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The effectiveness of a problem-based learning model grounded in socio-scientific issues on students' critical thinking skills regarding environmental change

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ABSTRACT

Students' relatively low level of critical thinking skills regarding environmental change underscores the need for a learning approach that meaningfully integrates scientific concepts with real-life issues. The purpose of this study was to determine how well a Problem-Based Learning (PBL) model combined with Socio-Scientific Issues (SSI) may help students develop their critical thinking abilities with reference to environmental change. A total of 23 tenth-grade students from a private high school in the Medan Tembung subdistrict participated in this study, which used a quasi-experimental design with a one-group pretest-posttest method. The SSI-based PBL intervention involved collaborative, real-world environmental problem-solving, encompassing investigation, evidence analysis, solution presentation, and reflection. The research instrument consisted of an essay test that had passed validity and reliability tests. The N-gain test, paired-sample t-test, and effect size were used to examine the data. With an N-gain value of 86%, classified as "effective" supported by the paired-sample t-test, which showed a significant difference between pre-test and post-test scores ($p < 0.001$) and a Cohen's d value of 7.333, classified as a "very large" effect, the results show that students' critical thinking abilities improved across all indicators. These results show that through problem-solving exercises, evidence-based reasoning, and environmental reflection, the SSI-based PBL model effectively develops students' critical thinking abilities. However, the results of this study are still limited to a single school with a relatively small sample size and no control group; therefore, future research is recommended to use a broader sample and a stronger experimental design.

INTRODUCTION

21st-century education requires students to possess learning skills and life skills (Oktaviyanti et al., 2025), one of which is critical thinking. Critical thinking is the ability to construct one's own understanding based on one's experiences and knowledge (Subarjo et al., 2024). Critical thinking is one of the higher-order thinking skills relevant to the current curriculum (Nadhiroh & Anshori, 2023). Additionally, Aprina et al. (2024) define critical thinking as the ability to analyze, distinguish, identify, and evaluate. This aligns with the view of Facione (2015), who claims that cognitive skills, such as interpretation, analysis, evaluation, inference, explanation, and self-regulation, are the foundation of critical thinking. According to Willingham (2007), critical thinking entails the capacity to consider an issue from multiple angles, maintain an open mind to new and contradictory information, reason impartially, demand evidence-based assertions, make fact-based conclusions, and solve problems. Critical thinking abilities are essential for helping people solve a variety of issues, especially scientific ones (Rahim, 2023).

The importance of these skills is increasing with the emergence of various global challenges, such as environmental change, the climate crisis, pollution, and the spread of information that is not always based on scientific evidence. In such situations, students are required to be able to analyze information from various perspectives, evaluate the accuracy of evidence, and make responsible decisions based on scientific reasoning. Therefore, critical thinking skills need to be integrated into the learning process, both as learning objectives and as a means to equip students to solve various real-life problems (Nafiah & Suyanto, 2014; Harpina et al., 2025). The development of these critical thinking skills is carried out through a learning process that involves observation, experience, reflection, reasoning, communication, and rational decision-making based on the evidence obtained (Ariani, 2020).

However, at present, critical thinking skills remain at a relatively low level in Indonesia (Sulaiman et al., 2025). This is reflected in the results of the 2022 Programme for International Student Assessment (PISA), which show that Indonesia's science literacy score reached only 383 points, still below the Organization for Economic Co-operation and Development (OECD) average of 485 points and ranked 63rd out of 73 participating countries (Ariani et al., 2025). These low achievements are consistent with various studies reporting that students' critical thinking skills in schools have not yet developed optimally. Preliminary research by Rahman et al. (2024) on science students at Matholi`ul Huda Islamic High School in Sokopuluhan, Pati, showed that students' critical thinking skills remained in the low category, with a percentage score of 44.88%. One contributing factor is the predominant use of teacher-centered learning. Similar results were also reported by Suja & Sabani (2023) among 11th-grade students at Dharmawangsa Private High School in Medan, indicating low critical thinking skills at a rate of 64.10%. In their analysis, the students' low critical thinking skills were attributed to a learning environment that had not accustomed students to higher-order thinking skills (HOTS) questions, resulting in their critical thinking skills not developing optimally.

Students' low critical thinking skills are influenced not only by the predominance of teacher-centered learning but also by a lack of opportunities for students to tackle contextual and open-ended problems. The learning process is still dominated by the presentation of concepts and the solving of routine problems, so students are rarely trained to analyze evidence, evaluate various alternative solutions, or construct scientific arguments based on real-life problems (Ariani, 2020; Umroh et al., 2025). In line with these findings, Hasibuan et al. (2025) and Putri et al. (2025) revealed that students' critical thinking skills have not developed optimally because they are not yet accustomed to connecting scientific concepts with real-world situations that require rational decision-making.

