



Integrating Problem-Based Learning and SSI-ESD Context to Foster Chemical Literacy and Environmental Awareness in Secondary Education

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Abstract: This study aimed to examine the differences in students' chemical literacy and environmental awareness, both jointly and separately, between those taught using problem-based learning (PBL) contextualized with Socio-Scientific Issues and Education for Sustainable Development (SSI-ESD) and those taught using a conventional scientific approach on the topic of climate change. The integration of PBL, SSI, and ESD creates a synergistic learning model that emphasizes real-world problem-solving, critical thinking, and sustainability awareness, which are essential competencies for 21st-century learning. A quasi-experimental design with a pre-test and post-test control group was employed to ensure a valid comparison. The research involved 144 Grade X students from two public senior high schools in Yogyakarta City, selected using class-level random sampling, consisting of two experimental classes ($n = 72$) and two control classes ($n = 72$). The experimental group was taught using a PBL-based SSI-ESD approach, while the control group received instruction through a traditional scientific approach. Research instruments included a validated chemical literacy test and an environmental awareness questionnaire. Data were analyzed using N-gain, MANOVA, and descriptive statistics to assess both improvement and effect size. The findings revealed significant differences in students' chemical literacy and environmental awareness between the two groups, as determined by MANOVA (Hotelling's Trace = 0.392; $p < 0.05$). The experimental group achieved higher N-gain scores in chemical literacy (0.52) and environmental awareness (0.53) compared to the control group (0.39 and 0.31, respectively). This learning approach demonstrated a large effect size on both skills simultaneously (0.282) and separately (0.183; 0.240). These results indicate that PBL-based SSI-ESD learning effectively enhances both students' chemical literacy and environmental awareness while supporting the implementation of current educational policies that promote Education for Sustainable Development (ESD) and competency-based learning in Indonesia, aligning with the *Merdeka Belajar* curriculum framework.

Keywords: chemical literacy, environmental awareness, PBL-SSI-ESD, student worksheet, climate change.

▪ INTRODUCTION

Education is a deliberately designed process that creates a learning environment enabling students to optimally develop their potential, encompassing aspects of spirituality, self-control, intelligence, and skills (Rahman et al., 2022). One of the main strategies to achieve these educational goals is through curriculum development. In Indonesia, the *Merdeka Curriculum* has been introduced as a response to the needs of 21st-century learning, emphasizing the empowerment of students (Tuerah & Tuerah, 2023).

In the context of 21st-century education, high-quality planning is required to equip the younger generation with globally relevant skills (Aryani et al., 2022). These skills include digital literacy, creative thinking, effective communication, and high productivity (Lemke, 2002). One important skill to be developed is science literacy, which encompasses chemical literacy as an integral part of science (Alvina et al., 2024; Turiman

et al., 2012). Chemical literacy refers to the ability to understand, apply, and evaluate chemical information in everyday life (Imansari et al., 2018).

On the other hand, environmental issues such as climate change and global warming have become global concerns that need to be addressed through education (Al-Ghussain, 2018; Sanchez et al., 2024). Students have the potential to act as agents of change in responding to environmental issues, yet research indicates that their environmental awareness remains low (Baga et al., 2024). This situation highlights the need for education that not only provides knowledge about environmental issues but also fosters attitudes of care and responsibility toward the planet's sustainability.

Natural phenomena resulting from environmental degradation, such as global warming and climate change, continue to increase over time (Al-Ghussain, 2018; Lelieveld et al., 2019; Xu et al., 2018). Global warming and climate change are widely discussed global issues and have become one of the main topics in policy-making in Indonesia (Ambarfebrianti & Novianty, 2021; Arwan et al., 2021). Changes in many extreme weather and climate events are linked to human influence, such as decreases in extreme cold temperatures, increases in extreme warm temperatures, extreme sea-level rise, and a growing number of heavy rainfall events in various regions (Pachauri et al., 2014). The impacts already felt by Indonesian society serve as an important reminder for the government and the education sector to take immediate action in climate change mitigation and adaptation. One relevant strategy is integrating climate change education into the school curriculum, enabling students not only to understand these phenomena but also to contribute to sustainable solutions (Sanchez et al., 2024).

