but also deliberately trains each SPS indicator within a sustainability-based physics context.

Based on these considerations, this study aims to examine improvements in students' science process skills through the implementation of sustainability-oriented STEM-PjBL-based physics worksheets on renewable energy topics. The study focuses on a solar tracker project because it provides a relevant context for linking physics concepts, renewable energy applications, engineering design, and sustainability issues. The novelty of this study lies in the integration of sustainability principles into the EDP stages within STEM-PjBL worksheets and the explicit mapping of these stages to ten integrated SPS indicators: observing, classifying, predicting, asking questions, formulating hypotheses, planning experiments, using tools and materials, conducting experiments, applying concepts, and communicating. Through this focus, the study is expected to contribute to physics education by offering an evidence-based worksheet model that supports scientific inquiry, contextual learning, and sustainability-oriented STEM practice.

II. METHODS

This study employed a quantitative research approach with a quasi-experimental design. A quantitative approach was considered appropriate because the study aimed to measure the effect of a specific instructional intervention on students' SPS using numerical data obtained from pretest and posttest scores. The research design used was a pretest-posttest control group design, which enables researchers to compare students' initial abilities before treatment and their achievement after treatment in two different learning conditions (Sugiyono, 2014). The design was classified as quasi-experimental because the participants were drawn from intact classroom groups, and individual random assignment to treatment conditions was not possible in the school setting. However, to strengthen internal validity, random selection was implemented at the class level via simple random sampling from the seven available tenth-grade classes. The research was conducted at SMAN 2 Banda Aceh during the odd semester of the 2023/2024 academic year. The population consisted of all tenth-grade students across seven classes, totaling 245 students. Two classes were selected as samples: class X4, consisting of 35 students, served as the experimental class, while class X6, also consisting of 35 students, served as the control class. The experimental class was taught using sustainability-oriented STEM-PjBL-based physics worksheets, whereas the control class was taught using conventional PjBL worksheets without explicit sustainability-oriented EDP structure.

Table 1. Research design

Class	Pre-test	Treatments	Post-test
Experiment	O_1	X_1	O_2
Control	O_1	X_2	O_2

The learning intervention was implemented over six 90-minute meetings within a three-week instructional period. Both classes studied the same renewable energy topic through a solar tracker project to ensure that the learning content and project theme remained comparable. The main distinction between the two groups lay in the instructional structure. In the experimental class, the worksheets were designed by integrating sustainability principles into the EDP stages, namely ask, imagine, plan, create, test, improve, and communicate. These stages were aligned with the development of SPS indicators, allowing students to identify problems, generate design ideas, plan investigations, build prototypes, conduct testing, revise their designs, and communicate their findings. In contrast, the control class implemented conventional PjBL using the same project theme but without systematic EDP-based guidance, explicit sustainability tasks, or direct mapping between project activities and SPS indicators. Both classes were taught by the same physics teacher to reduce instructor-related bias. Students worked in heterogeneous groups of four to five members based on academic ability, allowing collaborative learning and peer support during project completion.

Students' SPS were assessed using two main instruments. The first instrument was a written SPS test consisting of 20 items, including 10 multiple-choice items and 10 open-ended items. The test was developed based on ten integrated SPS indicators proposed by Tawil and Liliasari (2014), namely observing, classifying, predicting, asking questions, formulating hypotheses, planning experiments, using tools or materials, conducting experiments, applying concepts, and communicating. The multiple-choice items were scored dichotomously, with one point for each correct answer and zero for each incorrect answer. The open-ended items were assessed using an analytic rubric with scores ranging from 0 to 3 based on completeness, conceptual accuracy, and scientific reasoning. After score conversion, multiple-choice and open-ended components contributed equally to the total test score, with a maximum score of 100. The second instrument was an SPS observation sheet used to document students' scientific activities during the learning process. Observations were conducted during the second and fifth meetings to capture students' SPS performance in the middle and later stages of the intervention.

