



## The Effectiveness of STEM-PBL Learning Innovation in Climate Awareness Material to Improve Critical Thinking and Sustainability Consciousness of High School Students: Literature Review

Oleh:

Rosyidatul Mufida<sup>1</sup>, Daniya Nabila Bayuputri<sup>1</sup>, Nurita Apridiana Lestari<sup>1</sup>, dan Muhammad Nur Hudha<sup>2</sup>

<sup>1</sup>Jurusan Pendidikan Fisika, Universitas Negeri Surabaya, Surabaya, Indonesia

<sup>2</sup>Jurusan Pendidikan Ilmu Pengetahuan Alam, Universitas Negeri Sebelas Maret, Surakarta, Indonesia

\* Email: [nuritalestari@unesa.ac.id](mailto:nuritalestari@unesa.ac.id)

**Abstrak** — Krisis iklim menuntut sistem pendidikan menengah tidak hanya meningkatkan pengetahuan faktual, tetapi juga menumbuhkan kesadaran dan tindakan berkelanjutan di kalangan siswa. Salah satu pendekatan yang relevan adalah Pembelajaran Berbasis Masalah dalam Ilmu Pengetahuan, Teknologi, Teknik, dan Matematika (STEM-PBL), yang mengintegrasikan pemecahan masalah kontekstual, kolaborasi, dan penyelidikan berbasis bukti. Artikel ini bertujuan untuk mengkaji tren dan efektivitas implementasi STEM-PBL dalam materi kesadaran iklim di sekolah menengah atas, dengan fokus pada peningkatan keterampilan berpikir kritis dan kesadaran keberlanjutan. Penelitian ini menggunakan metode Tinjauan Literatur Sistematis (SLR) dengan pendekatan naratif, mengikuti pedoman PRISMA 2020. Artikel diperoleh melalui pencarian Google Scholar untuk periode 2020–2025 dengan kriteria intervensi STEM-PBL dalam materi kesadaran iklim di sekolah menengah atas dan penggunaan instrumen pengukuran keterampilan berpikir kritis dan kesadaran keberlanjutan. Dari 100 artikel awal, 46 lolos tahap kelayakan, dan setelah penilaian kualitas, 10 artikel dipilih untuk disintesis. Hasil penelitian menunjukkan bahwa STEM-PBL secara konsisten meningkatkan kemampuan analisis berbasis data, evaluasi, penalaran, dan argumentasi siswa sekolah menengah atas. Selain itu, kesadaran akan keberlanjutan meningkat melalui pengalaman autentik siswa dalam menyelidiki masalah iklim lokal, merancang solusi teknik, dan merefleksikan dampak sosial-lingkungan dari pilihan mereka. Beberapa penelitian menegaskan bahwa pemikiran kritis berfungsi sebagai jembatan kognitif yang mengubah pemahaman ilmiah menjadi nilai dan tindakan berkelanjutan. Kesimpulan studi ini adalah bahwa integrasi STEM-PBL tidak hanya memperkuat kompetensi abad ke-21 melalui berpikir kritis tetapi juga membentuk disposisi pro-lingkungan yang mendukung pencapaian Tujuan Pembangunan Berkelanjutan (SDGs), khususnya Tujuan 13. Batasan yang diidentifikasi meliputi cakupan sampel yang terbatas, heterogenitas desain, dan penggunaan instrumen non-standar, sehingga penelitian longitudinal dan lintas konteks lebih lanjut menjadi esensial.