In line with this need, chemistry education plays a strategic role because many of its concepts are directly related to environmental issues. However, chemistry is often considered difficult and abstract, requiring a more contextual and participatory approach (Antari et al., 2020; Prayunisa & Mahariyanti, 2022). One approach that can be implemented is Socio-Scientific Issues (SSI), which connects social issues with scientific concepts and encourages students to think critically and propose solutions (Dina et al., 2024; Rahmawati et al., 2023). Thus, SSI can serve as an effective means to meaningfully integrate climate change education into chemistry learning.

Socio-Scientific Issues (SSI) are presented as problems in which scientific knowledge and social awareness emerge in a mental conflict that requires science literacy to make responsible decisions (Sadler & Zeidler, 2009). Moreover, incorporating problems into the learning process provides students with opportunities to apply their knowledge in problem-solving (Capraro & Slough, 2013; Dolmans et al., 2005). The use of SSI facilitates students in constructing explanations of scientific phenomena. Additionally, problem-solving activities during the learning process help students gain a deeper understanding of scientific concepts.

The SSI approach is relevant to Education for Sustainable Development (ESD), which emphasizes students' involvement in decision-making for sustainable living (Summers et al., 2005). The primary goal of Education for Sustainable Development (ESD) is to equip the next generation to become responsible citizens in the future. Students are expected to actively contribute to democratic societies and support the development of sustainable communities. They must learn to take responsibility for their own actions while considering the impacts on future generations, in accordance with the principles of sustainable development (de Haan, 2006). The Problem-Based Learning

(PBL) model supports the principles of ESD and encourages students to solve problems collaboratively, contextually, and actively (Bascopé et al., 2019; Guerra, 2017). However, the implementation of PBL and the SSI-ESD approach is still rarely applied in chemistry education (Srirahmawati et al., 2023). Therefore, a learning model that can synergistically integrate all three is needed.

The PBL–SSI–ESD conceptual model integrates Problem-Based Learning (PBL) with the context of Socio-Scientific Issues (SSI) to support the goals of Education for Sustainable Development (ESD). This model positions SSI as scientific issues relevant to everyday life, such as climate change and global warming, prompting students to think critically, solve problems, and present science-based arguments. PBL serves as the main pedagogical approach, promoting action-oriented, community-based, and value-centered learning, in alignment with ESD principles. Through this integration, students not only gain conceptual understanding of chemistry but also develop environmental awareness, collaboration skills, and the ability to make responsible decisions on sustainability issues.

The implementation of this model also contributes to achieving the Pancasila Student Profile, particularly in the dimensions of Critical Thinking, Collaboration, and Global Diversity. Through PBL-based learning contextualized with SSI and ESD, students are not only trained to analyze and solve environmental problems such as climate change (fostering critical thinking). However, they are also encouraged to work collaboratively in groups (promoting collaboration) and understand global issues from a local perspective (supporting global diversity). Thus, this intervention serves as an operational approach aligned with the *Merdeka Belajar* curriculum, which emphasizes competency-based learning and character development.

To ensure the effective implementation of PBL-based learning within the SSI–ESD context, learning media that facilitate active, contextual, and collaborative learning are required. Student Worksheets (SW) are one such potential medium, as they can enhance student engagement, deepen conceptual understanding, and support chemical literacy and environmental awareness (Hairida & Setyaningrum, 2020; Nurmasita et al., 2023). However, to date, the development of PBL-based SW within the SSI-ESD context in chemistry learning remains limited. Therefore, PBL-based SW contextualized with SSI–ESD represents an innovative alternative to improve the quality of chemistry learning while simultaneously supporting the achievement of 21st-century skills. Based on the explanation above, this study is designed to address the following research questions (RQ):

- RQ1: Are there significant simultaneous differences in chemical literacy and environmental awareness between students taught using PBL-based worksheets contextualized with SSI-ESD and those taught using a scientific approach?
- RQ2: Are there significant differences in chemical literacy between the two groups?
- RQ3: Are there significant differences in environmental awareness between the two groups?

▪ METHOD

Participants

This study involved tenth-grade students from two public senior high schools in Yogyakarta, namely SMA Negeri 7 Yogyakarta and SMA Negeri 9 Yogyakarta. The

schools were selected using purposive sampling based on the following criteria: accredited as A, implementing the *Merdeka Curriculum*, equipped with laboratory facilities, projectors in every classroom, access to digital learning, and teaching climate change topics in grade X. The population included all tenth-grade classes in public senior high schools in Yogyakarta with similar characteristics. After selecting the schools, classes were randomly assigned, consisting of four classes (two experimental and two control classes) with an average of 35–36 students per class. Initial equivalence was tested using ANOVA and confirmed to be equal (sig. p-value higher than 0.05).

