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The effect of ESD-based problem based learning on grade 10 students' critical thinking skills and sustainability awareness

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ABSTRACT

21st-century learning requires students to develop critical thinking skills and sustainability awareness to address global challenges. Initial observations indicated that students' critical thinking skills ranged from less critical to moderately critical, while sustainability awareness was moderate. This study investigated the effect of ESD-based Problem-Based Learning (PBL) on these two outcomes among Grade 10 students at SMA Pertiwi 1 Padang. A quasi-experimental posttest-only control group design was employed, involving an experimental group receiving ESD-based PBL and a control group receiving the regular learning approach. Data were collected using a critical thinking essay test and a sustainability awareness questionnaire and analyzed using MANOVA. The results showed a significant multivariate effect (Wilks' $\Lambda = 0.285$, $F(2,62) = 77.707$, $p < 0.001$, $\eta^2p = 0.715$). Univariate analysis showed significant effects on critical thinking skills ($F = 152.873$, $p < 0.001$, $\eta^2p = 0.708$) and sustainability awareness ($F = 10.633$, $p = 0.002$, $\eta^2p = 0.144$). The experimental group obtained higher mean scores for critical thinking (78 vs. 52) and sustainability awareness (79 vs. 72). These findings indicate that ESD-based PBL was associated with higher critical thinking skills and sustainability awareness, although the findings are limited to immediate post-intervention outcomes.



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Introduction

21st-century learning is an approach that emphasizes the development of higher order thinking skills, learning skills, and literacy to equip students to face advancements in science and technology, as well as various global challenges. Learning skills include critical thinking, creativity, communication, and collaboration, all of which are essential competencies in 21st-century learning (Handini *et al.*, 2023). Learning requires students not only to master subject matter concepts but also to analyze problems, make rational decisions, and demonstrate concern for various issues occurring in their surrounding environment. Therefore, the development of critical thinking skills and sustainability awareness is a vital component in supporting students' attainment of the competencies needed in the 21st century (Abdurahman *et al.*, 2024).

Critical thinking skills are essential for students to analyze information, evaluate various alternatives for problem-solving, and make decisions based on evidence and logical reasoning. According to Syahputra (2024), learning should no longer be focused solely on mastering subject matter but must also develop essential skills such as critical thinking, creativity, problem solving, and decision making. The importance of developing these

skills is also evident from the results of the Programme for International Student Assessment (PISA), which show that Indonesian students' literacy, numeracy, and science skills remain below the international average (Alfaruqi & Nurwahidah, 2025). This situation highlights the need for a learning process that provides students with opportunities to actively engage in analyzing information and solving real-world problems.

In addition to critical thinking skills, students need to develop sustainability awareness, an understanding of the importance of environmental, social, and economic sustainability. This awareness is becoming increasingly important as various global issues emerge, such as climate change, environmental pollution, the loss of biodiversity, and the exploitation of natural resources. Students are not only expected to understand these issues conceptually but also to demonstrate concern and awareness when considering the impact of their actions on sustainability. Therefore, learning experiences should be designed to develop critical thinking skills while simultaneously fostering students' sustainability awareness. Critical thinking and sustainability awareness are complementary competencies because addressing sustainability problems requires students to analyze complex information and evaluate alternative solutions while considering their environmental, social, and economic consequences.

One educational approach that supports the development of these competencies is Education for Sustainable Development (ESD). ESD is an educational approach that equips students with the knowledge, skills, values, and attitudes necessary to make responsible decisions regarding environmental, social, and economic issues (Taimur *et al.*, 2020; Inayah *et al.*, 2023). Through ESD, learning focuses not only on mastering subject matter but also encourages students to understand the connections between various global issues and their daily lives, thereby enabling them to generate sustainability-oriented solutions. This aligns with Purnama & Hanifah (2021), who state that ESD equips students with the knowledge, skills, values, and attitudes needed to process information, make decisions, and take responsible actions regarding the environment, economic sustainability, and a just society for both current and future generations. Thus, integrating ESD principles into learning is a relevant approach to meeting the demands of 21st-century education.

