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SCIENCE LECTURE INNOVATION USING PJBLSTEM-ESD TO IMPROVE STUDENTS' CRITICAL THINKING SKILLS AND SUSTAINABILITY CONSCIOUSNESS TO STRENGTHEN SDGS 4

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ABSTRACT

The purpose of this research is to develop and implement project-based teaching materials with a STEM-ESD approach. These materials use a water theme in Science courses to strengthen the achievement of Sustainable Development Goals (SDG) 4 by improving students' critical thinking skills and sustainability consciousness. This research uses a mixed-methods approach with an Embedded Experiment Model design. The research instrument was developed through a validation process by 10 experts and a trial on 62 science education students to ensure validity and reliability. Implementation was carried out on a sample of 28 students from one university in Indonesia. Data collection used expert validation sheets, student response questionnaires, critical thinking tests, and sustainability consciousness scales. Analysis was carried out using Fuzzy Delphi Methods, the Rasch Model, N-Gain, and t-tests. Validation results showed that the teaching materials were very feasible to use (average validity of 89%). Empirical tests showed significant increases in critical thinking skills (N-gain = 0.39, medium effect size) and sustainability consciousness (N-gain = 0.30, low effect size). These findings confirm that implementing the PjBLSTEM-ESD model effectively contextualizes science concepts with sustainable development issues. It significantly supports the achievement of SDG 4 through meaningful and transformative education.

Keywords: project-based learning; STEM; ESD; critical thinking; fuzzy delphi methods

INTRODUCTION

The United Nations has formulated 17 Sustainable Development Goals (SDGs) targeted for achievement by 2030. One of them is SDG 4, which focuses on Quality Education. Education is globally recognized as a key instrument for achieving all SDGs, notably Target 4.7, which emphasizes integrating sustainability as learning objectives at all levels of education. However, conceptual refinement and operational clarity are still required to understand the relationship between the complexities of the concept of sustainability and learning outcomes in the context of Education for Sustainable Development (ESD) (Kioupi, 2019). ESD is a strategic approach to achieve these goals, yet this global agenda has received constructive criticism for its implementation and measurement of results. While the international community has exhibited a strong consensus in support of SDG 4.7, the definition of relevant indicators for assessing ESD success across countries and contexts remains unclear (Giangrande et al., 2019; Edwards et al., 2020).

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To achieve authentic ecological sustainability, a new paradigm of education for sustainable development is required, one that fosters ecologically sustainable behaviors, nurtures attitudes towards living organisms, and recognizes interconnectivity (Holma et al., 2025). Therefore, developing an adaptive competency framework that accommodates the diversity of learning outcomes is essential for aligning global goals with local realities.

ESD can be integrated with Science, Technology, Engineering, and Mathematics (STEM). This approach not only encourages mastery of critical thinking and problem-solving skills but also fosters awareness of sustainable values. Although STEM and ESD have been widely discussed in the literature, their integration into science learning in higher education continues to encounter significant challenges (Vilmala et al., 2022; Solihah et al., 2024). Science learning models tend to be dominated by traditional, lecture-centered approaches that emphasize the transfer of material rather than the development of transformative competencies and relevance to real-world issues such as environmental and sustainability issues (Bafarasat et al., 2025). Various efforts must be undertaken to reduce tensions related to sustainability issues through ESD (Duifhuis et al., 2025). According to survey results and previous research, students' ability to connect STEM knowledge, raise STEM interest and aspirations, and critical thinking skills to environmental sustainability issues, such as water conservation, remains low (Rogovaya et al., 2019; Wibowo et al., 2024; Gossen, 2025). This challenge is exacerbated by the lack of innovative teaching materials that operationalize STEM-ESD principles in context and practice through active learning strategies, such as project-based learning (PjBL). (Nurhidayah et al., 2021; Jang, 2022; Rehman et al., 2024).

Water is a fundamental environmental and sustainability issue, with direct implications for scientific literacy, ecosystem management, and quality of life. In an educational context, the theme of water is highly relevant for facilitating project-based learning and strengthening students' environmental awareness. However, a literature review indicates that the development of project-based water-themed teaching materials that simultaneously integrate STEM and ESD is still quite restricted, both in terms of the design stage and the validation of learning outcomes. Previous research has focused on training STEM skills, such as encouraging analytical and innovative thinking (Du Plessis, 2020; Fajrina et al., 2020; Hacioglu & Gulhan, 2021) without a sustainability context, or conversely, emphasizing ESD education without the interdisciplinary approach that is typical of STEM (Vásquez et al., 2021; Mohantyl, 2024; Fernando & Tajan, 2024). A systematic review revealed that most published research addresses these approaches separately. The authentic and synergistic integration of PjBL, STEM, and ESD, particularly in the context of water-related challenges aligned with SDG 6, remains underexplored, particularly on their simultaneous impact on cognitive (critical thinking) and affective (sustainability awareness) learning outcomes (Habibaturrohmah et al., 2023). The I-STEM-PjBL-ESD framework can be implemented by using problem-based learning to investigate students' learning in areas such as conceptual understanding, creativity, and their knowledge, attitudes, and behaviors toward sustainable development(Funa et al., 2024). Leading international publications, including those in science education, highlight the scarcity of empirical models that properly incorporate this framework using validated instruments to assess the effectiveness of multiple outcomes in the context of sustainability.

This research aims to develop and test the validity and effectiveness of project-based learning (PjBL) materials, supported by STEM-ESD tasks, on the theme of water in a college-level science course. The primary focus of the study is to analyze the contribution of this innovative teaching material to achieving SDG 4 by improving students' critical thinking skills and sustainability consciousness. Theoretically, this study presents a novel STEM and ESD integration model based on task-assisted thematic projects. It provides a significant contribution to the innovative pedagogical literature, with implications for transforming science learning into a more transformative and sustainable education.

The research questions are as follows:

(1). How does the development of teaching materials for the "Around Us" Science course using PjBLSTEM-ESD improve students' critical thinking skills and interest in science learning?;

(2) How can teaching materials for the "Around Us" Science course using PjBLSTEM-ESD improve students' critical thinking skills and consciousness of participation?