Students at a private high school in the Medan Tembung subdistrict still struggle with critical thinking, especially when it comes to the key subject of environmental change. Based on empirical observations conducted with teachers, it was found that most students still answer questions by

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quoting information from textbooks without demonstrating the ability to analyze, evaluate, or develop arguments based on their own understanding. Students also struggle when faced with contextual problems that require decision-making based on scientific evidence. Furthermore, an analysis of the learning process indicates that classroom activities are still dominated by teacher-centered learning, with an emphasis on presenting material and solving routine problems. As a result, students have not had sufficient opportunities to discuss, express their opinions, evaluate various alternative solutions, or relate biological concepts to real-world problems in their surroundings. This is consistent with the findings of Rozali et al. (2022), who claim that teacher-centered learning can cause students to become passive learners and have a detrimental effect on their capacity for critical thought.

Efforts to address this issue involve facilitating students through a learning approach that shifts from teacher-centered to student-centered, thereby encouraging them to develop critical thinking skills (Lusmianingtyas & Sriyanto, 2022). The application of problem-based learning (PBL) is one such strategy. PBL provides a method that puts students in scenarios where they have to find solutions to real-world issues. (Siswanto et al., 2025). According to Arends (2012), PBL is a learning model that presents students with a variety of authentic and meaningful real-world problem situations. PBL focuses on problem-solving as the core of the learning process (Harahap et al., 2025). PBL can enhance students' critical thinking skills because the indicators of critical thinking align with the stages of PBL implementation (Kusumawati et al., 2022). From the problem-orientation stage through the solution-evaluation stage, students are trained to interpret, analyze, evaluate, infer, explain, and engage in self-regulation, thereby enhancing their analytical skills; the entire PBL process systematically stimulates critical thinking skills. The PBL model's benefits include helping students become more adept at solving problems, increasing their interest in the subject matter, and encouraging independent learning, all of which contribute to a deeper comprehension of the subject matter (Saputra & Kuntjoro, 2019).

Problem-Based Learning (PBL) has been shown to improve critical thinking abilities through inquiry and problem-solving procedures; however, the quality of the issues utilised in the learning process greatly influences how effective PBL is. In the context of environmental change, issues such as environmental pollution, types of waste, and waste management are authentic problems that not only involve scientific concepts but are also related to social, economic, ethical, and policy aspects, thereby requiring students to consider various perspectives in decision-making (Fatimah & Rahayu, 2025). Therefore, learning requires a framework capable of integrating scientific knowledge with social considerations in the process of analysis and decision-making. One suitable framework is Socio-Scientific Issues (SSI) (Zeidler & Nichols, 2009).

Scientific knowledge and social awareness are intertwined in SSI, creating cognitive conflicts that call for decision-making (Sadler, 2004). According to Zeidler & Nichols (2009), SSI provides students with opportunities to engage in discussions, decision-making, and problem-solving based on scientific issues relevant to their lives (Sadler et al., 2016). To improve their critical thinking abilities, students are encouraged to examine and debate real-world problems and consider the moral and social ramifications of their choices through SSI-problem-based learning (Sari et al., 2025). SSI is crucial for students because it incorporates sociocultural, political, economic, and ethical factors, thereby encouraging students to understand and apply scientific explanations (Pamungkas et al., 2025). Muntari et al. (2024) also argue that SSI is important to introduce to students to stimulate critical thinking, analysis, and reasoning.

SSI can be integrated into constructivist learning models, specifically Problem-Based Learning (PBL). Problem-based learning integrated with SSI offers significant opportunities to enhance students' critical thinking skills because it requires the scientific and reflective analysis of real-world problems (Hernández-Ramos et al., 2021). According to Fatimah & Rahayu (2025), since both PBL and SSI place a strong emphasis on evidence-based reasoning and real-world problem-solving, their integration is thought to have enormous potential for enhancing critical thinking abilities. Based on the findings of Fita et al. (2021), it is evident that SSI-based PBL is effective in

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enhancing critical thinking skills. Therefore, the SSI approach should be integrated into the PBL model, enabling students to navigate life's challenges that have both social and scientific implications (Fakhirah et al., 2025). This SSI-based PBL aims to enable students to solve problems in their daily lives (Masfuah & Pratiwi, 2013). Furthermore, PBL is particularly effective when grounded in social issues directly related to real-life contexts that are conceptually closely tied to science (Wilsa et al., 2017)

In a previous study, Prismayadi (2024) claimed that the SSI-based PBL approach successfully improves critical thinking abilities in content about the respiratory system. These findings indicate that integrating SSI into the PBL framework can strengthen problem-solving through reasoning and decision-making, even when applied to material focused on biological concepts. In line with this, Fita et al. (2021) also demonstrated that SSI-based PBL effectively enhances critical thinking skills, indicating that SSI serves as a learning context that encourages the evaluation of scientific evidence and diverse perspectives in problem-solving. Meanwhile, Saputra & Kuntjoro (2019) showed that PBL on environmental change material effectively develops critical thinking skills; however, the learning process still focuses on problem-solving based on scientific concepts without integrating the social, ethical, and decision-making dimensions that characterize SSI. Based on these results, this study investigates how well SSI-based PBL may be included in high school environmental change courses to improve students' critical thinking abilities.