Based on the results of initial observations and interviews with biology teachers, the learning process still tends to be oriented toward conceptual mastery. Students have been given the opportunity to discuss and present their learning outcomes, but these activities have not yet fully encouraged students to analyze problems in depth, evaluate various alternative solutions, or make decisions based on evidence. Furthermore, real-world issues, particularly those related to climate change, have not been optimally utilized as a learning context. As a result, students are not yet accustomed to identifying problems, analyzing their causes and impacts, developing alternative solutions, or considering the environmental, social, and economic consequences of a decision.

This situation is also related to the implementation of teaching models in schools. Based on interviews with teachers, Problem-Based Learning (PBL) has been implemented in the classroom, but it has not been applied consistently in every lesson and is still limited to specific topics. On the other hand, ESD principles have not yet been systematically integrated into the learning process. This situation highlights the need for a learning model that can combine problem-solving activities with sustainability issues.

Researchers conducted preliminary tests of critical thinking skills and distributed a sustainability awareness questionnaire to Grade 10 students at three high schools. The data from the preliminary observations are presented in the following table.

Table 1. Preliminary Observation Results

Schools	Critical Thinking	Category	Sustainability Awareness	Category
A	36,64	Less Critical	68,36	Moderate
B	55,43	Moderately Critical	68,93	Moderate
C	57,69	Moderately Critical	67,63	Moderate

Based on the table, the average critical thinking skill scores fell into the less critical to moderately critical categories. These results indicate that students' critical thinking skills still need improvement, particularly in analyzing information, evaluating arguments, drawing conclusions, and determining solutions to problems. Meanwhile, the survey results show that the overall average score falls within the moderate category. These results indicate that students' sustainability awareness has begun to develop but still requires reinforcement through learning experiences that connect knowledge to sustainability issues in everyday life.

Given these conditions, a learning model is needed that can provide students with opportunities to actively engage in solving real-world problems while developing an awareness of sustainability. One model that possesses these characteristics is Problem-Based Learning (PBL). PBL uses real-world problems as the starting point for learning and encourages students to conduct investigations, gather information, analyze problems, and develop

solutions. This process transforms students into active learners who not only receive information but also think, search for and process data, and draw conclusions based on the results of their investigations (Amir, 2016; Lismaya, 2019).

Problem Based Learning (PBL) is closely linked to the development of critical thinking skills because, through the problem-solving process, students are trained to identify problems, seek and analyze information, develop solutions, and evaluate the problem solving process (Amaludin, 2022). Previous research has also shown that PBL can enhance critical thinking skills through the use of contextual problems that encourage students to analyze information, evaluate alternatives, and construct arguments based on evidence (Hakimah *et al.*, 2025; Sihotang *et al.*, 2025). However, PBL does not specifically guarantee that the solutions developed take sustainability principles into account. Therefore, the integration of Education for Sustainable Development (ESD) into PBL is necessary so that the problem-solving process also takes into account the interconnections between environmental, social, and economic aspects (Tristananda, 2018; Vioreza *et al.*, 2023). ESD-based PBL enables students to identify and analyze climate change issues, develop solutions, and evaluate the impact of their decisions on sustainability. Thus, this approach provides a pedagogical mechanism through which critical thinking can be applied to authentic sustainability problems while simultaneously fostering sustainability awareness.

Despite the growing body of research on PBL and ESD, studies integrating ESD principles into PBL and simultaneously examining their effects on students' critical thinking skills and sustainability awareness remain limited, particularly in secondary biology education. Previous studies have generally examined these outcomes separately or have used designs that provide limited comparative evidence regarding the effects of an integrated ESD-based PBL approach. This limitation leaves insufficient empirical evidence on whether ESD-based PBL can simultaneously support students' cognitive development and sustainability awareness within the same learning intervention. In the present study, critical thinking skills are operationalized as students' ability to provide simple explanations, build basic skills, draw conclusions, provide further explanations, and formulate strategies and tactics based on Ennis's framework. Sustainability awareness is operationalized through three dimensions: sustainability knowledge, sustainability attitude, and sustainability behavior. Therefore, this study employed a quasi-experimental posttest-only control group design to examine the effect of ESD-based PBL on these two dependent variables among Grade 10 students. The novelty of this study lies in providing comparative empirical evidence on the integrated effect of ESD-based PBL on critical thinking skills and sustainability awareness within a single secondary biology learning context.