METHODS

The research method used was a Mixed Methods with an Embedded Experimental approach (Creswell & Plano Clark, 2018b). This design combines qualitative and quantitative research methods within a single study to address a problem. This research aimed to develop students' critical thinking skills and Sustainability Consciousness through the use of the PjBLSTEM-ESD learning model in the Science Around Us learning. This model prioritizes quantitative data, with qualitative data inherent in this methodology (Kaushal et al., 2022).

This method was chosen because the collection of qualitative and quantitative data complements each other, strengthening the analysis in answering the research questions. This type of mixed-methods research is considered most appropriate for collecting data in research with interventions, where supporting data supplement the primary data. The quantitative data examined were students' critical thinking skills and Sustainability Consciousness after lectures, using the task-assisted PjBLSTEM-ESD model. Qualitative data were collected through lecture observations and interviews, which produced student responses. In addition, observations were made during the intervention related to the implementation of PjBLSTEM-ESD. The qualitative and quantitative data obtained were then analyzed to conclude the PjBLSTEM lecture program in the ESD context, focusing on improving students' critical thinking skills and Sustainability Consciousness.

The developed teaching materials were construct-validated by 10 Science Education experts before being empirically validated with 62 Science Education students from three universities. The validated and reliable instruments were subsequently piloted on 28 students studying Science Education at a university in Indonesia. In this research, the sampling technique used for quantitative data was random sampling. All participants volunteered for the Science Around Us course, ensuring that the research context is relevant to the implementation of the STEM-ESD approach in higher education. The use of a relatively small sample in this study is based on a mixed methods design with an embedded experimental approach, in which experimental (quantitative) methods are strategically integrated into a qualitative research framework, or vice versa, allowing researchers to gain a comprehensive understanding of both numerical and narrative data. The embedded experimental approach requires an in-depth exploration phase within a limited group or context, enabling comprehensive analysis of experimental results through data triangulation. In line with the recommendations of Creswell & Plano Clark (2018a), sample sizes in mixed methods research—particularly with embedded designs—do not need to be large; instead, they should be adjusted to the goal of obtaining meaningful data, field practices, and the limitations of the relevant population. As a result, the selection of a small sample in this study does not reduce the validity and reliability of the findings, but rather represents a data collection strategy that considers the complexity of the context, the specificity of the intervention, and the integration of qualitative and quantitative data analysis in an integrated manner, in accordance with the principles of embedded experimental mixed methods research.

The research was conducted in 7 main stages: (1) In the pre-intervention phase, a needs study was completed. This stage is an in-depth exploration of the problem being studied. Some of the activities carried out at this stage include: literature study, analysis, and synthesis of journals and reports, as well as lecturers' perceptions of the Natural Sciences Around Us lectures that have been implemented, the essential principles of Natural Sciences Around Us related to the ESD context, observations related to lectures, Critical Thinking Skills, and Sustainability Consciousness; (2) The design stage includes preparing the initial product draft. The initial product draft consists of an activity guide and a worksheet (task) consisting of four parts; (3) Development stage. At this stage, instruments were developed for implementation in the PjBLSTEM-ESD model, namely activity guides, worksheets (tasks) consisting of 4 sections, critical-thinking skills test questions, and student questionnaires. After the research instruments were created, they were validated and evaluated by experts before being improved for use in product testing; (4) The initial QUAN test stage involves gathering information on students' critical thinking skills using the evaluated test equipment; this part is often called the pretest;(5)The intervention stage involves implementing the PjBLSTEM-ESD in the Science Around Us lecture as well as identifying and collecting information on student activities during the learning activities (quality during the intervention). Data was also collected on: (1) the implementation of PjBLSTEM lectures related to the ESD context; (2) student learning experiences in the form of activities that develop critical thinking skills and Sustainability Consciousness. This was used as evaluation material to assess the advantages and disadvantages of implementing PjBLSTEM-ESD in the Science Around Us lecture and whether the planned activities have been achieved; (6) The final QUAN test stage is often known as the posttest. The analysis of student activity information during the intervention and the results of this final measurement functioned as the input for improving the quality of the "About Us" Science lecture using the PjBLSTEM-ESD model (quality after intervention). To strengthen data quality after the intervention, a questionnaire was distributed to students, and interviews with lecturers were conducted to assess learning; (7) Interpretation Stage, which was carried out using quantitative and qualitative data from the QUAN (qual) results. The capital letter QUAN indicates dominant quantitative data, while the lower-case letter qual indicates qualitative data or results that support and complement it.

The main instruments used in this research are as follows: (1) PjBLSTEM-ESD task validation sheet, which is used to assess student performance in project assignments; (2) Validation sheet and critical thinking test, which are used to measure students' thinking skills through the PjBLSTEM-ESD model; (3) Validation Sheet and Sustainability Awareness Questionnaire adapted for the college context.

The PjBLSTEM-ESD task, critical thinking test instrument, and sustainability consciousness questionnaire that had been developed were construct-validated by 10 experts and analyzed using the Fuzzy Delphi Method (FDM). FDM was conducted to improve the teaching materials (tasks) and to ensure the reliability and relevance of the interventions provided by the experts (de Hierro et al., 2021). Next, the critical thinking test instrument and the sustainability consciousness questionnaire were empirically validated on 62 science education students from three universities. The empirical validation results were analyzed using the Rasch model to examine the instrument's reliability and validity (Bond, 2015). The small sample size (62 respondents) in this research aligns with Rasch's recommendation that approximately 30–60 respondents can provide reasonably stable parameter estimates for instrument development studies and exploratory analyses, especially when test length and person–item targeting are adequate (Bintang & Suprananto, 2024). Pretest and posttest measurements were conducted using critical thinking and sustainability consciousness instruments, as well as focus group discussions to gain qualitative insights. N-Gain scores were calculated to assess improvements in student learning outcomes, and t-tests were used to compare pre- and post-intervention results.

RESULTS AND DISCUSSION

This research has successfully developed Project-Based STEM-ESD teaching materials with a water theme, integrated with strengthening SDG 4, aiming to improve students' critical thinking skills and sustainability awareness. The teaching materials have been validated by experts, with validation scores indicating high feasibility, and have received input for improvement. Limited implementation with science students shows that the teaching materials meet the needs of contextual and project-based science learning.

The needs assessment phase before the intervention was conducted by analyzing literature, reports, lecturers' perceptions, and observations of the "Seputar Kita" (Nearby Science) lectures. This demonstrated the importance of strengthening ESD integration in the learning process to improve students' critical thinking skills and sustainability consciousness.