Table 2. Blueprint of the SPS test

No	SPS indicator	Multiple choice	Open-ended	Total items
1	Observing	1	1	2
2	Classifying	1	1	2
3	Predicting	1	1	2
4	Asking questions	1	1	2
5	Formulating hypotheses	1	1	2

6	Planning experiments	1	1	2
7	Using tools/materials	1	1	2
8	Conducting experiments	1	1	2
9	Applying concepts	1	1	2
10	Communicating	1	1	2
	Total	**10**	**10**	**20**

Instrument quality was examined through expert validation and quantitative analysis. The content validity of the worksheets and SPS test was evaluated by two experts using Aiken's V Index. The validation results showed that the worksheets obtained an Aiken's V value of 0.96, while the SPS test obtained a value of 0.95, indicating that both instruments were valid because their values exceeded the minimum criterion of 0.80. Inter-rater reliability was calculated using Inter-Rater Agreement with Cohen's Kappa. The worksheets obtained an agreement value of 0.556, and the teaching module obtained a value of 0.588, both categorized as good agreement. In addition, the SPS test was analyzed using SPSS version 25.0 to examine item validity and reliability. The reliability coefficient was 0.882, categorized as very high, and the discrimination index was 0.918, categorized as very good. These results indicate that the instruments were sufficiently reliable and appropriate for measuring students' SPS in the context of renewable energy learning.

Table 3. EDP stages and activities in the experimental class

EDP stage	Meeting	Student activities	Sustainability integration	SPS indicators trained
Ask	1	Identifying problems related to solar tracker efficiency; discussing why solar panels need to track the sun	Connecting to energy crisis and renewable energy	Observing, asking questions
Imagine	1-2	Brainstorming possible solar tracker designs; predicting which design yields the highest efficiency	Considering material efficiency and environmental impact	Predicting, applying concepts
Plan	2	Designing the experiment; determining variables (control, manipulation, response); drawing the solar tracker design	Planning to use recyclable materials	Planning experiments, classifying

Create	3	Building the solar tracker prototype using simple tools	Using environmentally friendly materials	Using tools/materials, conducting experiments
Test	4-5	Testing the solar tracker by measuring light intensity and comparing with fixed solar panels; recording data	Measuring efficiency to reduce energy waste	Conducting experiments, observing, grouping
Improve	5-6	Analyzing test results; identifying weaknesses; redesigning and retesting	Optimizing design for better efficiency	Applying concepts, communicating
Communicate	6	Presenting final results; writing reports; discussing findings	Explaining environmental benefits of the design	Communicating, applying concepts

Data were analyzed using SPSS version 25.0. Before hypothesis testing, prerequisite tests were conducted to ensure that the data met the assumptions for parametric analysis. The Shapiro-Wilk test was used to examine data normality, while Levene's test was used to examine homogeneity of variance. Students' improvement in SPS was calculated using the normalized gain (N-gain) formula proposed by Hake (2002), namely the difference between posttest and pretest scores divided by the difference between the maximum score and the pretest score. The N-gain results were interpreted using three categories: high for $g \geq 0.70$, medium for $0.30 \leq g < 0.70$, and low for $g < 0.30$. After the assumptions of normality and homogeneity were met, an independent-samples t-test was conducted at the 0.05 significance level to determine whether there was a significant difference in SPS improvement between the experimental and control classes.

Table 4. N-gain index category

Skor N-gain	**Category**
$g \geq 0.70$	High
$0.30 \leq g < 0.70$	Medium
$g < 0.30$	Low

The overall research procedure consisted of preparation, implementation, and completion stages. During the preparation stage, the researchers identified the research problem, reviewed the relevant literature, determined the research design, developed the learning instruments, and validated them. During the implementation stage, pretests were administered to both classes, followed by the instructional intervention and classroom observations. During the completion stage, posttests were administered, data were analyzed, and conclusions were drawn based on the empirical findings. The complete flow of the research procedure is presented in Figure 1.