Method

This study employed a quantitative quasi-experimental design with a posttest-only control group design. The study was conducted at SMA Pertiwi 1 Padang during the even semester of the 2025–2026 academic year. The population consisted of all Grade 10 students at the school. A purposive sampling technique was used to select intact classes with comparable characteristics based on predefined criteria. The criteria included being taught by the same biology teacher, following the same curriculum and instructional content, and having similar prior academic achievement based on biology assessment scores obtained before the intervention. Thus, comparable academic achievement was determined based on the similarity of students' prior biology assessment scores. These criteria were used to minimize potential differences between the groups before the intervention. Random assignment was not feasible because students were already organized into intact classes by the school. Based on these criteria, class X.E2 was selected as the experimental group ($n = 31$), while class X.E4 was selected as the control group ($n = 34$). The experimental group received Problem-Based Learning (PBL) integrated with Education for Sustainable Development (ESD), whereas the control group received the regular learning approach implemented by the teacher.

In the experimental group, ESD principles were integrated into the PBL stages through climate change issues addressing environmental, social, and economic dimensions. Students were engaged in activities involving the identification and analysis of climate change problems, investigation of their impacts, collaborative development of solutions, and reflection on the sustainability implications of proposed solutions. Thus, ESD integration was operationalized through the incorporation of environmental, social, and economic considerations into the problem identification, investigation, solution development, and reflection activities within the PBL process. The learning process was observed and accompanied by the biology teacher in each session to monitor the consistency of the planned learning activities and the implementation of the PBL stages and ESD components.

The research instruments consisted of a critical thinking skills test in the form of essay questions and a sustainability awareness questionnaire. The critical thinking skills test was developed based on Ennis's indicators, including providing a simple explanation, building basic skills, drawing conclusions, providing further explanations, and formulating strategies and tactics. The sustainability awareness questionnaire was developed based on three indicators: sustainability knowledge, sustainability attitude, and sustainability behavior. Before being used in the main study, both instruments underwent expert validation and empirical testing. The item validity coefficients for both instruments ranged from 0.41 to 1.00, corresponding to validity categories ranging from sufficient to very high. The critical thinking skills instrument demonstrated a Cronbach's alpha coefficient of 0.95, while the sustainability awareness instrument demonstrated a Cronbach's alpha coefficient of 0.90; both were categorized as very high reliability. Items that did not meet the predetermined validity criteria were revised or excluded before data collection.

Research data were collected through a posttest measuring critical thinking skills and a sustainability awareness questionnaire administered after the learning process was completed. Because the study employed a posttest-only design, critical thinking skills and sustainability awareness were not measured before the intervention. Therefore, baseline equivalence for the two dependent variables could not be directly established. Instead, comparability between the experimental and control classes was addressed during purposive sampling based on prior biology assessment scores, together with the use of the same biology teacher, curriculum, and instructional content as selection criteria.

The data were analyzed descriptively and inferentially using IBM SPSS Statistics version 20. Descriptive statistics included the mean, standard deviation, minimum, and maximum scores for each group. Prior to hypothesis testing, the assumptions for MANOVA were examined. Normality was assessed using the Shapiro-Wilk test. The results indicated that the critical thinking skills data were normally distributed in both the experimental group ($p = 0.060$) and the control group ($p = 0.066$). Similarly, the sustainability awareness data were normally distributed in the experimental group ($p = 0.084$) and the control group ($p = 0.072$). Homogeneity of variances was assessed using Levene's test. The results showed homogeneous variances for critical thinking skills ($p = 0.586$) and sustainability awareness ($p = 0.233$). Furthermore, the homogeneity of covariance matrices was examined using Box's M test. The test yielded Box's $M = 2.957$, $F = 0.952$, and $p = 0.415$, indicating that the covariance matrices were homogeneous. Overall, all significance values were greater than 0.05; therefore, the data met the assumptions required for MANOVA.