The design and development stage was carried out for the PjBLSTEM-ESD task, critical thinking questions, and the sustainability awareness questionnaire. The results of the PjBLSTEM task are shown in Figure 1. The expert's input for task improvement included emphasizing certain important sections by bolding them to draw students' attention. However, there was no general feedback on the instrument; only improvements to the formatting of some questions. All of this input was implemented, resulting in an instrument suited for field testing with students.

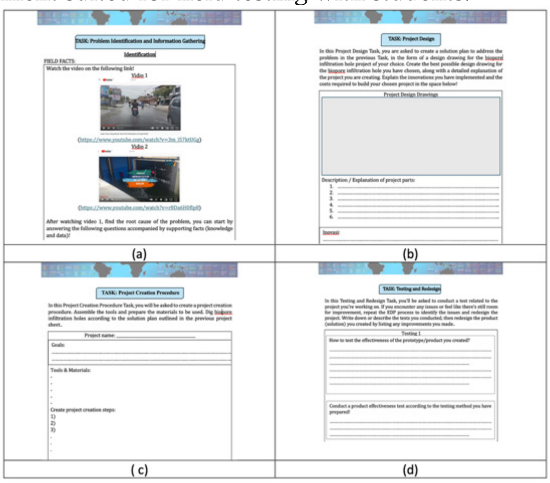

Figure 1. PjBLSTEM-ESD Task Design

Experts validated the instruments in this study. The expert validation results were analyzed using the Fuzzy Delphi Method (FDM) to develop valid, relevant water-themed learning indicators based on expert consensus. There are six steps in the FDM process: 1) Initial design and data collection, 2) Selection of an expert panel, 3) Preparation and testing of the Fuzzy Delphi questionnaire, 4) Consensus iteration process, 5) Data analysis and preparation of results, and 6) Validation and reporting. The Fuzzy Scale, a 5-point scale derived from the Likert Scale, was used in the second step of the linguistic selection process to assess expert agreement, as shown in Table 1 (Jaya et al., 2022; Badin & Hamid, 2023). The Fuzzy Scale assigns a fuzzy value to each Likert scale value, ranging from 0 to 1, enabling more accurate analysis of expert opinion.

Table 1. Fuzzy Scale – 5 Point Scale

Level of Agreement	Likert Scale	Fuzzy Scale		
Strongly Agree	5	0,6	0,8	1
Agree	4	0,4	0,6	0,8
Unsure whether to agree or disagree	3	0,2	0,4	0,6
Disagree	2	0	0,2	0,4
Strongly Disagree	1	0	0	0,2

In the Fuzzy Delphi method, an item or element can only be accepted if it meets several validity criteria. First, the threshold value (‘d) between the average fuzzy numbers must be less than 0.2, as it indicates that the experts have reached spatial agreement on the item. Second, to assess majority agreement, the percentage of consensus among experts must reach or exceed a minimum threshold, typically above 75%. Third, to ensure that the item has sufficient quantitative evidence, the defuzzification value or average fuzzy score of the experts’ responses must be above the α-cut value (usually “α-cut ≥ 0.5”) (Yusoff et al., 2021; Abdul Rahman et al., 2021). Fourth, this process must involve a panel of experts with appropriate experience, expertise, and academic backgrounds. There were 10 experts in science education. The results of the FDM analysis for the PjBLSTEM-ESD task instrument, critical thinking skills, and sustainability awareness are shown in Tables 2, 4, and 5 below.

Table 2. Functionality of the Task of PjBLSTEM-ESD based on Fuzzy Delphi Methods (FDM) Analysis

Number of Experts	Item	Fuzzy Triangle Conditions		Fuzzy Evaluation Process Requirements				Expert Agreement	Item received	Ranking
		Value d	% Expert Agreement	m1	m2	m3	Fuzzy Score (A)			
10	1	0,00	100	0,60	080	1,00	0,80	Accept	0,80	1
	2	0,00	100	0,60	080	1,00	0,80	Accept	0,80	2
	3	0,00	100	0,60	080	1,00	0,80	Accept	0,80	3
	4	0,00	100	0,60	080	1,00	0,80	Accept	0,80	4
	5	0,00	100	0,60	080	1,00	0,80	Accept	0,80	5
	6	0,00	100	0,60	080	1,00	0,80	Accept	0,80	6
	7	0,00	100	0,60	080	1,00	0,80	Accept	0,80	7
	8	0,00	100	0,60	080	1,00	0,80	Accept	0,80	8
	9	0,00	100	0,60	080	1,00	0,80	Accept	0,80	9
	10	0,00	100	0,60	080	1,00	0,80	Accept	0,80	10
	11	0,00	100	0,60	080	1,00	0,80	Accept	0,80	11
	12	0,00	100	0,60	080	1,00	0,80	Accept	0,80	12

The PjBLSTEM-ESD task, which has been declared valid by experts, was then implemented for Science Education students. The implementation of the task for the Science Around Us course used the PjBLSTEM-ESD model to train students’ critical thinking skills and sustainability awareness. Table 3 presents a guide to student learning activities in the “Science Around Us” course using the PjBL-STEM-ESD assignment approach. Table 3 summarizes the activity stages, the learning objectives for each phase, and concrete tasks students must complete. By following this guide, the learning process is expected to be structured, encouraging student activeness, collaboration, and creativity in completing assignments, while simultaneously integrating the STEM approach and awareness of the principles of continuing education (ESD). Thus, Table 3 serves as an important reference for more systematic learning and relevance to the needs of the 21st Century.