Although environmental change has been extensively studied, research on the effectiveness of applying SSI-contextualized PBL models to this subject remains limited compared to general PBL/SSI research. This is evidenced by the study by Fatimah & Rahayu (2025), which notes that the majority of SSI-based PBL studies focus on topics such as the digestive system (Aisy et al., 2024), biodiversity (Santika et al., 2018), the plastic problem (López-Fernández et al., 2022), and ecology and biodiversity (Febriyanti & Nurseha, 2025); however, few have centered their analysis specifically and in depth on environmental change topics using the SSI-based PBL model.

This summary indicates that there is still a research gap regarding the application of the SSI-based PBL model to environmental change themes; the majority of prior studies have mainly looked at the application of SSI-based PBL to other biology topics, while there are still relatively few studies that specifically integrate both approaches into environmental change topics. This study aims to evaluate how well students' critical thinking skills in environmental change-related subjects may be enhanced by the SSI-based PBL. It is hoped that the findings of this study will theoretically advance socio-scientific issue-based learning and provide useful guidance for educators in creating contextual learning that prioritizes the development of students' critical thinking skills.

METHODS

Research Design

This study used a one-group pretest-posttest quasi-experimental design with a quantitative methodology (see Table 1). This design was chosen because the study was conducted under real-world conditions at a private high school in the Medan Tembung subdistrict, which had only one 10th-grade class, making it impossible to form a control group or randomize the subjects (Creswell, 2015). The study was conducted at a private high school in Medan Tembung Subdistrict from April to May 2026.

Population and Samples

The study was conducted at a private high school in Medan Tembung Subdistrict from April to May 2026. The study population consisted of 23 10th-grade students, representing the entire 10th-grade cohort at the school; therefore, total sampling was employed, with the entire population serving as the study sample (Arikunto, 2010). Through this design, students' critical thinking skills

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were measured before (pretest) and after (posttest) the implementation of the SSI-based PBL to identify changes in learning outcomes (Creswell, 2014).

Table 1

Single-group pretest–posttest research design.

Pre-test	Treatment	Posttest
O1	X	O2

Note: O1: Pretest, O2: Posttest, X: SSI-based PBL approach

Instruments

Tests, interviews, and documentation were used to acquire the data. The main tool was an essay test with six items based on Facione's (2005) indicators of critical thinking skills: interpretation, analysis, assessment, inference, explanation, and self-regulation (see Table 2). The instrument was designed with reference to the learning objectives and the critical thinking skill indicators being measured. Before being used in the study, the instrument first underwent content validity validation by an expert validator with expertise in biology education to assess the appropriateness of the indicators, content, construction, and language. The validator's feedback was used as the basis for revising the instrument before empirical testing. The instrument's validity and reliability were tested in an experimental class, an 11th-grade class that had previously studied the topic of environmental change. To facilitate the data analysis process, the gathered data were then processed using Microsoft Excel 2021. The results of the instrument's validity test for each indicator are presented in Table 2.

Table 2

Critical thinking skills instrument.

Critical Thinking Indicators	Learning Objectives	Achievement Indicators	Test Questions
Interpretation	Students can identify environmental changes and water pollution through real-world cases and environmental issues, and relate them to SSI (Social Security Innovation) regarding the causes of significant environmental changes and water pollution.	Students can explain the meaning of the problem clearly and accurately.	Based on the above discussion, analyze the environmental changes and water pollution that have occurred. In your opinion, what are the main causes of these problems as they relate to human activities and social issues in North Sumatra?
Analysis	Students can distinguish between air pollution and soil pollution by observing their surroundings and analyzing videos or images systematically and scientifically.	Students can write down the steps needed to solve these problems.	a) Based on the situation presented, analyze the forms of air pollution and soil pollution in the images and text you have observed.