Research Design and Procedures

This study employed a cluster quasi-experimental design with a pre-test–post-test control group design, where the unit of assignment was intact classes (clusters). The experimental group received PBL-based learning contextualized with SSI–ESD, while the control group received learning based on a scientific approach. The climate change context was selected based on globally relevant issues aligned with the curriculum and the local conditions of Yogyakarta, which faces various environmental impacts. Four specific scenarios used in the learning process were: (1) methane emissions from Piyungan landfill; (2) Urban Heat Island (UHI) in urban areas; (3) prolonged drought; and (4) tree planting to reduce greenhouse gas emissions. The research procedures included: (1) development of learning materials and instruments; (2) theoretical and empirical validation; (3) pre-test; (4) treatment over two meetings (each 2×45 minutes) during April–May 2025; (5) post-test; and (6) data analysis.

Instrument

The instruments consisted of a chemical literacy test comprising 23 reasoned multiple-choice questions (Two-Tier) and an environmental awareness questionnaire with 26 Likert-scale statements. The instruments were developed based on a synthesis of chemical literacy indicators from Celik (2014); Cigdemoglu & Geban (2015); Shwartz et al. (2006a, 2006b); and Thummathong & Thathong (2016), while environmental awareness indicators were adapted from Adriyanto et al. (2021); Bozoglu et al. (2016); Kalkan & Demirbas (2017); and Orbanić & Kovač (2021). Content validity was assessed through expert judgment by two chemistry education lecturers at UNY, and empirical validity was analyzed using the Rasch model (Infit MNSQ criterion 0.77–1.33; Measure -2 to +2). Three pre-test items and four post-test items in the chemical literacy test, as well as four questionnaire items, were deemed invalid and removed. The reliability of the chemical literacy test items ranged from 0.93 to 0.94 (very good), while the questionnaire had a reliability of 0.99 (excellent). Person reliability for the test was 0.62–0.63 (poor), and for the questionnaire, it was 0.80 (adequate), which is still acceptable for educational research.

Data Analysis

The data were analyzed using descriptive and inferential statistics. Score improvement was calculated using N-gain (Hake, 1998), and the effect of the treatment was tested using MANOVA after meeting the assumptions (Shapiro-Wilk normality, Levene's homogeneity, and Mahalanobis outlier test). The effect size was calculated using partial eta squared, with a large effect categorized as ≥ 0.14 (Cohen, 1988).

▪ RESULT AND DISSCUSSION

The MANOVA assumption tests were conducted in accordance with the criteria outlined by Hair et al. (2010), Pituch & Stevens (2016), and Stevens (2009). The results indicated that all assumptions were met, including: dependent variables measured at the interval level, independent design, adequate sample size ($n = 72$ per group), absence of multivariate outliers, normal distribution (Shapiro–Wilk, $p > 0.05$), linear relationships between variables ($p > 0.05$), homogeneity of variance–covariance matrices (Box’s M , $p = 0.218$), and no multicollinearity (Tolerance = 0.733; VIF = 1.364). The correlation between dependent variables was 0.516, categorized as moderate. With all assumptions satisfied, the MANOVA was performed using Hotelling’s Trace and Roy’s Largest Root statistics.

The MANOVA using Hotelling’s Trace and Roy’s Largest Root yielded a significance value of $0.000 < 0.05$, leading to the rejection of H_0 . This result confirms a significant simultaneous difference in chemical literacy and environmental awareness between students who participated in PBL-based learning contextualized with SSI-ESD and those who participated in scientific approach-based learning on the topic of climate change. The Tests of Between-Subjects Effects also produced a significance value of $0.000 < 0.05$, indicating a significant difference in the effect of the instructional treatment on each dependent variable, namely chemical literacy and environmental awareness.

Chemical literacy was measured using a test instrument consisting of reasoned multiple-choice questions (Two-Tier), while environmental awareness was measured using a questionnaire. The data obtained were analyzed using N-gain, MANOVA, and descriptive statistics. The results were then compared between students who participated in PBL-based learning contextualized with SSI-ESD and those who received learning based on a scientific approach on climate change topics.

RQ 1: A Significant Difference in Chemical Literacy and Environmental Awareness Was Found Between Students in the Experimental Group and Those in the Control Group

The average N-gain for students’ chemical literacy and environmental awareness is presented in Tables 1 and 2.