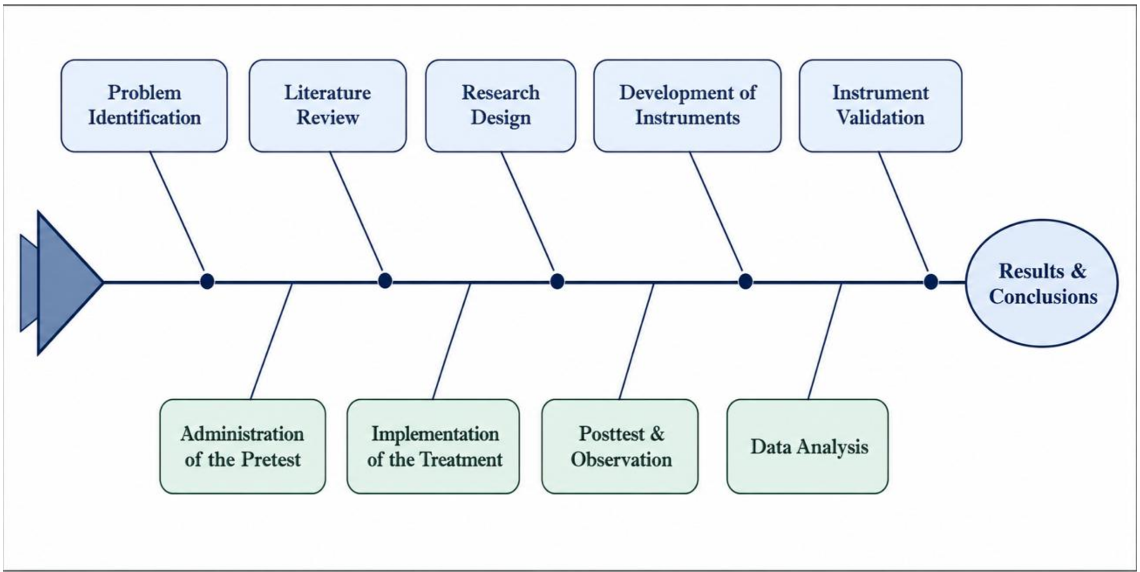

Figure 1. The procedure of this study

III. RESULTS

The pretest results showed that students in the experimental and control classes had comparable initial SPS. As presented in Table 3, the experimental class obtained a mean pretest score of 36.7, while the control class obtained a mean pretest score of 34.6. This indicates that both groups started from a relatively similar level of SPS before the instructional intervention was implemented. After the learning process, both groups showed improvement in their posttest scores. However, the experimental class achieved a higher mean posttest score of 81.2 compared with 76.3 in the control class. The normalized gain analysis also showed that the experimental class obtained an N-gain score of 0.70, which falls into the high category, whereas the control class obtained an N-gain score of 0.63, which falls into the medium category. These results indicate that students who learned through sustainability-oriented STEM-PjBL-based physics worksheets showed greater improvement in SPS than students who learned through conventional PjBL.

Table 3. Mean SPS scores for the experimental class and the control class

Class	Pre-test average	Post-test average	N-gain	Category
Experiment	36.7	81.2	0.70	High
Control	34.6	76.3	0.63	Medium

Before conducting hypothesis testing, the assumptions of normality and homogeneity were examined. The Shapiro-Wilk normality test indicated that all pretest and posttest data were normally distributed. As shown in Table 4, the significance values were 0.299 for the experimental pretest, 0.067 for the control pretest, 0.082 for the experimental posttest, and 0.221 for the control posttest. Since all significance values were greater than 0.05, the data met the assumption of normal distribution. Levene's test also indicated that the data were homogeneous.

Table 4. Results of the normality test for SPS data

Data	Statistic (shapiro-wilk)	Sig.	Result
Experimental class pre-test	0.964	0.299	Normal
Control class pre-test	0.942	0.067	Normal
Experimental class post-test	0.945	0.082	Normal
Control class post-test	0.960	0.221	Normal

As presented in Table 5, the significance value for the pretest data was 0.220, while the significance value for the posttest data was 0.438. Both values exceeded 0.05, indicating that the variance between the experimental and control classes was homogeneous. Therefore, the data fulfilled the prerequisite assumptions for parametric hypothesis testing.