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Critical Thinking Indicators	Learning Objectives	Achievement Indicators	Test Questions
Evaluation	Students can study various types of waste and efforts	to solve environmental problems through logical analysis of social-scientific issues (SSI).	Students can present solutions
Conclusion	Students can explain the utilization of waste and environmental ethics through the analysis of Social-Scientific Issues (SSI) in relevant contexts.	Students can draw logical conclusions based on the questions provided.	Based on the reading, as a student, design a plan to repurpose waste into products that can reduce the volume of waste. Explain your design.
Explanation	Students evaluate the impact of environmental changes and pollution on living organisms and society, and express their opinions based on the results of their analysis and scientific evidence.	Students can present their final results.	Based on the passage, evaluate the impact of environmental change and pollution on living organisms and society. Provide reasons and supporting evidence for your opinion.
Self-Regulation	Students formulate alternative solutions to the problems of environmental change and pollution that are contextual, realistic, and sustainable based on PBL–SSI.	Students can propose alternative solutions to these problems.	Based on the issues in the reading, propose alternative solutions to address environmental change and pollution that can be realistically and sustainably implemented in the surrounding environment. Explain why you chose your solution.

Table 3
Results of the empirical validity test.

Indicator	Calculated r	Table r	Description
Interpretation	0.517	0.456	Valid
Analysis	0.593	0.456	Valid
Evaluation	0.593	0.456	Valid
Conclusion	0.671	0.456	Valid
Explanation	0.556	0.456	Valid
Self-Regulation	0.575	0.456	Valid

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According to Table 2's empirical validity test results, every test item is considered valid as its computed r value is higher than the table r value (0.456). The instrument exhibited acceptable internal consistency, with a Cronbach's alpha coefficient of .787, exceeding the conventional threshold of .70. Table 4 displays the instrument for critical thinking skills.

Procedures

This research was conducted in three main stages: preparation, implementation, and completion. During the preparation stage, the researcher first coordinated with and obtained permission from the school, conducted preliminary observations with the biology teacher at SMAS IRA to identify the students' conditions and abilities, determined the research sample, and prepared learning materials, including lesson plans, worksheets (LKPD), and research instruments in the form of essay-based pretest and posttest questions. Next, the implementation phase began with administering a pretest to all research participants. This was followed by a learning process using the SSI-based PBL model in accordance with the planned learning steps, and concluded with the administration of a posttest. In the final stage, all research data were collected, processed, and analyzed to obtain research findings, which were then used to prepare the report and draw conclusions. Based on the results of this analysis, the researchers determined that the learning activities would be implemented over three sessions. Each session was designed to cover two issues aligned with the learning objectives. The first session focused on Issues 1 and 2 (SSI 1 and 2), the second on Issues 3 and 4 (SSI 3 and 4), and the third on Issues 5 and 6 (SSI 5 and 6). When the PBL model is implemented, there are five primary learning stages: students are presented with a problem; they are organised for learning activities; they conduct individual and group investigations; they create and present their work or products; and, lastly, they analyse and assess the problem-solving process they have undertaken (Arends, 2012). Mapping of socio-scientific issues and biological concepts is shown in Table 4. Implementation on students' worksheet and assessment indicators in Table 5 and SSI-based PBL syntax in Table 6.

Table 4

Mapping of socio-scientific issues and biological concepts.

Code	SSI Issue & Social Phenomenon	Related Biological Concepts	SSI Indicator
SSI-1	Water pollution from household waste; trash dumping into rivers	Environmental pollution, water quality, aquatic ecosystems	Environmental science and ethics
SSI-2	Air and soil pollution caused by open burning of trash and the accumulation of plastic waste in the surrounding environment; use of single-use plastics	Soil pollution, air and soil pollutants	Scientific, social, and environmental aspects
SSI-3	Types of waste resulting from the increase in organic and inorganic waste; low waste sorting rates	Types and classification of waste	Science, economics, environment
SSI-4	Waste utilization, such as converting organic waste into compost and plastic waste into eco-bricks to reduce environmental pollution; conflict between economic interests and environmental sustainability	Recycling, waste management, and environmental ethics	Science, economics, sustainability
SSI-5	Environmental pollution impacts human health and biodiversity: low	The impact of pollution on biodiversity	Science, health, environment

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Code	SSI Issue & Social Phenomenon	Related Biological Concepts	SSI Indicator
	public participation in environmental management		
SSI-6	Design contextual, realistic, and sustainable environmental management solutions: low awareness of waste management	Environmental management, sustainability, and conservation of natural resources	Science, social issues, and ethics

Table 5
Implementation on students' worksheet and assessment indicators.

Code	Implementation in Worksheets	Essay Test Indicator
SSI-1	Case study analysis of water pollution and its impacts	Explains link between human activity and environmental change
SSI-2	Observations of the surrounding environment or analysis of images/ videos of air and soil pollution	Analyzing the long-term impact of plastic waste
SSI-3	Case study analysis of household or small-scale industrial waste management	Analyzing types of waste and mitigation efforts
SSI-4	SSI-based assignments on waste utilization and environmental ethics	Explain waste utilization and evaluate indicators of environmental ethics.
SSI-5	Evaluate the impact of pollution on living organisms and communities using data, graphs, or simple scientific articles	Evaluating the impact of environmental pollution
SSI-6	Designing alternative solutions to environmental problems	Formulating alternative solutions

Table 6
SSI-based PBL syntax.