Table 1. Average N-gain results for chemical literacy

Group	Number of Students	Average Score		
		Pre-test	Post-test	N-gain
Control	72	75.38	85.78	0.39
Experimental	72	76.47	89.00	0.52

Table 2. Average N-gain results for environmental awareness

Group	Number of Students	Average Score		
		Pre-test	Post-test	N-gain
Control	72	75.40	83.64	0.31
Experimental	72	75.06	88.39	0.53

The students’ chemical literacy and environmental awareness data from the pre-test and post-test scores were converted into N-gain values. These N-gain values were used

to calculate the means and were further analyzed using MANOVA with Hotelling's Trace and Roy's Largest Root statistics. The results showed a significant difference between the control and experimental groups. The average N-gain for chemical literacy was 0.39 for the control group and 0.52 for the experimental group, both of which were categorized as medium (Table 1). For environmental awareness, the control group scored 0.31 and the experimental group 0.53, also falling within the medium category (Table 2). Although both are in the same category, the experimental group showed higher results, with an N-gain difference of 0.13 in chemical literacy and 0.22 in environmental awareness.

This improvement indicates that PBL-based learning contextualized with SSI-ESD has a more significant impact on students' critical thinking skills in understanding environmental issues and fosters environmentally responsible attitudes. The N-gain differences of 0.13 and 0.22, although within the medium category, reflect the potential to strengthen students' competencies in addressing climate change issues more consciously and based on scientific knowledge. This suggests that implementing this approach on a larger scale could contribute to developing a generation that not only understands chemistry concepts also tends to act in more environmentally friendly ways.

The MANOVA results showed a significance value of $0.000 < 0.05$, indicating that H_0 was rejected and H_a accepted. This means there is a significant difference in chemical literacy and environmental awareness between students who participated in PBL-based learning contextualized with SSI-ESD and those who received a scientific approach. Furthermore, the Partial Eta Squared value obtained was 0.282, exceeding 0.14 and falling within the large effect criterion. This indicates that the simultaneous effective contribution has a strong impact. When analyzed separately for each dependent variable, the effective contribution to students' chemical literacy was 0.183, classified as a large effect, and to students' environmental awareness was 0.240, also classified as a large effect. The high Partial Eta Squared values (>0.14) indicate that the learning intervention has a substantial impact on two primary aspects: chemical literacy and environmental awareness.

This is in line with the study by Rubini et al. (2019), which stated that problem-based learning within an SSI context can enhance science literacy through the application of knowledge in real-life situations. Rahmawati et al. (2023) also demonstrated that a similar approach effectively improves environmental awareness and higher-order thinking skills. Zulfah et al. (2024) supported that ESD-based PBL enhances environmental literacy. A similar opportunity is also provided through the implementation of the scientific approach, in which students are encouraged to actively participate in discussions to build a conceptual understanding of chemistry material. This approach aligns with the Pancasila Student Profile in the Merdeka Curriculum, particularly in the dimension of cooperation, with the sub-element of being responsive to the social environment. It emphasizes that students who reflect the Pancasila Student Profile are able to actively contribute to social situations around them, creating positive change. Furthermore, it supports the dimension of global diversity, especially the sub-element of participating in collective decision-making, indicating that students are capable of engaging in decision-making processes through dialogue or joint discussion. Additionally, this activity also develops the dimension of critical thinking, where students are trained to evaluate information, identify cause-and-effect relationships, and develop solutions based on logical and analytical reasoning.

The implementation of PBL-based learning contextualized with SSI–ESD has been proven effective in enhancing students’ chemical literacy and environmental awareness. The use of electronic worksheets that feature environmental issues encourages students to solve problems and seek solutions, thereby stimulating their critical thinking skills (Hanifha et al., 2023). Naibaho et al. (2025) stated that the use of SSI-integrated PBL-based worksheets has a positive impact on the improvement of students’ environmental literacy. Similarly, Rahmawati et al. (2023) emphasized the importance of developing environmental awareness through higher-order thinking skills. Muflikhah (2023) also reported that ESD-based PBL models effectively enhance science literacy and sustainable awareness. Furthermore, SSI-based environmental issue contexts consistently improve argumentation skills, decision-making, and social awareness, particularly in the context of climate change education (Sari et al., 2025).