Results and Discussions

Descriptive Statistics of Students' Critical Thinking Skills and Sustainability Awareness

Table 2 presents the descriptive statistics of students' critical thinking skills and sustainability awareness in the experimental and control groups.

Tabel 2. Descriptive Statistics of Students' Critical Thinking Skills and Sustainability Awareness

Data	Experimental Group		Control Group	
	Critical Thinking Skills	Sustainability Awareness	Critical Thinking Skills	Sustainability Awareness
N	31	31	34	34
Maximum	98	95	68	82
Minimum	61	64	41	51
Mean	78	79	52	72

For critical thinking skills, the experimental group obtained a mean score of 78, with scores ranging from 61 to 98, whereas the control group obtained a mean score of 52, with scores ranging from 41 to 68. Thus, the experimental group had a 26-point higher mean score than the control group. Based on the predetermined performance categories, the experimental group was categorized as critical, whereas the control group was categorized as moderately critical.

For sustainability awareness, the experimental group obtained a mean score of 79, with scores ranging from 64 to 95, while the control group obtained a mean score of 72, with scores ranging from 51 to 82. The experimental group therefore had a 7-point higher mean sustainability awareness score than the control group.

Overall, the descriptive results show that students who received ESD-based PBL obtained higher posttest scores for both critical thinking skills and sustainability awareness than students in the control group. To determine whether these observed differences were statistically significant, a multivariate analysis was subsequently conducted using Multivariate Analysis of Variance (MANOVA).

Effect of ESD-Based PBL on Critical Thinking Skills and Sustainability Awareness

To determine whether ESD-based Problem-Based Learning (PBL) significantly affected students' critical thinking skills and sustainability awareness, the data were analyzed using Multivariate Analysis of Variance (MANOVA). MANOVA was used to examine the simultaneous effect of the learning intervention on the two dependent variables (Maharani *et al.*, 2024) (Riyanto *et al.*, 2026). The results of the multivariate analysis are presented in Table 3.

Table 3. Results of the Multivariate Analysis

<i>Effect</i>	<i>Wilks' Lambda</i>	<i>F</i>	<i>df</i>	<i>Sig.</i>	<i>Partial Eta Squared</i>
Group	0,285	77,707	2; 62	0,0001	0,715

As shown in Table 3, the multivariate analysis revealed a statistically significant effect of group on the combined dependent variables, Wilks' $\Lambda = 0.285$, $F(2, 62) = 77.707$, $p < 0.001$, partial $\eta^2 = 0.715$. This result indicates that ESD-based PBL had a statistically significant effect on the combined outcomes of critical thinking skills and sustainability awareness. The partial eta squared value of 0.715 indicates a large multivariate effect.

Effect of ESD-Based PBL on Each Dependent Variable

Following the significant multivariate result, follow-up univariate analyses were conducted to examine the effect of ESD-based PBL on each dependent variable. The results are presented in Table 4.

Table 4. Univariate Effect of ESD-Based PBL on Each Dependent Variable

<i>Variable</i>	<i>F</i>	<i>Sig.</i>	<i>Partial Eta Squared</i>	<i>Description</i>
Critical Thinking Skills	152,873	0,0001	0,708	Significant
<i>Sustainability Awareness</i>	10,633	0,002	0,144	Significant

As shown in Table 4, ESD-based PBL had a statistically significant effect on students' critical thinking skills, $F = 152.873$, $p < 0.001$, partial $\eta^2 = 0.708$. The partial eta squared value indicates a large effect.