PBL Syntax	Teacher Activities	Student Activities
Students are introduced to the problem (SSI)	Problem (SSI) • The teacher presents a contextual and relevant problem for students to solve. At this stage, the teacher may present videos, images, or news articles related to social scientific issues (IMS) • The teacher provides guiding questions to direct students' learning objectives.	• Students actively ask questions, respond, and answer the teacher's questions • Students observe explanations, instructional videos, or images presented by the teacher
Students are organized to learn.	Discussion (SSI) • The teacher forms small groups so that students can discuss the Student Worksheets (LKPD).	• Students work in groups and begin their discussions.
Investigations are conducted	Discussion (SSI) • The teacher supervises and guides students as they discuss and	• Students gather information by reading the material and asking the

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PBL Syntax	Teacher Activities	Student Activities
individually or in groups.	gather relevant information to complete the Student Worksheets (LKPD) using textbooks and other reference materials.	teacher about concepts they do not fully understand.
Developing and Presenting Work	Decision Making (SSI) • The teacher guides each group to present the results of their investigation in their own words • The teacher asks students to present the results of their discussion • Argumentation (SSI) • Question-and-answer session and argumentation/debate activities.	• Students plan and prepare their work and divide tasks among group members. • Students present their findings. • Students are expected to ask questions and engage in argumentation actively.
Analysis and evaluation of the problem-solving process	• The teacher provides an evaluation and feedback on the presented results. • The teacher confirms and clarifies • The results of the students' discussion.	• Students listen to the teacher's explanations and feedback.

Source: Arends (2012)

Data Collection and Analysis

By comparing pretest and posttest results using the Normalized Gain (N-Gain) methodology to measure student progress after the learning intervention, the effectiveness of the Problem-Based Learning (PBL) paradigm was evaluated. The category for N-gain score is showed in Table 8. The following formula was used to perform the calculations. An inferential analysis was then used to determine the significance of the difference between the pretest and posttest scores. The Shapiro-Wilk test was employed to ascertain whether the data were normal before hypothesis testing because the sample size was less than 50. To ascertain if the data were regularly distributed, a paired-sample t-test was employed. However, if the data were not normally distributed, the Wilcoxon Signed-Rank test was used (Sianturi, 2025). The effect of using the SSI-based PBL paradigm on critical thinking skills was evaluated using Cohen's d effect size. All analyses were conducted using IBM SPSS Statistics 27 for Windows, with a significance level of $\alpha = 0.05$.

Table 8

N-gain effectiveness.

N-gain score (%)	Category
< 40	Ineffective
40 – 45	Less Effective
56 – 75	Moderately Effective
>76	Effective

RESULTS AND DISCUSSION

The results show that the application of the Problem-Based Learning (PBL) model based on Socio-Scientific Issues (SSI) improved students' critical thinking abilities about environmental change

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subjects. Following the learning process, there was an improvement in indicator interpretation, analysis, assessment, inference, explanation, and self-regulation. Comparing pretest and posttest results revealed significant improvements, as seen in Figure 1. These findings suggest that SSI-based PBL fosters active and reflective learning processes and improves students' higher-order thinking abilities.

Figure 1
Summary of average percentage scores on pre-test and post-test based on critical thinking indicators.