Table 3. Student Activity Guide for the Science Around Us Lecture using the PjBLSTEM-ESD Task

Weeks	PjBLSTEM-ESD Syntax	Task PjBLSTEM-ESD	Student Activities
1	Pre test	-	Students work on pretest questions
2	Identifying the Problem and Launching the Project	**Problem identification** and information gathering tasks	Students are trained to identify real-world problems relevant to the theme (ESD) through field observations. This process encourages them to think critically by sorting relevant information, connecting theory to real-world phenomena, and asking reflective questions that lead to problem-solving
3	Building Knowledge, Understanding, and Skills	Problem identification and information gathering tasks	Students build the knowledge, understanding, and skills needed to complete projects
4	Developing and revising ideas and Product Based on STEM and ESD principles	Project design task	Students develop analytical and evaluative thinking skills as they plan projects. They must consider technical aspects, sustainability, and implementation feasibility in their designs. They are also challenged to make decisions based on a range of possible solutions.
		Task procedure for creating a project	Students must be able to translate their designs into concrete implementation, considering procedural effectiveness, material efficiency, and other supporting factors. They also conduct risk analysis and problem-solving when facing technical obstacles during the project development process.
		Trial and redesign tasks	Students test their project results using scientific methods, analyze the results, and evaluate the effectiveness and efficiency of the products they create. They are also trained to think reflectively, identify project shortcomings, and determine improvement strategies.
5	Presenting Product and Answer to Driving Question	-	Students present the results of the projects they have worked on
6	Posttest		Students work on posttest questions.

The "Science Around Us" learning syntax Table, which is based on PjBL-STEM-ESD, thoroughly illustrates how each stage of the learning process is designed to provide comprehensive experiences and skills relevant to 21st-century demands. In the initial stage, a pretest serves as a diagnostic tool, mapping students' initial understanding, enabling teachers to adjust teaching strategies for greater effectiveness. The problem identification and information-gathering process in the second and third weeks emphasizes the importance of direct observation and reflective thinking, encouraging students to connect theory to facts in their immediate environment. This stage is crucial for improving critical reasoning skills, sorting relevant information, and developing insights into sustainability issues.

Furthermore, as students enter the design and revision phase of a product grounded in STEM and ESD principles, they face the real-world challenge of applying their knowledge practically through a solution or prototype. Students learn to analyze technical feasibility and material efficiency, identify risks, and solve problems that may arise during project implementation. Experimentation, refinement, and reflection on the results not only develop scientific skills and evaluative thinking but also encourage students to take responsibility for the decisions made during the learning process.

The project presentation phase provides students with the opportunity to practice scientific communication skills, answer key questions, and present their processes and outcomes to others, fostering self-confidence and argumentation skills. At the end of the activity, a post-test is used to measure improvements in knowledge and skills after the entire series of activities has been completed. Thus, this syntax focuses not only on the outcome but also on the process of developing soft skills—such as collaboration, creativity, and critical thinking—as well as on integrating sustainability values, all of which are essential in modern project-based education.

Table 4 below presents the results of the Functionality of the Critical Thinking Skills Instrument analysis using the Fuzzy Delphi (FDM) method. This Table shows the instrument's validity level and experts' assessment of the function and feasibility of each critical thinking skill indicator developed. The FDM analysis was used to obtain consensus and assess the importance of each indicator through a multi-experiment evaluation process. Thus, the resulting instrument can be optimally used to measure critical thinking skills in a relevant educational context.

Table 4. Functionality of the Critical Thinking Skills Instrument based on Fuzzy Delphi Methods (FDM) Analysis

Number of Experts	Item	Fuzzy Triangle Conditions		Fuzzy Evaluation Process Requirements				Expert Agreement	Item received	Ranking
		Value d	% Expert Agreement	m1	m2	m3	Fuzzy Score (A)			
10	1	0,11	90	0,56	0,76	0,96	0,76	Accept	0,76	9
	2	0	100	0,6	0,8	1	0,80	Accept	0,80	1
	3	0,05	100	0,58	0,78	0,98	0,78	Accept	0,78	6
	4	0,09	90	0,56	0,76	0,96	0,76	Accept	0,76	10
	5	0,09	90	0,56	0,76	0,96	0,76	Accept	0,76	11
	6	0	100	0,6	0,8	1	0,80	Accept	0,80	2
	7	0,05	100	0,58	0,78	0,98	0,78	Accept	0,78	7
	8	0,12	90	0,6	0,8	1	0,78	Accept	0,78	8
	9	0,09	80	0,56	0,76	0,96	0,76	Accept	0,76	12
	10	0	100	0,6	0,8	1	0,80	Accept	0,80	3
	11	0	100	0,6	0,8	1	0,80	Accept	0,80	4
	12	0	100	0,6	0,8	1	0,80	Accept	0,80	5

Based on the information presented in Table 4, there is a slight variation in the level of consensus, ranging from 80% to 100%. However, the difference in d values between experts is minimal (0.00-0.12). Items with a level of expert agreement of 100% and d = 0.00 (such as items 2, 6, 10, and 12) indicate absolute agreement with no disagreement in expert interpretation. In contrast, items with d = 0.12 and a 90% confidence interval (such as item 8) indicate that consensus remains strong enough to be accepted despite slight differences in perception. The defuzzification scores (A) for all items are below 0.76, indicating that all items have substantial quantitative support and are above the commonly used minimum α threshold. In practice, items with an A score of 0.80, such as items 2, 6, 10, and 11, can be considered the "strongest" or most agreed-upon part of the instrument, and therefore worthy of prioritization in instrument development and use. Conversely, an item with an A score of 0.76 may still be acceptable. However, its relative weaknesses may need to be addressed in subsequent development, such as clarifying wording or meaning. Overall, these results indicate that the instrument has adequate stability and internal consistency based on the FDM method. According to research (Atarhim et al., 2023; Ocampo, 2023), the use of the Fuzzy Delphi Method (FDM) for instrument validation ensures that each item meets internal consistency and stability thresholds, such as an α-cutoff of >0.5 and a consensus of ≥75%. All results indicate that the instrument performs stably and consistently. These results also suggest that researchers can use this component to safely assess their critical thinking skills.

Table 5 below describes the function of the Sustainability Consciousness instrument based on an analysis using the Fuzzy Delphi (FDM) method. This Table shows the level of agreement and validity of the indicators reviewed by experts, ensuring the instrument can be used effectively to measure sustainability consciousness.