A statistically significant effect was also found for sustainability awareness, $F = 10.633$, $p = 0.002$, partial $\eta^2 = 0.144$. This effect size also falls within the large-effect range. Overall, the univariate results confirm that ESD-based PBL significantly affected both critical thinking skills and sustainability awareness, with a substantially larger effect observed for critical thinking skills than for sustainability awareness.

The Effect of ESD-Based Problem-Based Learning on Students' Critical Thinking Skills

The findings demonstrated that ESD-based Problem-Based Learning (PBL) significantly affected students' critical thinking skills. The experimental group obtained a higher mean score than the control group, with mean scores of 78 and 52, respectively. The univariate analysis confirmed a statistically significant effect of ESD-based PBL on critical thinking skills, $F = 152.873$, $p < 0.001$, with a Partial Eta Squared (η^2p) value of 0.708, indicating a large effect. This finding suggests that the implementation of ESD-based PBL was associated with substantially higher critical thinking outcomes among students in the experimental group.

The finding is consistent with previous empirical studies reporting that PBL can improve students' critical thinking skills through active engagement in problem identification, information analysis, discussion, and solution development. Amin *et al.* (2020), reported that students' critical thinking development was associated with learning activities that encouraged motivation and higher-order thinking. Similarly, Kardoyo *et al.*, (2020) found that student-centered learning can promote active student engagement and improve learning outcomes. This approach provides meaningful learning experiences while helping students develop critical thinking skills optimally (Tanjung & Utami, 2023). Hasna (2023), Fitria *et al.* (2025), dan Gunawan *et al.* (2025) likewise reported that learning approaches involving real-world problems and sustainability-related contexts can support students' abilities to analyze problems, evaluate information, and formulate solutions. More recent evidence further supports the effectiveness of PBL for critical thinking. Fahmi *et al.*, (2026), using a quasi-experimental pretest-posttest control group design involving 45 university students, reported a significant effect of PBL on critical thinking skills ($p < 0.05$). These findings are broadly consistent with the present study,

although differences in participants, educational levels, instructional duration, learning contexts, research designs, and assessment instruments may contribute to differences in the magnitude of the observed effects.

The consistency of these findings is also supported by evidence syntheses. Indriyani *et al.*, (2022) systematically reviewed 24 studies on PBL implementation in Indonesia and found that 12 studies specifically examined critical thinking. Their review indicated that PBL, particularly when supported by student worksheets and other instructional media, was effective in improving students' critical thinking, motivation, and learning outcomes. Similarly, Bonafide *et al.*, (2021) conducted a meta-analysis of 15 studies examining PBL and students' critical thinking skills. The analysis showed that students' critical thinking scores increased by an average of 35.10%, while the effect sizes across the reviewed studies ranged from 0.037 to 1.20. Yohannes *et al.*, (2021) also reported a high pooled effect of PBL on students' mathematical critical thinking skills, with a Hedges' g of 0.970 (95% CI = 0.727–1.214). Their analysis further indicated that treatment duration contributed to differences in effect sizes among studies. Taken together, these findings provide converging evidence that PBL has the potential to improve critical thinking across different educational levels and subject areas. However, the effect sizes should not be directly compared numerically with the present Partial Eta Squared value because different studies use different effect-size metrics and research designs.

The development of critical thinking skills is also supported by the implementation of each ESD-based PBL framework, which actively engages students in the problem-solving process (Syamsudin, 2020). The relatively large effect observed in the present study can be understood from the characteristics of the ESD-based PBL learning process. PBL places students in situations that require them to actively identify problems, seek and analyze relevant information, evaluate possible solutions, and make decisions based on evidence. During the orientation stage, students were exposed to contextual climate change problems that encouraged them to identify the causes and consequences of the problems. During the investigation stage, students searched for information, discussed evidence, formulated possible explanations, and considered alternative solutions. The presentation and discussion stages provided opportunities for students to communicate arguments, respond to different perspectives, and evaluate proposed solutions, while the reflection stage encouraged students to reconsider their reasoning and the appropriateness of the solutions developed. These activities correspond closely with the critical thinking indicators assessed in this study.