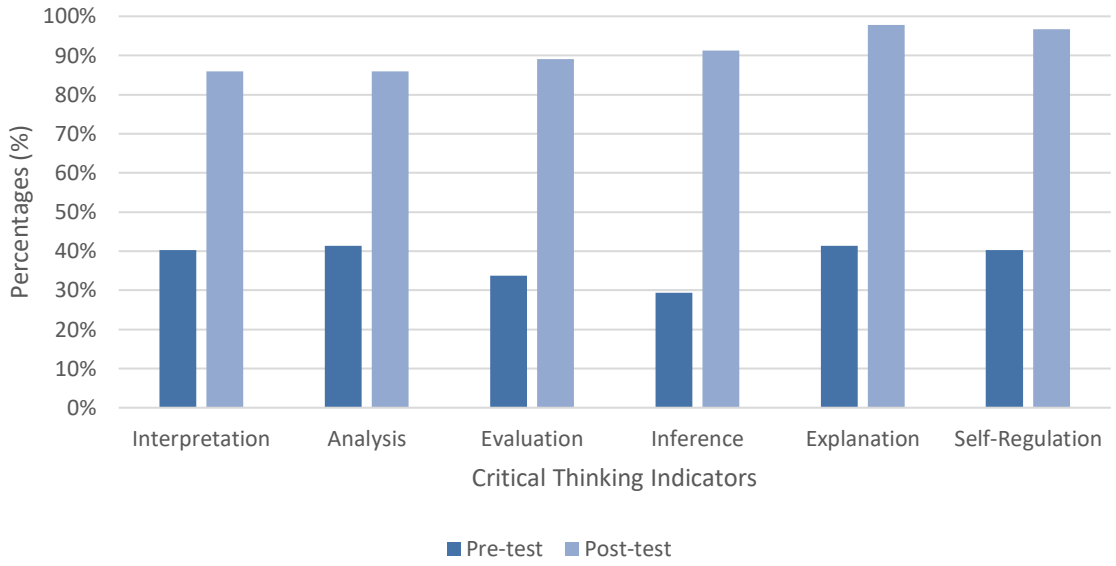

Figure 1 shows a comparison of the average percentages of students' critical thinking skills on the pretest and posttest based on six critical thinking indicators. In general, all indicators showed improvement after the instruction. On the pretest, the percentage scores ranged from 29% to 41%, while on the posttest, they increased to 86%–98%. The highest posttest score was achieved by the explanation indicator (98%), followed by self-regulation (97%), inference (91%), evaluation (89%), and interpretation and analysis, which each reached 86%. Meanwhile, the lowest pretest score was for the inference indicator (29%), while the highest scores were for the analysis and explanation indicators (41%). Additionally, normalized gain (N-gain) was used to assess the efficacy of the teaching based on the extent of the development in students' critical thinking abilities, as depicted in Figure 1. Table 9 shows the analysis's findings.

Table 9
N-gain results for students' critical thinking skills.

Assessment	Average Score	Max. score	N-Gain (%)	Criterion
Pre-test	9.04	24	86	Effective
Post-test	21.87	24		

The data in Table 9 show that the average pre-test score was 9.04 out of a maximum score of 24, while the average post-test score increased to 21.87. The calculated N-gain was 86%, which, according to Sukarelawan et al. (2024), falls into the "effective" category. To provide a more detailed picture, N-gain calculations were also performed for each critical thinking indicator, and the results are presented in Figure 2 below.

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Figure 2
Diagram of N-gain percentages based on critical thinking indicators.

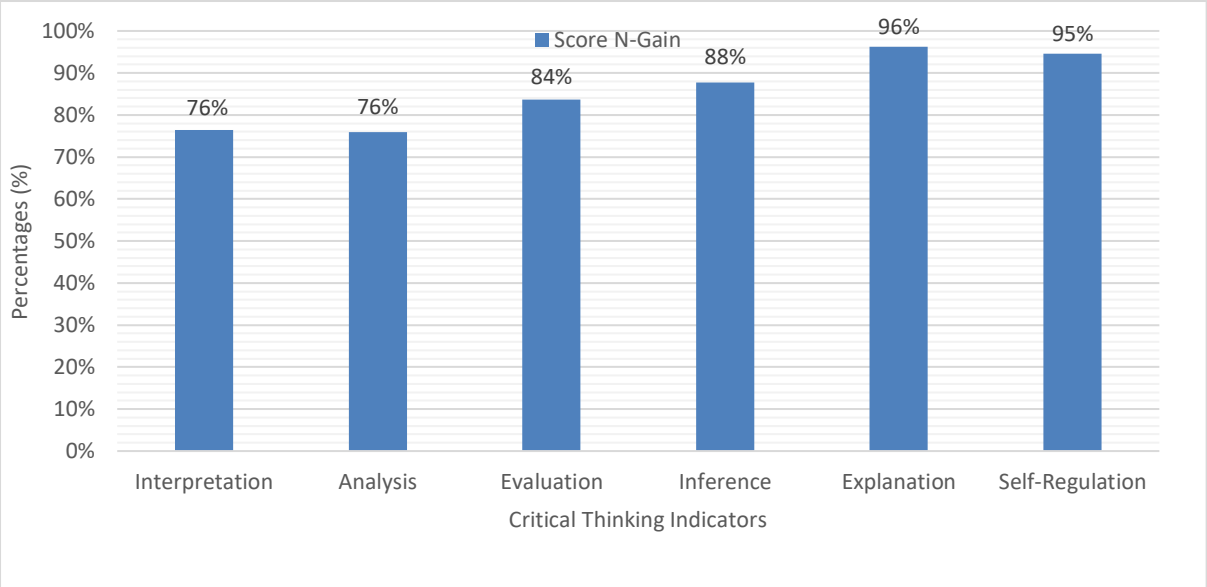

Figure 2 shows that all indicators achieved an N-gain value in the effective category, with percentages of 76% for the interpretation and analysis indicator, 84% for evaluation, 88% for inference, 96% for explanation, and 95% for self-regulation. The highest N-gain score was obtained for the explanation indicator, while the lowest scores were found for the interpretation and analysis indicators. However, the N-gain results only describe the magnitude of the improvement descriptively. Therefore, inferential statistical analysis is needed to test whether these improvements are statistically significant.