Table 5. Functionality of the Sustainability Consciousness Instrument based on Fuzzy Delphi Methods (FDM) Analysis

Number of Experts	Item	Fuzzy Triangle Conditions		Fuzzy Evaluation Process Requirements				Expert Agreement	Item received	Ranking
		Value d	% Expert Agreement	m1	m2	m3	Fuzzy Score (A)			
	1	0,098	80	0,560	0,760	0,960	0,760	Accept	0,760	29
	2	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	1
	3	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	18
	4	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	19
	5	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	20
	6	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	21
	7	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	22
	8	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	23
	9	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	2
	10	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	24
	11	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	3
	12	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	4
	13	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	5
	14	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	6
10	15	0,098	80	0,560	0,760	0,960	0,760	Accept	0,760	30
	16	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	25
	17	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	7
	18	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	8
	19	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	9
	20	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	10
	21	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	26
	22	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	27
	23	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	11
	24	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	12
	25	0,055	90	0,580	0,780	0,980	0,780	Accept	0,780	28
	26	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	13
	27	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	14
	28	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	15
	29	0,055	90	0,580	0,780	0,980	0,780	Accept	0,800	16
	30	0,000	100	0,600	0,800	1,000	0,800	Accept	0,800	17

Table 5 clearly shows that most sustainability consciousness instruments achieved a defuzzification score of A = 0.800, indicating the "highest" position and the strongest consensus among experts. Collectively, these highest-scoring items are considered highly valid and stable because they represent the elements of sustainability awareness most widely recognized by experts. However, some items, such as items 1 and 15, have lower A scores of 0.760. While these items still fall into the "Accept" category, their scores indicate that experts viewed them differently—that is, their meaning, wording, or scope may be less precise than other items.

From a practical perspective, items with a score of 0.800 should serve as a solid foundation and primary reference source when developing scales or questionnaires in the field. This is because these items demonstrate the highest levels of measurement and inter-respondent consistency comparable to expert opinion. Conversely, items with a score of 0.760 may be suitable for definition refinement or editorial revision before widespread use to reduce ambiguity. For example, researchers could pilot-test respondents to assess their understanding of the topic, or conduct qualitative interviews to identify aspects of the topic that lead to differing interpretations among experts. Overall, the results of this Fuzzy Delphi validation indicate that the sustainability awareness tool has a strong foundation. However, further efforts are needed, particularly to revise items with slightly low defuzzification scores, and to conduct field (pilot) testing to assess empirical validity and reliability in the target population.

Following expert construct validation, the instrument for critical thinking skills and sustainability consciousness was also empirically validated with 60 science education students from various campuses in Pekanbaru. Based on the Rasch analysis, the reliability score of the critical thinking skills instrument item was 0.74, indicating that the instrument's validity was in the moderate category. The results of the Rasch analysis for each item are shown in Tables 4 and 5 below. In the Rasch model, an item is considered acceptable if it meets several diagnostic criteria. The infit and outfit mean square (MNSQ) values are close to 1 (usually in the range of ±0.5 to 1.5, or with a narrow tolerance, depending on the context). The Z-standardized fit (ZSTD) shows no significant deviation (usually in the range of around ±2), indicating that the item response pattern is consistent with the model's predicted behavior (neither too random nor too deterministic) (Hayat et al., 2020; Abdellatif, 2023). Point-Measure Correlation (PT-Measure Correlation, also known as "item-person correlation" or "item polarity") measures whether items "run" in the same direction as the latent trait. Items must have a sufficiently high positive correlation. A standard threshold is greater than 0.4–0.85.

Table 6 below presents the order of suitability of each item on the critical thinking skills instrument based on a fit-order analysis. This Table shows the results of the item fit test against the measurement model, allowing us to determine which items are most appropriate for accurately and reliably measuring critical thinking skills.

Table 6. Output Item Fit Order Critical Thinking Skills Instrument

Entry Number	Total Score	Total Count	Measure	Model S.E.	Infit		Outfit		PTMeasure		Exact Match		Item
					MNSQ	ZSTD	MNSQ	ZSTD	CORR	EXP		EXP%	
10	60	62	-1.27	.74	1.09	.35	1.90	1.10	A .14	.24	93.9	93.9	S10
5	45	62	1.85	.38	1.33	2.26	1.42	2.47	B .51	.65	54.5	66.6	S5
4	54	62	.47	.43	1.20	.95	1.28	.91	C .36	.47	69.7	76.6	S4
1	45	62	1.85	.38	1.06	.49	1.15	1.00	D .62	.65	66.7	66.6	S1
2	59	62	-.81	.62	1.06	.28	.84	-.01	E .28	.30	90.9	90.8	S2
9	55	62	.27	.45	.83	-.68	.66	-.96	e .54	.44	81.8	79.2	S9
11	58	62	-.46	.55	.81	-.41	.50	-.91	d .45	.34	87.9	87.8	S11
12	58	62	-.46	.55	.81	-.41	.50	-.91	c .45	.34	87.9	87.8	S12
3	57	62	-.18	.51	.80	-.58	.58	-.88	b .49	.38	84.8	84.7	S3
7	60	62	-1.27	.74	.80	-.16	.33	-.76	a .37	.24	93.9	93.9	S7
MEAN	56.3	62.0	-.54	.75	.98	.2	.91	.1			81.2	82.8	
P.SD	5.5	.0	1.56	.49	.18	1.1	.48	1.1			12.6	9.7	

Based on the Item Fit results shown in Table 6, the MNSQ infit and outfit scores are within tolerable ranges, while the Z-STD is not extreme. Most critical thinking skills instruments demonstrate adequate fit with the Rasch model. Entry 10 and several other items demonstrate excellent balance, with corresponding OBS% and EXP% percentages. In contrast, Entry 5 is noteworthy for its significant difference between OBS% and EXP%, as well as for its relatively high outfit and Z-STD scores, both of which exceed the criterion. The scores indicate greater variation in respondents' perceptions than the model predicts. However, this item was retained because the MNSQ infit and Point-Measure Correlation (PT-Measure Corr) continue to match the criterion. Furthermore, location (measure) estimates indicate that some items are perceived as "easier" (negative values) and others as "more difficult" (positive values), resulting in a wide range of difficulty levels. To ensure construct alignment and instrument sensitivity, items with low fit deviations or correlations should be reviewed editorially or retested in a field context, while all components should be retained.

Table 7 below displays the order of suitability for each item in the Sustainability Consciousness instrument based on the fit-order analysis results. This Table presents the most appropriate and valid items for measuring sustainability consciousness based on the measurement model used in the research.