The integration of ESD further strengthened the contextual nature of the problems presented to students. Climate change was not discussed solely as a biological or environmental issue but as a sustainability issue involving interconnected environmental, social, and economic dimensions. Consequently, students were required to consider not only the causes and impacts of climate change but also the consequences of alternative solutions from multiple perspectives. This contextual and multidimensional learning process is consistent with the principles of ESD, which encourage learners to use knowledge to understand complex sustainability problems and develop appropriate responses (Pratiwi *et al.* 2019; Wiono & Mukarromah 2026). The alignment between ESD and critical thinking development is also supported by studies emphasizing that sustainability-oriented learning encourages students to critically examine problems and make responsible decisions (Matitaputty *et al.*, 2022). Thus, the contribution of the present study is not only the implementation of PBL but also the integration of sustainability dimensions into the problems through which students practiced critical thinking.

The methodological variations among previous studies also provide an important context for interpreting the present findings. Several previous studies have used pretest-posttest designs, systematic reviews, or meta-analytic approaches, whereas the present study employed a posttest-only control group design. For example, Fahmi *et al.*, (2026) used a pretest-posttest control group design, allowing changes in critical thinking to be examined across the intervention period. In contrast, the meta-analyses by Bonafide *et al.*, (2021) and Yohannes *et al.*, (2021) synthesized findings across multiple studies and therefore provide broader evidence regarding the effectiveness of PBL but involve heterogeneous samples, instruments, and intervention characteristics. These methodological differences indicate that the effectiveness of PBL may depend not only on the learning model itself but also on the duration, implementation context, instructional support, and characteristics of the learners.

The large effect size obtained in the present study ($\eta^2p = 0.708$) also provides evidence of the practical importance of the intervention, rather than merely indicating statistical significance. However, the effect size should be interpreted within the context of the study design. Because the study used intact classes selected through purposive sampling and a posttest-only design, the observed difference cannot be interpreted independently of potential pre-existing differences between groups. Nevertheless, the use of the same teacher, the same instructional topic, and comparable prior academic achievement as selection criteria provided some control over potential differences between the groups. Overall, the findings indicate that integrating ESD principles into PBL provides a meaningful instructional context for developing students' critical thinking skills,

particularly through authentic problem solving, evidence-based reasoning, evaluation of alternatives, and decision making.

The Effect of ESD-Based Problem-Based Learning on Students' Sustainability Awareness

The findings also demonstrated that ESD-based Problem-Based Learning (PBL) significantly affected students' sustainability awareness. The experimental group obtained a higher mean sustainability awareness score than the control group, with mean scores of 79 and 72, respectively. The univariate analysis showed a statistically significant effect of ESD-based PBL on sustainability awareness, $F = 10.633$, $p = 0.002$, with a Partial Eta Squared (η^2p) value of 0.144. This finding indicates that the implementation of ESD-based PBL was associated with higher sustainability awareness among students in the experimental group. Compared with the effect observed for critical thinking skills ($\eta^2p = 0.708$), the effect on sustainability awareness was smaller, suggesting that changes in sustainability awareness may require more sustained learning experiences and opportunities for students to translate awareness into consistent attitudes and behaviors.

The finding is consistent with previous studies demonstrating the potential of ESD-oriented learning to develop students' awareness of sustainability issues. Syahirah *et al.* (2025) reported that ESD can equip students with knowledge and skills needed to make environmentally responsible decisions, while Nugraheny *et al.* (2025) emphasized the role of ESD in developing knowledge, attitudes, values, and commitment toward sustainability. Similarly, Zulfah *et al.* (2024) found that integrating PBL and ESD through real-world problem solving can support students' understanding of sustainability issues and encourage environmental concern and responsible responses. Other studies have also emphasized that contextual learning involving environmental, social, and economic dimensions can help students understand sustainability issues in relation to real-life situations (Rohmah & Lestari, (2024); Nursadijah *et al.* (2022). These findings are further supported by Putri *et al.*, (2019), who found that the implementation of Real World Situation PBL using an ESD context could improve students' sustainability awareness profiles. Their study involved Grade 10 students and showed that the integration of real-world sustainability issues into PBL provided opportunities for students to engage with sustainability problems through learning activities.