The differences in chemical literacy and environmental awareness between the experimental and control groups were attributed to variations in the learning treatments. The experimental group participated in PBL-based learning, contextualized with SSI–ESD, focusing on environmental issues within the climate change topic. This approach encouraged students to understand the connection between concepts and real-world phenomena. This approach trained them to argue, think critically, and formulate sustainable solutions based on knowledge and experience. Students were also invited to reflect on the problem-solving processes they undertook. In contrast, the control group received learning based on the Scientific Approach, which focused more on observing, questioning, and concluding activities without promoting deep contextual connections. Consequently, the control group students were less encouraged to develop environmental awareness. This demonstrates that contextual and meaningful education can foster environmentally responsible attitudes (Amran et al., 2019; Asad et al., 2022; Jannah et al., 2013; Mandler et al., 2012; Orbanic & Kovač, 2021).

RQ2: A Significant Difference In Chemical Literacy Was Found Between Students in the Experimental Group and Those in the Control Group

The description of students’ chemical literacy data is presented in Tables 3 and 4.

Table 3. Descriptive data on chemical literacy in the control group

Data Type	Category		Average Score
	Lowest Score	Highest Score	
Pre-test	51	89	75.38
Post-test	79	95	85.78

Table 4. Descriptive data on chemical literacy in the experimental group

Data Type	Category		Average Score
	Lowest Score	Highest Score	
Pre-test	50	89	76.47
Post-test	80	96	89.00

The analysis of the Tests of Between-Subjects Effects in the MANOVA indicated that PBL-based learning contextualized with SSI–ESD has a significant effect on students’ chemical literacy. The analysis showed a significance value of 0.000, which is

less than 0.05. This indicates a difference in chemical literacy between students who participated in PBL-based learning contextualized with SSI-ESD and those who received learning based on the Scientific Approach in the context of climate change. Furthermore, based on Tables 3 and 4, the average posttest scores of chemical literacy in the experimental group were higher than those of the control group. Thus, it can be concluded that there is a significant difference in chemical literacy between students taught using PBL-based learning contextualized with SSI-ESD and those taught using the Scientific Approach in the context of climate change.

These findings indicate that PBL-based learning contextualized with SSI-ESD not only produces statistically significant differences but also has a tangible impact on improving students' chemical literacy. This improvement reflects the strengthening of their ability to understand, analyze, and connect chemical concepts with climate change issues relevant to everyday life. Therefore, the implementation of this approach has the potential to enhance the quality of more contextualized science learning and equip students with critical thinking skills necessary for making responsible scientific decisions in the future.

The difference in chemical literacy between the control and experimental groups is attributed to the influence of PBL-based learning contextualized with SSI-ESD on the experimental group. The stages of this learning model guide students to identify problems, gather information, analyze data, and reflect on their investigations (Rahmadani, 2019). The PBL-SSI-ESD learning stages enable students to be more actively engaged in the learning process. They are encouraged to gradually find solutions to a problem, from problem orientation to drawing conclusions, with guidance from the teacher as a facilitator. In this process, students are engaged through four discourses linked to climate change concepts, enabling them to connect scientific knowledge with real environmental issues relevant to their daily lives. The four discourses are: 1) The Impact of Waste Management at Piyungan Landfill on Climate Change; 2) The Threat of Climate Change to the Agricultural Sector in the Special Region of Yogyakarta; 3) Urban Heat Island (UHI) and Its Impact on Climate Change; and 4) The Threat of Climate Change to the Tourism Sector in the Special Region of Yogyakarta.

The effect of PBL-based learning contextualized with SSI-ESD on students' chemical literacy is reinforced by previous studies, such as those conducted by Azizah et al. (2021), Refmidawati & Megahati S. (2023), and Sari & Wiyarsi (2021). These studies indicate that this learning model or approach is effective in enhancing students' chemical literacy skills.

RQ 3: A Significant Difference in Environmental Awareness Was Found Between Students in the Experimental Group and Those in the Control Group

The description of students' environmental awareness data is presented in Tables 5 and 6.

Table 5. Descriptive data on environmental awareness in the control group

Data Type	Category		Average Score
	Lowest Score	Highest Score	
Pre-test	58	86	75.40
Post-test	72	98	83.64

Table 6. Descriptive data on environmental awareness in the experimental group

Data Type	Category		Average Score
	Lowest Score	Highest Score	
Pre-test	60	86	75.06
Post-test	80	99	88.39

The effect of PBL-based learning contextualized with SSI–ESD on students' environmental awareness is demonstrated through the analysis of the Tests of Between-Subjects Effects in the MANOVA. The results show a significance value of 0.000, which is less than 0.05, leading to the rejection of H_0 and the acceptance of H_a . Thus, there is a significant difference in environmental awareness between students who participated in PBL-based learning with an SSI–ESD context and those who received learning through a scientific approach on climate change material. This finding is reinforced by the data in Tables 5 and 6, which indicate that the average post-test scores of the experimental group's environmental awareness questionnaire were higher than those of the control group. Therefore, it can be concluded that PBL-based learning contextualized with SSI–ESD is significantly more effective in enhancing students' environmental awareness.