Table 5. Results of the homogeneity test for SPS data

Data	Statistic Levene	Sig.	Result
Pre-test experiment & control	1.530	0.220	Homogeneous
Post-test experiment & control	0.610	0.438	Homogeneous

The independent samples t-test was then conducted to determine whether there was a significant difference between the experimental and control classes. The results are presented in Table 6. The pretest comparison showed a significance value of 0.336, which is greater than 0.05. This result indicates that there was no statistically significant difference between the two classes before the intervention. In contrast, the posttest comparison showed a significance value of 0.030, which is lower than 0.05. This finding indicates a statistically significant difference in SPS achievement between students taught using sustainability-oriented STEM-PjBL-based worksheets and those taught using conventional PjBL. The posttest mean difference suggests that the experimental treatment contributed to higher SPS performance after the intervention.

Table 6. Results of the independent samples t-test

Data	Average experiment	Average control	t-score	Sig.	Decision
Pre-test	36.7	34.6	0.969	0.336	H_0 Accepted
Post-test	81.2	76.3	2.211	0.030	H_0 Rejected

A more detailed analysis was conducted by examining the N-gain scores for each SPS indicator. As shown in Table 7, the experimental class achieved higher N-gain scores than the control class across all indicators. The highest N-gain in the experimental class was observed for the predicting indicator, with a score of 0.70, which was categorized as high. Other indicators in the experimental class were in the medium category, including observing (0.43), grouping (0.50), formulating the problem (0.57), hypothesizing (0.59), planning the experiment (0.63), using tools or materials (0.60), carrying out experiments (0.62), applying concepts (0.65), and communicating (0.47). In the control class, most indicators were also in the medium category but observing (0.23) and communicating (0.15) were categorized as low. The largest difference between the two classes was found in the communicating indicator, with a difference of 0.32, followed by observing with a difference of 0.20, predicting with a difference of 0.16, and carrying out experiments with a difference of 0.15. These findings indicate that the experimental treatment had a positive effect across all SPS dimensions, with the strongest relative advantage observed in communication and observation skills.

Table 7. Comparison of N-gain values per SPS indicator

SPS indicator	N-gain experiment class	Category	N-gain control class	Category	Difference
Observe	0.43	Medium	0.23	Low	0.20
Grouping	0.50	Medium	0.44	Medium	0.06
Predict	0.70	High	0.54	Medium	0.16
Formulate the problem	0.57	Medium	0.53	Medium	0.04
Hypothesize	0.59	Medium	0.50	Medium	0.09
Plan the experiment	0.63	Medium	0.56	Medium	0.07
Using tools/materials	0.60	Medium	0.50	Medium	0.10
Carrying out experiments	0.62	Medium	0.47	Medium	0.15
Applying concepts	0.65	Medium	0.57	Medium	0.08
Communicate	0.47	Medium	0.15	Low	0.32

The comparison of N-gain scores between the experimental and control classes is also illustrated in Figure 2. The figure visually confirms that the experimental class obtained a higher overall N-gain score than the control class. The experimental class reached the high category with an N-gain of 0.70, while the control class remained in the medium category with an N-gain of 0.63. This graphical evidence supports the quantitative findings presented in Tables 3 and 7, showing that the sustainability-oriented STEM-PjBL-based worksheets were associated with greater improvements in students' SPS.