Similarly, Agusti *et al.*, (2019), reported that PBL integrated with ESD in the context of global warming could improve students' critical thinking while also developing their sustainability awareness. However, their findings revealed that students' sustainability awareness was not equally developed across different dimensions. Students demonstrated relatively high emotional awareness, whereas sustainability practices were still infrequently performed. This finding is particularly relevant to the present study because it indicates that an increase in sustainability awareness may initially be reflected in students' concern and attitudes before being consistently translated into sustainability-oriented practices.

These learning processes correspond with the three dimensions of sustainability awareness examined in this study: sustainability knowledge, sustainability attitude, and sustainability behavior. Sustainability knowledge is supported when students acquire an understanding of sustainability problems and their consequences. Sustainability attitude can be developed through activities that require students to consider responsibility, values, and different perspectives when evaluating solutions. Meanwhile, sustainability behavior is related to the extent to which students report applying sustainability-oriented considerations in their daily lives. Thus, the significant result obtained in this study suggests that ESD-based PBL can contribute to the development of sustainability awareness as a multidimensional construct rather than merely increasing students' conceptual understanding of environmental issues. This multidimensional nature is also reflected in previous research. Putri *et al.*, (2019) categorized sustainability awareness into sustainability practice awareness, behavioral and attitude awareness, and emotional awareness, and found that these dimensions did not necessarily show the same level of development. Their findings indicated that emotional awareness was relatively high, whereas sustainability practice awareness remained limited.

The smaller effect size for sustainability awareness ($\eta^2p = 0.144$) compared with critical thinking skills ($\eta^2p = 0.708$) is also an important finding. Critical thinking was directly practiced throughout the PBL activities because students repeatedly analyzed problems, evaluated information, formulated arguments, and developed solutions. In contrast, sustainability awareness encompasses knowledge, attitudes, and reported behavior, which may be influenced by factors beyond classroom instruction, such as students' prior experiences, family environment, school culture, and opportunities to practice sustainable behavior. Therefore, although ESD-based PBL produced a statistically significant effect, the development of sustainability awareness may require longer-term and more continuous interventions involving authentic sustainability practices beyond classroom activities.

The findings of Agusti *et al.*, (2019) provide further support for this interpretation. Although the students demonstrated high emotional awareness, several sustainability practices were still reported at relatively low levels. For example, only 13% of students reported composting food waste, while sustainability practice

awareness overall remained lower than emotional awareness. This pattern suggests that understanding and caring about environmental issues do not automatically result in consistent sustainability practices. In other words, students may develop an awareness of environmental responsibility before they develop the habits and routines necessary to express that awareness through everyday behavior.

More recent evidence from Maulina *et al.*, (2026) also strengthens this interpretation. Their study integrated PBL with ESD/SDG-related content and contextualized sustainability issues through ethno-comics and real-world environmental problems. The study reported that the integration of PBL with ESD could enhance students' sustainability awareness while simultaneously developing critical thinking skills. Importantly, their findings also showed that the development of behavioral and attitudinal awareness was not necessarily immediate. The authors explained that although the learning process could increase students' social awareness and concern for sustainability, the development of positive attitudes and behaviors required time and gradual habituation. This finding is consistent with the present study, in which the effect of ESD-based PBL on sustainability awareness was statistically significant but substantially smaller than its effect on critical thinking.