A normality test was the first step in inferential statistical analysis, which was followed by a paired-sample t-test and the computation of the effect size (Cohen's d). The Shapiro-Wilk test results showed that the pretest ($p = 0.054$) and posttest ($p = 0.059$) data were normally distributed ($p > 0.05$), meeting the criteria for paired-sample t-test analysis. The results of the paired-sample t-test is showed in Table 10.

Table 10
Results of the paired-sample t-test.

Comparison	Mean Difference	*t*	*df*	Sig. (*p*)	Significance Level (α)
Pretest – Posttest	-12.826	-35.168	22	<0.001	0.05

The paired-sample t-test in Table 10 produces a p-value of less than 0.001, which is below the $\alpha = 0.05$ significance level. These results demonstrate that students' critical thinking skills greatly increased following the implementation of the Problem-Based Learning (PBL) paradigm based on Socio-Scientific Issues (SSI). The previously reported N-gain results likewise support this conclusion, and both analyses consistently show that the SSI-based PBL model successfully enhances critical thinking abilities. As shown in Table 11, the effect size estimate also reveals a relatively large effect category (Cohen's d = 7.333). These findings suggest that implementing the SSI-based PBL model not only produced a statistically significant improvement but also had a significant effect on students' critical thinking skills.

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Table 11
Results of the effect size analysis of the implementation of SSI-based PBL.

Effect Size	Value	Category
Cohen's *d*	7.333	Very large effect (Cohen, 1998)

Based on the data presented, the research results show that the SSI-based PBL model has proven effective in developing students' critical thinking skills regarding environmental change. These findings are supported by increased scores on all critical thinking indicators (Figure 1), N-gain values in the "effective" category (Table 9), significant differences between the pretest and posttest (Table 10), and a very large effect size (Table 11). These results indicate that integrating socio-scientific issues into the PBL syntax creates a learning experience that encourages students to think more analytically, reflectively, and evidence-based.

This phenomenon can be explained by the characteristics of Problem-Based Learning (PBL) based on Socio-Scientific Issues (SSI), which prioritises students in the learning process. Through the PBL framework, students are actively engaged in identifying problems, conducting investigations, discussing alternative solutions, and presenting and reflecting on their findings. These activities encourage students to construct knowledge independently through interaction with real-world problems and collaborative work. This procedure is consistent with constructivist theory, which holds that meaningful learning experiences and students' active participation in expanding their comprehension are how knowledge is created (Vygotsky, 1978; Savery, 2006).

The success of this learning is further reinforced by the integration of Socio-Scientific Issues (SSI) as the learning context. Environmental issues, such as pollution and waste management, present complex, contextual problems with no single, absolutely correct answer. These conditions encourage students to identify relevant information, evaluate the credibility of evidence, compare alternative solutions, construct logical arguments, and reflect on the consequences of every decision made. Students gain conceptual comprehension as well as integrated practice of several critical thinking skills through this procedure. These results are consistent with Zeidler et al. (2005), who claim that by fostering scientific debate and evidence-based decision-making, socio-science issue-based learning can improve critical thinking abilities. Upon closer inspection, an analysis based on each indicator's N-gain values (Figure 2) reveals that the degree of improvement was not consistent. These differences show that, depending on the features of the cognitive processes formed throughout the learning process, each component of critical thinking abilities reacted differently to the use of the SSI-based PBL paradigm.

The "explanation" (96%) and "self-regulation" (95%) indicators showed the most significant improvements in SSI-based PBL learning. Although both indicators developed optimally, the mechanisms behind the improvement in each indicator differed depending on the supporting learning activities. The students' intensity primarily influenced the improvement in the "explanation" indicator in communicating and defending their reasoning during the inquiry and presentation processes. During instruction on environmental change, students were not only asked to find solutions to issues such as water pollution, air pollution, waste management, and environmental change, but also to justify the scientific rationale behind those solutions to other groups. During presentations, students had to explain the relationship between the facts they discovered, the concept of environmental change, and the scientific evidence used. When faced with questions or objections from other groups, they were encouraged to revisit the arguments they had constructed, address weaknesses in their reasoning, and consider additional evidence before defending their conclusions. Through these activities, students' "explanation" skills developed further because they had repeated opportunities to articulate their thought processes explicitly. Masitoh et al. (2017) also found in their study that the "explanation" indicator showed the greatest increase because students had ample opportunities to express ideas, defend their

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opinions, and provide evidence-based reasoning during the process of formulating hypotheses, discussing them, and analyzing the results.