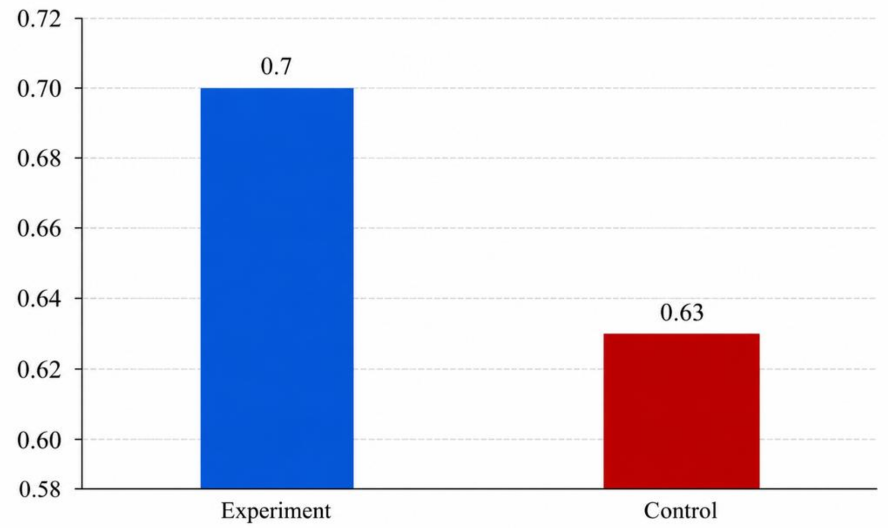

Figure 2. Comparison of N-gain by SPS indicator between the experimental class and the control class

The observation data further supported the test results. As shown in Table 8, the experimental class achieved an average SPS observation percentage of 66.56%, categorized as high, whereas the control class achieved 56.09%, categorized as sufficient. In the experimental class, the observation percentage increased from 55.31% in the first meeting to 77.81% in the second observation meeting. In the control class, the percentage increased from 51.88% to 60.31%. Although both classes showed improvement during the learning process, the increase in the experimental class was greater. These results indicate that students in the experimental class were more actively engaged in SPS-related activities during the learning process than students in the control class.

Table 8. Results of student SPS observations

Class	Meet	Percentage (%)	Category	Average
Experiment	I	55.31%	Enough	66.56% (High)
Experiment	II	77.81%	High	
Control	I	51.88%	Enough	56.09% (Enough)
Control	II	60.31%	Enough	

IV. DISCUSSION

The findings of this study indicate that sustainability-oriented STEM-PjBL-based physics worksheets led to greater improvements in students' SPS than conventional PjBL. The experimental class obtained a higher posttest mean score and reached a high N-gain category, while the control class remained in the medium category. The significant posttest difference between the two classes suggests that integrating sustainability principles, STEM learning, project-based activities, and the EDP provided a more structured and meaningful learning environment for developing SPS. This result is consistent with the theoretical position that SPS are not merely procedural skills but integrated scientific competencies involving mental, manual, and social dimensions required to acquire and apply scientific knowledge (Adam et al, 2022). In this study, students in the experimental class were not only required to understand renewable energy concepts but also to identify problems, formulate predictions, design experiments, use tools, test prototypes, evaluate results, and communicate findings. Such activities closely align with the nature of SPS and explain why the experimental class showed greater improvement.

The improvement observed in the experimental class can be interpreted through the pedagogical characteristics of STEM-PjBL. STEM learning provides opportunities for students to connect scientific concepts with technological applications, engineering design, and mathematical reasoning, while PjBL situates these processes within authentic project activities. Previous literature has shown that STEM-based learning environments can strengthen students' scientific reasoning and inquiry practices when learning tasks are contextual, problem-oriented, and connected to real-world phenomena (Li et al., 2020; Wahono et al., 2020). In this study, the solar tracker project provided a concrete context for students to apply physics concepts related to renewable energy, light intensity, and energy efficiency. The use of a project context also required students to work collaboratively, make design decisions, and evaluate empirical evidence, which are essential conditions for SPS development. Therefore, the higher SPS achievement in the experimental class was likely related to the systematic alignment between the learning model and the scientific practices expected in the assessment.

The predicting indicator showed the highest N-gain in the experimental class. This result suggests that the Ask and Imagine stages of the EDP were particularly effective in training students to anticipate possible outcomes before conducting experiments. In these stages, students were encouraged to identify problems related to solar tracker efficiency, generate possible design alternatives, and predict which design would produce better energy absorption. Prediction is a central SPS component because it requires students to use prior knowledge, recognize patterns, and formulate reasoned expectations about scientific phenomena. The sustainability dimension strengthened this process by asking students to consider material efficiency, environmental impact, and the relevance of renewable energy when making predictions. This finding is in line with Sari et al. (2020), who reported that STEM education in an inquiry-based learning environment improves students' ability to predict and reason about experimental outcomes. The result also supports the broader argument that contextualized STEM activities can enhance scientific thinking when students are required to connect conceptual understanding with empirical investigation.