This interpretation is consistent with Damayanti & Surjanti (2022), who demonstrated the potential of PBL within an ESD context to develop sustainability awareness through active engagement in environmental activities. Muflikhah (2023) likewise emphasized the role of ESD in increasing students' awareness of human impacts across environmental, economic, and social dimensions. The implementation of PBL within an ESD context is believed to foster meaningful learning that encourages students to become agents of change (Alhayat *et al.*, 2023). The findings of Putri *et al.*, (2019) Agusti *et al.*, (2019) and Maulina *et al.*, (2026) further indicate that authentic and contextual sustainability problems can strengthen students' awareness, but that the transformation of awareness into consistent sustainability practices may require repeated learning experiences and opportunities for habituation. Overall, the findings indicate that ESD-based PBL can provide a contextual learning environment for developing sustainability awareness while simultaneously engaging students in critical analysis and problem solving. The integration of sustainability dimensions into authentic problems allows students to connect biological knowledge with broader environmental, social, and economic consequences. However, because sustainability awareness was measured through a questionnaire, the findings should be interpreted as evidence of students' reported sustainability awareness rather than direct evidence of long-term behavioral change. The distinction between awareness and behavior is particularly important in light of previous findings showing that students may demonstrate strong emotional or attitudinal awareness while still showing limited engagement in sustainability practice

Several limitations should be considered when interpreting the findings of this study. First, the study employed purposive sampling with intact classes rather than individual random assignment. Although the classes were selected based on the same teacher, the same instructional topic, and comparable prior academic achievement, selection bias cannot be completely excluded. Therefore, the significant differences observed between the groups should be interpreted with consideration of the quasi-experimental nature of the study. Second, the study used a posttest-only control group design. Consequently, changes in students' critical thinking skills and sustainability awareness from before to after the intervention could not be directly measured. Although prior academic achievement was considered in selecting the classes, it does not provide the same information as baseline measurements of the two dependent variables. Future studies should consider a pretest-posttest design or randomized controlled design, where feasible, to provide stronger evidence regarding changes attributable to the intervention.

Third, the study was conducted in a single school with a relatively small sample of Grade 10 students. Therefore, the generalizability of the findings to students from other schools, regions, educational levels, or cultural contexts is limited. Future research should replicate the study across multiple schools and with larger and more diverse samples to strengthen external validity. The distinction between awareness and behavior is particularly important in light of previous findings showing that students may demonstrate strong emotional or attitudinal awareness while still showing limited engagement in sustainability practice Maulina *et al.*, (2026), who recommended expanding research to more diverse school and regional contexts and conducting longitudinal research to examine the longer-term effects of PBL-based sustainability learning. Finally, sustainability awareness was measured using a self-report questionnaire. Although the instrument underwent expert validation and empirical testing, self-reported responses may not fully represent students' actual sustainability-related behavior. In addition, the study did not employ blinded assessment procedures for the essay-based critical thinking test. Future studies could incorporate blinded or independent scoring, performance-based assessments, behavioral observations, and interviews to provide a more comprehensive evaluation of students' critical thinking and sustainability-related outcomes. Longitudinal observation of sustainability practices would also be valuable for determining whether the awareness developed through ESD-based PBL is subsequently translated into stable sustainability-oriented behaviors.

Conclusions

The findings demonstrate that ESD-based Problem-Based Learning (PBL) significantly affected students' critical thinking skills and sustainability awareness. The effect on critical thinking was substantial ($\eta^2p = 0.708$), while sustainability awareness also showed a statistically significant effect, $F = 10.633$, $p = 0.002$, with a moderate effect size ($\eta^2p = 0.144$). The experimental group obtained a higher mean sustainability awareness score than the control group (79 vs. 72), indicating a 7-point difference between groups. The larger effect size for critical thinking suggests that this outcome was more strongly associated with the PBL intervention, whereas sustainability awareness may require more sustained learning experiences because it encompasses knowledge, attitudes, and reported behaviors. However, these findings represent immediate post-intervention outcomes only. Because the study employed a posttest-only quasi-experimental design without follow-up assessment, the results cannot establish long-term retention or sustained changes in sustainability-related behavior. Future studies should therefore employ pretest-posttest and longitudinal designs with follow-up assessments to examine whether the observed effects are maintained over time. Behavioral observations or performance-based measures could also complement self-reported sustainability awareness and provide stronger evidence of sustained behavioral change.

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