Table 7. Output Item Fit Order Sustainability Consciousness Instrument

Entry Number	Total Score	Total Count	Measure	Model S.E.	Infit		Outfit		PTMEASUR		Exact Match		Item
					MNSQ	ZSTD	MNSQ	ZSTD	CORR	EXP	0BS%	EXP%	
30	223	62	1.13	.15	1.26	1.29	1.32	1.48	.62	.69	37.3	48.0	S30
28	233	62	.88	.16	1.68	2.89	1.82	3.11	.53	.69	32.2	49.0	S28
8	245	62	.56	.17	1.33	1.52	1.19	.84	.66	.68	62.7	51.0	S8
29	245	62	.56	.17	.96	-.15	1.12	.58	.67	.68	55.9	51.0	S29
26	246	62	.53	.17	1.33	1.52	1.86	3.04	.59	.68	55.9	51.0	S26
27	250	62	.41	.18	.86	-.63	.93	-.22	.70	.67	59.3	53.0	S27
12	257	62	.18	.18	1.26	1.19	1.23	.92	.64	.67	54.2	53.9	S12
25	258	62	.15	.18	1.10	.54	1.30	1.15	.65	.67	57.6	54.0	S25
15	260	62	.08	.19	.71	-1.44	.67	-.1.34	.73	.66	66.1	55.5	S15
22	260	62	.08	.19	.68	-1.67	1.16	.66	.72	.66	59.3	55.5	S22
18	261	62	.04	.19	.84	-.73	.99	.06	.70	.66	66.1	56.8	S18
21	261	62	.04	.19	.63	-1.94	.74	-1.00	.74	.66	64.4	56.8	S21
16	262	62	.01	.19	.92	-.33	.92	-.23	.70	.66	72.9	57.1	S16
20	262	62	.01	.19	.86	-.64	1.08	.39	.69	.66	67.8	57.1	S20
5	263	62	-.03	.19	1.21	.98	1.03	.19	.63	.66	54.2	57.7	S5
9	263	62	-.03	.19	.61	-2.04	.57	-1.81	.75	.66	72.9	57.7	S9
17	264	62	-.07	.19	.52	-2.70	1.26	.98	.72	.66	69.5	57.9	S17
23	264	62	-.07	.19	.55	-2.43	.65	-1.38	.75	.66	69.5	57.9	S23
11	265	62	-.10	.19	.76	-1.17	.77	-.79	.69	.66	61.0	58.1	S11
14	265	62	-.10	.19	.88	-.50	.94	-.12	.69	.66	69.5	58.1	S14
19	266	62	-.14	.20	.58	-2.24	.66	-1.28	.74	.65	71.2	58.7	S19
24	267	62	-.18	.20	1.01	.10	1.03	.20	.68	.65	69.5	58.9	S24
6	268	62	-.22	.20	1.43	1.83	1.16	.63	.59	.65	71.2	58.9	S6
7	269	62	-.26	.20	1.61	2.46	1.32	1.08	.55	.65	57.6	60.5	S7
10	270	62	-.30	.20	.57	-2.32	.50	-1.95	.74	.65	72.9	60.7	S10
4	271	62	-.34	.21	1.34	1.48	1.06	.30	.57	.65	54.2	60.9	S4
13	271	62	-.34	.21	1.25	1.13	1.00	.11	.64	.65	62.7	60.9	S13
1	275	62	-.52	.21	1.45	1.84	2.46	3.32	.56	.64	62.7	61.9	S1
3	280	62	-.76	.23	1.07	.35	.77	-.57	.63	.63	64.4	65.3	S3
2	287	62	-1.18	.26	1.15	.63	.96	.05	.57	.61	67.8	73.9	S2
MEAN	261.0	62.0	.00	.19	1.01	.0	1.08	.3			62.1	57.3	
P.SD	12.7	.0	.45	.02	.33	1.6	.40	1.3			9.4	5.0	

During the instrument validation process, 68 respondents from three universities in Indonesia enrolled in the Science Education program, participated in the validity and reliability testing of each indicator item developed. This diverse range of respondents ensured that the instrument validation results reflected the diverse characteristics of potential users at the university level. Based on the analysis, all instrument items were found to be valid and suitable for measuring the targeted aspects in the science education environment. Furthermore, in the implementation or initial pilot phase, the instrument was administered to 28 students to identify its effectiveness and acceptability in a real-life learning context. Thus, the instrument underwent a comprehensive validation process and initial implementation testing before being used more widely.

The quantitative results of the initial (pretest) critical thinking skills and the quantitative results of the final test after implementation, as well as the increase in each student's critical thinking skill score, were analyzed using N-Gain, as shown in Table 8 below.

Table 8. N-Gain Critical Thinking Skills Score

Students	Pretest Score	Posttest Score	Max Score	N Gain	Category
Student 1	8	16	24	0.50	Medium
Student 2	0	16	24	0,67	Medium
Student 3	8	14	24	0,38	Medium
Student 4	14	16	24	0,20	Low
Student 5	8	10	24	0,13	Low
Student 6	7	16	24	0,53	Medium
Student 7	11	18	24	0,54	Medium
Student 8	0	10	24	0,42	Medium
Student 9	0	13	24	0,54	Medium
Student 10	8	14	24	0,38	Medium
Student 11	10	14	24	0,29	Low
Student 12	10	14	24	0,29	Low
Student 13	9	10	24	0,07	Low
Student 14	7	14	24	0,41	Medium
Student 15	10	14	24	0,29	Low
Student 16	0	14	24	0,58	Medium
Student 17	12	16	24	0,33	Medium
Student 18	9	14	24	0,33	Medium
Student 19	0	4	24	0,17	Low
Student 20	10	18	24	0,57	Medium
Student 21	10	16	24	0,43	Medium
Student 22	0	16	24	0,67	Medium
Student 23	10	16	24	0,43	Medium
Student 24	12	18	24	0,50	Medium
Student 25	12	12	24	0,00	Low
Student 26	0	10	24	0,42	Medium
Student 27	0	16	24	0,67	Medium
Student 28	4	8	24	0,20	Low

Table 8 shows that most participants experienced an increase in critical thinking skills after the intervention, with N-Gain values in the moderate range (0.30 ≤ N-Gain ≤ 0.70). This finding indicates the relative effectiveness of the PjBLSTEM-ESD model in promoting cognitive change in students. However, there was variability in achievement between individuals, with some students showing high achievement (N-Gain up to 0.67) and others in the low category (N-Gain 0.00, 0.07, 0.13). This reflects the heterogeneity of the intervention effect, possibly influenced by pretest factors, learning motivation, cognitive style, and level of engagement during the active learning process (Fatmawati et al., 2025). Further discussion confirmed that active learning strategies such as guided inquiry and cognitive conflict generally resulted in moderate improvements in critical thinking skills, but did not necessarily lead participants to achieve universally high levels of achievement (Naderi et al., 2022; Shockden & Onyejekwe, 2025; Huang, 2025). This highlights the need for instructional differentiation to accommodate learners' diverse characteristics. Adapting instruction, providing additional interventions for learners with lower developmental levels, and providing metacognitive support during learning are key strategies for maximizing all learners' achievement at higher critical levels (Martin & Bolliger, 2022).