The communication indicator showed the largest difference between the experimental and control classes, although the experimental class remained in the medium N-gain category for this indicator. This pattern indicates that communication skills improved more strongly when students were explicitly guided to present, justify, and revise their project outcomes. In the experimental class, the Communicate stage required students to explain the design and function of their solar tracker, present test results, respond to feedback, and describe the environmental relevance of their product. These activities created repeated opportunities for students to transform experimental data into scientific explanations. Haryanti and Suwarma (2018) emphasized that STEM-based learning can improve students' communication skills because it requires students to express ideas, explain procedures, and present products in a scientific manner. The relatively low score of the control class on this indicator suggests that conventional PjBL may provide project experience but does not automatically develop scientific communication unless communication tasks are explicitly structured. Thus, the explicit integration of communication activities within the EDP appears to be an important component of the worksheet design.

The indicators of planning and conducting experiments also showed consistent improvement in the experimental class. These results are important because planning and conducting experiments represent core SPS components that determine the quality of students' scientific inquiry. Through the plan stage, students were guided to determine variables, design procedures, and prepare the experimental setup. Through the create and test stages, they used tools and materials, built the solar tracker prototype, measured light intensity, compared results, and recorded data. This sequence provided students with systematic experience in conducting scientific investigation rather than simply following teacher instructions. Ridha et al. (2022) stated that STEM-PjBL learning tools designed through structured EDP stages can effectively support students in designing and carrying out experiments. The findings of this study support this claim because the experimental worksheets made the relationship between project activities and SPS indicators more explicit. By contrast, the control class completed the same general project but without the sustainability-oriented EDP structure, which may explain its lower N-gain in these indicators.

The observing and grouping indicators showed different patterns of improvement. The observing indicator improved more strongly in the experimental class than in the control class, indicating that structured worksheet guidance helped students conduct more systematic observations. Observation in science learning requires more than simply seeing phenomena; it involves identifying relevant features, recording data carefully, and recognizing changes or patterns in empirical events. In the solar tracker project, students observed light intensity, prototype movement, efficiency differences, and design limitations. These activities were strengthened by the sustainability context, as students had to relate their observations to energy efficiency and resource use. Meanwhile, the grouping indicator showed only a small difference between the two classes. This may indicate that classification skills can be developed through various project-based activities, even when the learning structure is less explicit. Mukaromah et al. (2022) found that STEM-based exploratory learning can support students in grouping variables and developing creative solutions. The present finding extends this argument by showing that classification may improve in both STEM-oriented and conventional project settings, although structured sustainability-oriented worksheets still produced a slightly higher gain.

The indicators of formulating hypotheses and applying concepts also improved in the experimental class. This result suggests that students were able to connect renewable energy concepts with scientific reasoning and design decisions. In the hypothesis-forming process, students were not only asked to predict physical outcomes but also to consider how design choices might affect energy efficiency and environmental impact. This is important because sustainability-oriented science learning requires students to evaluate scientific problems from both conceptual and practical perspectives. The application of concepts was strengthened during the Create, Test, and Improve stages, where students applied physics concepts to build, test, and revise the solar tracker prototype. Fiteriani et al. (2021) reported that PjBL through a STEM approach can improve creative problem-solving and metacognitive skills in physics learning. These competencies are closely related to students' ability to formulate hypotheses and apply concepts, as both require them to monitor their reasoning, evaluate evidence, and revise solutions in light of empirical results.

The observation data further reinforce the test results. Students in the experimental class demonstrated a higher average percentage of SPS-related activities than those in the control class. This indicates that the sustainability-oriented STEM-PjBL worksheets not only improved test performance but also supported more active engagement during the learning process. The increase in observed SPS activity from the first to the second observation meeting suggests that students became more familiar with inquiry-oriented and design-based learning as the intervention progressed. This finding is consistent with the view that meaningful STEM learning requires active participation in authentic tasks rather than passive reception of information (Wahono et al., 2020). It also aligns with Zizka et al. (2021), who argued that integrating sustainability into STEM programs can promote authentic engagement because students perceive learning as relevant to real-life issues and future challenges. In this study, the renewable energy context appeared to provide an authentic problem frame that encouraged students to participate more actively in scientific activities.