**Kata kunci:** STEM-PBL, pemikiran kritis, kesadaran keberlanjutan, kesadaran iklim.

**Abstract** — The climate crisis demands that secondary education systems not only improve factual knowledge, but also foster awareness and sustainable action among students. One relevant approach is Science, Technology, Engineering, and Mathematics Problem Based Learning (STEM-PBL), which integrates contextual problem solving, collaboration, and evidence-based inquiry. This article aims to examine the trends and effectiveness of STEM-PBL implementation in climate awareness material in high schools, with a focus on improving critical thinking skills and sustainability consciousness. The research uses the Systematic Literature Review (SLR) method with a narrative approach, following the PRISMA 2020 guidelines. Articles were obtained through a Google Scholar search for the period 2020–2025 with the criteria of STEM-PBL intervention in climate awareness material in high schools and the use of critical thinking and sustainability consciousness measurement instruments. Of the 100 initial articles, 46 passed the eligibility stage, and after quality assessment, 10 articles were selected for synthesis. The results of the study show that STEM-PBL consistently improves high school students' data-based analysis, evaluation, inference, and argumentation skills. In addition, sustainability awareness increases through students' authentic experiences in investigating local climate issues, designing engineering solutions, and reflecting on the socio-environmental impacts of their choices. Several studies confirm that critical thinking serves as a cognitive link that translates scientific understanding into sustainable values and actions. The conclusion of this study is that the integration of STEM-PBL not only strengthens 21st-century competencies through critical thinking but also shapes pro-environmental dispositions that support the achievement of the SDGs, particularly goal 13. Limitations identified include limited sample coverage, heterogeneity of designs, and the use of non-standardized instruments, making further longitudinal and cross-context research essential.

**Keywords:** STEM-PBL, critical thinking, sustainability consciousness, climate awareness.

## Introduction

The climate crisis requires secondary education systems to not only increase factual knowledge, but also foster awareness and sustainable action among students. In Indonesia, recent policy analysis shows that there is still a gap between climate change policy and education policy, so the integration of climate awareness material into the formal curriculum is not yet optimal (Tang, 2024). This situation calls for contextual, interdisciplinary, and measurable pedagogical strategies at the school level.

In the field of pedagogy, one appropriate approach is STEM–Problem-Based Learning (STEM-PBL), which encourages students to investigate real-world problems such as global warming or the greenhouse effect and then design evidence-based solutions. The integration of STEM with PBL enables the exploration of science, technology, engineering, and mathematics concepts within an authentic inquiry framework. Problem-Based Learning (PBL) is a contextual approach that encourages authentic problem solving, collaboration, and independent learning. A recent meta-analysis of 66 studies shows that PBL has a positive effect on academic achievement, affective attitudes, and thinking skills, including problem solving and collaboration, with an overall effect on meaningful learning outcomes. At the high school level, PBL learning tends to be stronger than at other levels, providing a pedagogical reason for applying it to climate awareness material. The impact of PBL on 21st-century competencies, integrated with the STEM framework, is increasingly recommended. This shows that STEM-based PBL (STEM-PBL) significantly increases creativity, a construct that correlates with critical thinking in the context of open reasoning and solution design, making it relevant to complex issues such as climate change (Kwon, 2025). This integration provides a strong pathway from scientific understanding to the engineering of sustainable solutions.

The integration of STEM with PBL (STEM-PBL) adds depth to the inquiry process through scientific modeling, engineering design, and mathematical quantification practices, thereby making solution justification more structured. STEM-PBL shows a moderate positive effect on student learning outcomes, with variations in effect according to level, duration, and variety of teaching strategies. At the same time, STEM learning can improve problem-solving skills that are closely related to critical reasoning in constructing and evaluating data-based arguments. STEM-PBL can be applied through the phases of

problem orientation, investigation, design, testing, and reflection, while maintaining the conceptual demands of the science subjects studied in school. When PBL is combined with STEM components (modeling, engineering, quantification) and local climate issues, the potential for critical thinking can be enhanced through data inquiry and evidence-based reasoning. According to Astuti 2023 in Indonesia, PBL-based learning on climate awareness material with the topic of global warming is considered valid and practical for the high school context, and its impact on students' critical thinking skills has been tested. However, most studies stop at the feasibility test stage without quantitatively evaluating the impact of learning using standardized instruments.