Building on these findings, implementing innovative learning models, such as PjBL-STEM-ESD, must be consistently supported by school policies that encourage instructional adaptation and individual progress monitoring. Reflective-metacognitive concepts and data-driven instructional support can facilitate more equitable and effective growth in critical thinking, while contributing to the implementation of 21st-century learning that is inclusive and responsive to sustainability needs (Almulla, 2020).

The increase in each student's sustainability consciousness score was analyzed using N-Gain, as shown in Table 9 below.

Table 9. N-Gain Sustainability Consciousness Score

Students	Pretest Score	Posttest Score	Max Score	N Gain	Category
Student 1	111	119	150	0,21	Low
Student 2	120	126	150	0,20	Low
Student 3	104	113	150	0,20	Low
Student 4	104	131	150	0,59	Medium
Student 5	127	129	150	0,09	Low
Student 6	96	118	150	0,41	Medium
Student 7	108	128	150	0,48	Medium
Student 8	118	135	150	0,53	Medium
Student 9	108	113	150	0,12	Low
Student 10	114	123	150	0,25	Low
Student 11	121	127	150	0,21	Low
Student 12	104	121	150	0,37	Low
Student 13	111	129	150	0,46	Medium
Student 14	98	106	150	0,15	Low
Student 15	105	107	150	0,04	Low
Student 16	118	121	150	0,09	Low
Student 17	128	130	150	0,09	Low
Student 18	106	121	150	0,34	Medium
Student 19	116	126	150	0,29	Low
Student 20	143	145	150	0,29	Low
Student 21	96	121	150	0,46	Medium
Student 22	97	106	150	0,17	Low
Student 23	136	144	150	0,57	Medium
Student 24	141	145	150	0,44	Medium
Student 25	130	132	150	0,10	Low
Student 26	65	115	150	0,59	Medium
Student 27	75	75	150	0,00	Low
Student 28	102	128	150	0,54	Medium

Most students experienced an increase in scores on the sustainability consciousness measure from pretest to posttest, as shown in Table 9. However, most of the improvements are in the Low category based on their N-Gain scores, indicating that the increase relative to the maximum potential is still slight. Only a small proportion of students are in the Medium category, indicating that the efforts undertaken have not yet achieved a broad transformation in sustainability consciousness. Furthermore, there are some extreme situations. For example, students who started with very low scores showed significant improvement, resulting in a high N-Gain; conversely, students with high initial scores had little opportunity to improve, resulting in a low N-Gain.

This phenomenon suggests that students with high initial scores experience a ceiling effect, in which they struggle to achieve significant improvement because they are already close to the maximum score. Conversely, students with relatively low initial scores are more likely to experience substantial improvement if the intervention is well implemented. Therefore, to further develop sustainability education interventions, a more segmented approach is required (Pada et al., 2025), as well as the integration of sustainability values into the curriculum, intensive training for teachers, and the use of innovative learning media (Andriansyah et al., 2025). These strategies may include supplemental materials, differential scaffolding, or personalized approaches for students already at intermediate to advanced levels to allow them to develop further. In contrast, students with lower scores may require reinforcement of basic concepts and initial motivation. Learning outcomes were analyzed quantitatively to evaluate the effect of the STEM-ESD integrated project-based learning model on students' critical thinking skills and sustainability consciousness. The Kolmogorov-Smirnov normality test indicated that the data for both variables were normally distributed (Asymp. Sig. = 0.099 for critical thinking skills and 0.200 for sustainability consciousness; $p > 0.05$), allowing further analysis with a paired-samples t-test.

The t-test results showed statistically significant improvements in both domains after the learning intervention. For critical thinking skills, the Sig. (2-tailed) value = $0.001 < 0.05$, indicating a significant difference between pretest and posttest scores. Similar findings were also obtained for sustainability consciousness (Sig. (2-tailed) = $0.001 < 0.05$), indicating that implementing the PjBLSTEM-ESD model effectively increased students' understanding and consciousness of sustainability issues. In critical pedagogy, STEM-PBL integrated EDP can be used to systematically develop students' STEM literacy and thinking skills through engineering design thinking processes, thereby broadening students' cognitive development and perspectives and reducing reliance on routine practices in conventional pedagogy (Abdurrahman et al., 2023).

These results confirm the effectiveness of the PjBLSTEM–ESD approach in developing higher-order thinking skills while building students' ecological awareness. Theoretically, these findings support previous views that PjBL encourages collaborative, interdisciplinary, iterative, and authentic learning (Almulla, 2020), thereby strengthening students' cognitive and affective engagement. The implication is that integrating PjBL, STEM, and ESD principles can provide a practical framework for 21st-century education focused on developing sustainable competencies and responsibilities.

Qualitative data from student reflections and focus group interviews further supported the quantitative findings. Students reported that engaging in authentic, interdisciplinary projects helped them better understand the complexities of sustainability issues and apply scientific knowledge in meaningful contexts. The most important insights emerging from this study were real-world relevance, critical thinking through group work, and increased consciousness and responsibility for sustainability issues. 1) Real-World Relevance. Students stated that working on sustainability-themed projects made learning more relevant and motivating. They appreciated the opportunity to address real social problems through their projects. 2) Collaborative Reasoning and Perspective-Taking. Group work facilitated dialogue, debate, and negotiation of ideas. Many students noted that this process improved their ability to think critically and consider multiple perspectives before making decisions. 3) Increased Consciousness and Responsibility for Sustainability. Participants described a heightened sense of responsibility for environmental and social issues. Several students reported changes in their personal behavior, such as using clean water more effectively, digging their own biopore holes at home, and initiating sustainability campaigns on campus. One student stated:

"This project made me realize that sustainability is not just about nature, but also about how we live, how we consume, and how we collaborate with others to solve problems".