An important contribution of this study lies in the explicit integration of sustainability principles into each stage of the EDP within STEM-PjBL worksheets. Previous research has demonstrated the value of STEM learning and PjBL in improving scientific competencies, but many studies focus primarily on product development or general project activities, without explicitly embedding sustainability within the inquiry structure. In contrast, this study positioned sustainability not as an additional topic but as a guiding principle for problem identification, design planning, material selection, testing, improvement, and communication. This approach is consistent with the argument that sustainability education should connect scientific knowledge with environmental and social problem solving (Agbor et al., 2025; Mngomezulu & Ramaila, 2025). It is also aligned with SDG 4, which emphasizes quality education that supports sustainable development and lifelong learning (Ferguson et al., 2018; Işıkgöz & Öztunç, 2025). Therefore, the findings contribute to physics education by offering a worksheet model that connects SPS development with sustainability-oriented STEM practice.

The use of a solar tracker project also enhances the intervention's relevance. Renewable energy provides an appropriate context for learning physics because it connects scientific concepts to current environmental and technological challenges. Through this project, students explored how solar panel efficiency can be improved by tracking sunlight, thereby linking mechanics, energy conversion, measurement, and environmental considerations. This context allowed students to understand physics as a tool for solving real-world sustainability problems rather than as a set of isolated formulas. González-Gómez and Jeong (2022) emphasized that science teaching approaches connected to sustainable development can make learning more meaningful and responsive to contemporary challenges. Similarly, Kurniawan et al. (2025) showed that integrating STEM design thinking into education for sustainable development can support students' scientific modeling skills. The present study complements these findings by showing that a sustainability-oriented STEM-PjBL worksheet can also strengthen SPS in high school physics learning.

Although the findings are positive, several interpretive boundaries should be acknowledged. The study measured SPS directly through tests and observations, but ecological awareness was not assessed using a validated instrument. Therefore, while students demonstrated environmentally conscious behaviors during the project, such as considering recyclable materials and discussing energy efficiency, this outcome should be interpreted as an incidental indication rather than a directly measured effect. This distinction is important to maintain the methodological accuracy of the study. In addition, the intervention was conducted in one school with two intact classes over six meetings, which may limit the generalizability of the findings. Nevertheless, the significant posttest difference, the higher N-gain in the experimental class, and stronger observational results provide empirical support for the effectiveness of the worksheet model in the context studied.

V. CONCLUSION AND SUGGESTIONS

This study concludes that implementing sustainability-oriented STEM-PjBL-based physics worksheets significantly improved high school students' SPS in renewable energy topics. The experimental class showed a higher improvement than the control class, as indicated by an N-gain score of 0.70 in the high category, compared with 0.63 in the medium category for the control class. The independent samples t-test also showed a significant difference between the two classes after the intervention, indicating that the use of sustainability-oriented STEM-PjBL worksheets had a positive effect on students' SPS. Across SPS indicators, the experimental class achieved higher gains than the control class, with the strongest improvement observed in predicting and the largest difference found in communicating. These findings demonstrate that integrating sustainability principles into the stages of the EDP can provide a structured learning environment that supports students in observing, predicting, designing experiments, using tools, conducting investigations, applying concepts, and communicating scientific findings.

This study has several limitations that should be considered when interpreting the findings. The sample was limited to two classes in one senior high school, which restricts the generalizability of the results to broader educational contexts. The intervention was also conducted over six meetings, so a longer implementation period may be needed to examine the sustained development of all SPS indicators. In addition, although students showed environmentally conscious behaviors during the project, ecological awareness was not directly measured using a validated instrument. Future research is recommended to apply this worksheet model to larger and more diverse samples, different physics topics, and longer instructional periods. Further studies should also include validated measures of ecological awareness and other affective outcomes to examine the broader impact of sustainability-oriented STEM-PjBL. The contribution of this study lies in offering an evidence-based physics worksheet model that explicitly integrates sustainability principles into STEM-PjBL and maps the stages of the EDP to

SPS indicators, thereby supporting more contextual, inquiry-oriented, and sustainability-relevant physics learning.

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