This article emphasizes two main outcomes. First, critical thinking, which is broadly measured by the California Critical Thinking Skills Test (CCTST) based on the APA Delphi consensus (Facione, 2013). Second, sustainability consciousness, which encompasses the dimensions of knowingness, attitudes, and behavior, is generally measured using the Sustainability Consciousness Questionnaire (SCQ) (Gericke et al., 2019; Hijazi, 2024). International evidence supports that PBL effectively improves critical thinking (Strobel & van Barneveld, 2009), but in the context of climate-themed high schools, the use of standard instruments such as CCTST and SCQ is still limited. This opens up space for a systematic review to map trends, evaluate effectiveness, and identify methodological gaps. Therefore, this study presents a Systematic Literature Review (SLR) on the trends and effectiveness of STEM–PBL on the topic of climate awareness in high schools with the following objectives: (1) to map research trends, and (2) to synthesize effectiveness on critical thinking and sustainability consciousness, with reporting following PRISMA 2020 (Page et al., 2021).

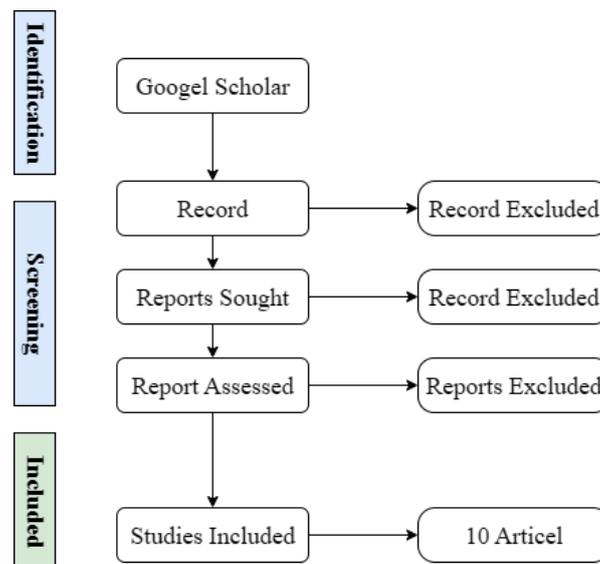
## Method

The research method used in this study was a Systematic Literature Review (SLR). This technique was used to collect and analyze research related to “Trends and Effectiveness of STEM-PBL Learning Innovations in Climate Awareness Material to Improve Critical Thinking and Sustainability Consciousness of High School Students.” The SLR approach was chosen so that the process of searching and selecting articles was orderly, transparent, and replicable, while also producing an evidence-based synthesis (Adiputra & Heryadi, 2021). This study was designed as a narrative literature review to map the trends and

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effectiveness of STEM-PBL learning innovations in climate awareness material at the high school level. The narrative approach was chosen so that the review could highlight the context of implementation in the classroom, variations in learning designs, and various learning outcome indicators, particularly critical thinking (CT) and sustainability consciousness (SC). Articles were searched for using Google Scholar as the main database due to its cross-publisher coverage and high accessibility to educational literature. Keywords were compiled to capture variations of terms relevant to the title, namely STEM problem-

based learning, climate change, critical thinking, sustainability consciousness, and high school students. The search was conducted for the period 2020–2025 to focus on the latest developments in the foundational literature, namely the SCQ instrument, which can be referred to as necessary to confirm the measurement construct (Gericke et al., 2019; Ogishima et al., 2023). The complete flow of the eligibility screening identification is presented in the PRISMA Diagram (Figure 1) in accordance with the SLR reporting guidelines (Page et al., 2021).



**Figure 1.** SLR stages in the PRISMA diagram

The identification stage produced 100 initial articles from Google Scholar that were potentially relevant to the topic. All initial findings were exported, manually deduplicated, and then entered the screening stage through reading the titles and abstracts to assess their suitability with the STEM-PBL focus on climate awareness material at the high school level and the reporting of critical thinking and sustainability consciousness. After screening, articles that passed entered the eligibility stage with full text reading to verify the existence of PBL-based STEM learning interventions, clarity of climate material context, and the use of critical thinking and sustainability consciousness indicators. At the end of the eligibility stage, 46 articles that met the topic and level restrictions were selected. Next, a quality assessment was conducted to weigh the methodological strength of each study and the

clarity of its reporting. The assessment considered the suitability of the STEM-PBL intervention design, then considered the alignment of the CT instruments, namely related to reasoning rubrics, evidence evaluation tasks, metacognitive reflection, and the alignment of SC instruments on literacy and climate action indicators with learning objectives, as well as the accuracy of data analysis. Based on quality assessment, 10 articles were deemed eligible for inclusion in the final synthesis. The synthesis process was conducted narratively and thematically. First, the included articles were characterized (country, sample, duration, climate topic focus, STEM-PBL tools and phases, and CT/SC instruments). Second, the findings were compared to identify patterns of consistency and variability in CT and SC outcomes, as well as the proximity of the projects to local climate issues.