Furthermore, the significant increase in self-regulation indicates that students are not only able to present arguments but also to evaluate and refine their thought processes during learning. This ability develops as students compare their initial conclusions with the evidence gathered during their investigation and then reassess whether their chosen solution is still supported by sufficient evidence. During the reflection stage, the teacher guides students in identifying weaknesses in their arguments and considering improvements to the decisions they have made. This process of monitoring, evaluation, and revision trains students to consciously correct their reasoning so that the resulting decisions become more logical and evidence-based. This aligns with Syarifah et al. (2025), who state that self-regulation skills develop through reflecting on thinking strategies and learning outcomes, enabling students to improve their decisions based on the feedback they receive.

In contrast, interpretation and analysis showed the lowest improvement (76%). These results do not indicate that these two skills are difficult to develop, but rather that they develop more gradually. At this stage, students are not yet directly asked to make decisions, but must first understand the characteristics of the problem, identify relevant information, and relate it to the scientific concepts they have already learned. During the problem-orientation stage, students first analyzed various cases involving water pollution, air pollution, and soil pollution. They identified the causes, forms of pollution, and the relationship between human activities and changes in environmental quality before discussing alternative solutions. These activities required students to distinguish between scientific facts, opinions, and less relevant information, thereby allowing their interpretation and analysis skills to be developed gradually. These findings are consistent with Tiruneh et al. (2018), who explain that interpretation and analysis are foundational thinking skills that develop gradually before students can evaluate, infer, or explain. Similar results were also reported by Farras et al. (2026), who found that students require more time to develop the ability to analyze information than to present the results of a discussion.

Once students can understand and analyze information, their evaluation (84%) and inference (88%) skills begin to develop through the process of making decisions regarding various alternatives for resolving environmental issues. In the lessons on waste utilization and efforts to address pollution, each group generated different solutions, requiring students to compare the effectiveness of each alternative based on scientific evidence, environmental impact, social consequences, and feasibility of implementation. This process hones evaluation skills, as students assess the strength of arguments before accepting a solution. Furthermore, inference skills develop when all evaluation results are integrated into a conclusion agreed upon by the group. The slightly higher score for inference compared to evaluation indicates that, after gathering various pieces of evidence and input during discussions, students find it relatively easier to formulate a decision than to assess the quality of each piece of evidence critically.

Overall, the differences in improvement across all indicators indicate that the SSI-based PBL model not only improves students' critical thinking abilities but also helps them develop each critical thinking component according to the features of the cognitive processes involved. In other words, the differences in the degree of improvement among indicators do not indicate any weaknesses in the learning model but rather reflect the complexity of each critical thinking skill, which develops gradually throughout the learning process. These findings are also consistent with previous researches (Wilsa et al., 2017; Prasetyo et al., 2024), which reported that the integration of PBL and SSI is effective in enhancing students' critical thinking skills. The consistency of these findings suggests that the effectiveness of SSI-based PBL does not depend on a specific research context but reflects the characteristics of a learning model that systematically trains students to construct scientific arguments, evaluate evidence, and make decisions based on logical reasoning.

Nevertheless, the improvement in critical thinking skills observed in this study was likely influenced by more than just the implementation of the SSI-based PBL model. Increased learning

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motivation stemming from topics closely related to students' lives, the intensity of group discussions that facilitated the exchange of ideas and feedback, and students' growing familiarity with critical thinking question formats may also have contributed to the results. Furthermore, the use of a one-group pretest-posttest design allows for the influence of external factors that cannot be fully controlled during the study. Therefore, although the increases in pretest, posttest, and N-gain scores indicate that SSI-based PBL is effective in improving students' critical thinking skills, the interpretation of the results must still account for the possible contributions of these other factors. It is advised that future studies include a control group or a more robust experimental design in order to more precisely identify the impact of the SSI-based PBL model.

CONCLUSION

These findings indicate that the implementation of the Problem-Based Learning (PBL) paradigm, supported by Socio-Scientific Issues (SSI), enhances students' critical thinking skills in environmental change education. This improvement is evidenced by pre-test scores in the low category (29%–41%) and post-test scores that increased to 86%–98%. The paired-sample t-test results, which demonstrated a significant difference between the pre-test and post-test ($p < 0.001$), confirm the N-gain of 86% in the "effective" category and the effect size (Cohen's $d = 7.333$), indicating a very strong effect. The findings suggest that activities such as analysis, discussion, and decision-making based on scientific evidence can enhance critical thinking skills through SSI-based PBL learning. Nevertheless, the study's findings are still restricted to a single school, have a small sample size, and lack a comparison group. To improve the findings' generalizability, it is advised that future studies use a larger sample size and an experimental design including a control group.

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