These results suggest that PBL-based learning, contextualized with SSI–ESD, can have a more tangible impact on fostering students' environmental awareness. The observed improvements are not only statistically significant but also have the potential to influence students' daily behaviors, such as reducing the use of single-use plastics, conserving water and energy, and actively participating in environmental preservation activities. This underscores that learning approaches connecting scientific issues with social and environmental contexts can effectively prepare the younger generation to become agents of change in addressing climate change challenges.

The difference in environmental awareness between the control and experimental groups is attributed to the implementation of PBL-based learning contextualized with SSI–ESD in the experimental group. This approach effectively links chemistry concepts with relevant environmental issues, encouraging students to think both conceptually and contextually. Environmental issue contexts were selected due to their close relevance to future sustainability. This treatment has been shown to enhance environmental awareness and foster students' responsibility toward environmental preservation (Susilawati et al., 2021). This finding aligns with Günter et al. (2017), who reported that PBL integrated with green chemistry principles effectively improves students' understanding and awareness of sustainability issues.

The scientific approach-based learning implemented in the control group involved group investigations but did not guide students in formulating sustainable solutions that considered environmental, social, and economic impacts. The presentation of results was limited to question-and-answer sessions without in-depth intergroup discussions. This approach emphasized cognitive aspects more heavily and provided little opportunity for reflection on values, attitudes, and responsibility toward environmental issues, thereby failing to directly foster environmental awareness. As a result, the level of environmental awareness in the control group was lower compared to the experimental group, which participated in PBL-based learning contextualized with SSI–ESD, promoting critical thinking and concern for sustainability. This aligns with Salsabila et al. (2019), who found that students' low environmental awareness is likely due to insufficient understanding of

the scientific processes behind environmental phenomena, such as methane formation in landfills and its impact on climate change. Enhancing students' sustainability awareness is closely linked to their ability to comprehend how and why environmental processes occur, rather than merely recognizing phenomena at a surface level.

This study has several limitations, including time constraints that prevented some learning stages, such as Guiding Group Investigations and Developing and Presenting Results, from being carried out optimally, thereby limiting data collection and intergroup discussions. Students were also not yet accustomed to PBL-based learning contextualized with SSI-ESD, requiring longer explanations and guidance than planned. In addition, the busy school schedule affected students' focus and enthusiasm, highlighting the need for personalized approaches and additional motivation to maintain their engagement throughout the learning process.

▪ CONCLUSION

This study demonstrates that PBL-based learning, contextualized with SSI-ESD, significantly enhances students' chemical literacy and environmental awareness compared to scientific approach-based learning on climate change topics. MANOVA and N-gain analyses indicated significant differences with moderate improvement levels, with the experimental group achieving higher average scores (chemical literacy: 0.52; environmental awareness: 0.53) than the control group (0.39; 0.31). These findings are important as they support the implementation of contextual learning that fosters both conceptual understanding of chemistry and the development of environmentally responsible attitudes, aligning with the Merdeka Belajar curriculum and strengthening 21st-century competencies such as critical thinking, problem-solving, and responsible scientific decision-making.

The implications of this study suggest that PBL-based learning, contextualized with SSI-ESD, can serve as an effective strategy in science education to foster both students' chemical literacy and environmental awareness, potentially shaping environmentally responsible behavior and preparing them to contribute to sustainability. However, this study has limitations, including a restricted learning time that prevented some PBL stages from running optimally, and students' low familiarity with PBL-SSI-ESD-based worksheets, which required more intensive guidance. Additionally, the busy school schedule affected students' focus and enthusiasm, highlighting the need for personalized approaches and extra motivation to maintain engagement throughout the learning process. Therefore, it is recommended that policymakers and school principals provide more flexible time for project- and problem-based learning, offer teacher training on implementing PBL-SSI-ESD, and facilitate the provision of innovative worksheets integrated with sustainability issues to make learning more meaningful and impactful.

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