These findings confirm the effectiveness of the integrated PjBLSTEM-ESD model in enhancing critical thinking and sustainability awareness, thereby filling a gap left by previous research that tends to separate the STEM and ESD domains (Guo et al., 2020; Sihombing et al., 2024). Unlike previous research (Purnamasari et al., 2024; Jang, 2022) that focuses solely on creativity or cognitive skills, this study shows that integrating STEM and ESD project-based learning in higher education produces synergistic effects across two domains: cognitive and affective. Furthermore, instrument validation using Fuzzy Delphi and Rasch demonstrates methodological progress compared to previous approaches (Amanova et al., 2025; Badin & Hamid, 2023), providing robust and appropriate measures for cross-disciplinary assessment in a sustainability-focused context. Qualitative data underscores the importance of real-world relevance and collaborative reasoning:

1. Students highlighted increased engagement through authentic projects, critical argumentation, and ongoing responsibility through group awareness (Zhang et al., 2023).
2. Projects change personal behavior, reflecting the affective impacts (Almulla, 2020).

Through task-based PjBL methods, integrating STEM with ESD enables students to consider values such as social, economic, and environmental impacts. They also learn scientific logic and analysis (Barbiéri et al., 2023). Therefore, critical thinking is integrated into the project-related decision-making process, not simply an abstract exercise. This aligns with previous research showing that PjBL-STEM improves students' critical thinking and creativity (Zulyusri et al., 2023; Chistyakov et al., 2023). A narrative review of 19 articles over five years found that project-based learning strategies are effective in enhancing students' critical and creative thinking skills, particularly through syntactic steps such as essential questions, collaborative planning, timelines, and deadlines. PjBL effectively improves students' learning outcomes and critical thinking skills in science and STEAM contexts. This is supported by other studies, which found that the project-based learning process using orange peels and banana waste as coagulants has successfully strengthened STEM students' critical thinking skills in water treatment, with the result that the banana coagulant is more effective at reducing turbidity. Both coagulants met the South African SANS241 standard for drinking water quality (Oyewo et al., 2022). It can be concluded that PjBL has been proven in higher education to improve student learning outcomes in the affective, cognitive, and behavioral domains through various measurement tools, including questionnaires, interviews, observations, rubrics, tests, artifacts, self-reflection journals, and data records. However, future research is needed to deepen the understanding of the student learning process and its outcomes (Guo et al., 2020).

Students involved in projects with a sustainability context are more aware that advances in science and technology have social and environmental consequences. Real-world projects allow students to learn more about waste, conservation, energy efficiency, and social responsibility. This furthers the goal of higher education to produce sustainable citizens and competent graduates. Previous research has focused more on enhancing students' creativity or critical thinking (Purnamasari et al., 2024) and found that implementing the PjBL model with ESD during five meetings increased students' creative thinking skills with an average N Gain of 0.58 (medium category), compared to the control group with an N Gain of 0.25 (low category), but relatively few measured students' sustainability consciousness directly.

However, recent findings suggest that PjBL based on ESD can indeed train sustainability-related competencies. PjBL ESD is a practical learning innovation that improves critical thinking skills and strengthens local wisdom values(Vilmala et al., 2025)—based on (Setiawan et al., 2023). Indonesian students participating in the ESD-PjBL project experienced significant changes in their mindsets, daily sustainable practices, and pro-environmental values, as evidenced by reflective journals, observations, and campaign activities. Complementary results were found in STEM implementation, which has introduced an effective interdisciplinary education model that equips students with 21st-century skills, particularly in addressing global challenges such as climate change and the SDGs. STEM for Sustainability (STEM4S) encourages the integration of multidisciplinary curricula and design-based assignments that facilitate critical thinking and problem-solving. This research formulates a design education framework that integrates problem- and project-based learning with the double diamond model for innovation, as implemented at National Taiwan Normal University. Qualitative and quantitative analyses were conducted to evaluate the implementation and future application prospects of the STEM4S framework (Chan & Nagatomo, 2022). At the higher education level, Espino-Díaz et al. (2025)

found that the PjBL-SDG module increased students' awareness and personal growth towards the SDGs, while Rahmawati et al. (2025) reported that STEAM-PBL combined with design thinking fosters environmental literacy and active engagement in sustainability issues. Together, these findings strengthen the conclusion that integrating ESD. Further research on PjBL-STEM-ESD has been conducted with junior high school students. However, the science teacher profile related to SDGs-based theory and practice shows a high category, with an average score percentage of 81.5% for the knowledge aspect, 85.63% for the attitude aspect, and 80.88% for the practice aspect, indicating that continuous efforts are still required to strengthen comprehensive understanding that can be integrated into science learning in schools (Vilmala et al., 2022). Likewise, teachers' perceptions of ESD-integrated STEM: they have heard about it but do not know how to implement it in classroom learning (Vilmala et al., 2022). The development of STEM-based teaching materials—Project-Based Learning (PjBL) on the subject of environmental pollution—has been demonstrated to enhance students' critical thinking skills and sustainability consciousness, as evidenced by the validation results, which show a feasibility percentage of 85% for critical thinking skills assessment and 97% for sustainability consciousness, both of which are classified as very feasible. These findings indicate that integrating the PjBL-STEM model and the ESD approach into science learning in junior high schools is effective in facilitating teachers in implementing the principles of sustainable education more effectively(Setyowati et al., 2022). Theoretical implications highlight the integration of cognitive, emotional, and interdisciplinary aspects in PjBL for holistic development, while operational implications emphasize institutional support, teacher training, and flexible curriculum policies (Sánchez-García & Reyes-de-Cózar, 2025).

CONCLUSION

This research demonstrates that the development and implementation of project-based learning materials using a STEM-ESD approach significantly improve students' critical thinking skills and sustainability consciousness in higher education, as evidenced by statistical tests and a high N-gain. The synthesis of PjBL, STEM, and ESD not only strengthens the achievement of SDG 4 but also encourages collaboration, critical argumentation, and the internalization of sustainability values in students' behavior. These findings underscore the relevance of innovative learning models that respond to the demands of the 21st Century and highlight the importance of instructional differentiation and metacognitive support to accommodate student diversity, ensuring inclusive, effective, and sustainable learning.

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