## Result and Discussion

This study discusses the effectiveness of STEM-PBL learning on climate awareness

material to improve critical thinking and sustainability consciousness among high school students. The results of this study are described using a prism diagram to obtain data. The collected

data can be used to explain the issues behind this study. A total of 10 scientific articles relevant to the research problem were used as the final scientific articles for this study. The data obtained was then grouped according to the research questions. This coding was given alphabetical symbols. The letter A indicates articles that discuss trends and the effectiveness of STEM-PBL learning on climate awareness material. The letter B is used for articles that discuss the effectiveness of STEM-PBL

learning in improving critical thinking among high school students. The letter C was used for articles discussing the effectiveness of STEM-PBL learning in improving the sustainability consciousness of high school students. Meanwhile, the letter D indicated articles discussing the effectiveness of STEM-PBL learning in improving the critical thinking and sustainability consciousness of high school students. The division of categories can be seen in Table 1 below.

**Table 1.** Number of Codes A, B, C, and D

No	Code	Description	Number of Articles
1	A	STEM-PBL on climate awareness	2
2	B	Critical thinking	3
3	C	Sustainability Consciousness	3
4	D	Critical thinking and Sustainability Consciousness	2

In Table 1, 10 articles selected through SLR were mapped to four main topic codes. Code A (STEM-PBL on climate awareness material) included 2 articles (20%), highlighting problem-based learning design to strengthen knowledge and context of climate issues. Code B (critical thinking) contains 3 articles (30%) that focus on improving analytical, reasoning, and problem-solving skills through PBL syntax within the STEM framework. Code C (sustainability consciousness) also consists of 3 articles (30%) that assess the dimensions of awareness, attitudes, and tendencies toward sustainable behavior among students. Code D (critical thinking and sustainability consciousness) contains 2 articles (20%) that simultaneously target high-level cognitive achievements and the formation of sustainability awareness. The distribution is relatively balanced with a slight dominance in critical thinking and sustainability awareness achievements, indicating that STEM-PBL on climate awareness material is not only directed at content mastery but also at the formation of 21st-century skills and value orientation for sustainable action. A detailed description of the findings and characteristics of each code is presented in the following section.

#### **A. Trends And Effectiveness Of STEM-PBL Learning On Climate Awareness Materials**

Over the past three to four years, research in Indonesia has shown a clear shift towards problem-based learning combined with a STEM approach to climate awareness topics in high schools. Problem-Based Learning, which intersects with ESD (education for sustainable development), encourages cognitive behavioral engagement and strengthens students' sustainability awareness, such as changes in mindset, climate change literacy, and climate action in line with the

Merdeka Curriculum's push for PBL on global issues such as alternative energy, global warming, and climate change. PBL is an approach that focuses learning on solving authentic problems through teamwork, inquiry, and reflection. When integrated with STEM, each phase of the investigation utilizes science (explaining phenomena), technology (accessing and presenting data), engineering (designing solutions and prototypes), and mathematics (modeling and analyzing results). In the classroom, teachers act as facilitators who guide the identification of problems, formulation of hypotheses, collection and analysis of evidence, design of solutions, and communication of data-based decisions. In Indonesia, PBL studies on the topic of global warming show the strengthening of critical thinking and problem-solving, for example in classes that implement ESD-based PBL (Putri, 2021) and the development of PBL-based GLOWASEA media to train critical thinking (Widodo et al., 2024). These findings confirm that this approach has proven effective in the context of science education in Indonesia, where the development and application of STEM-PBL in environmental education can improve students' problem-solving skills, and where PBL in physics on the topic of climate change can improve critical thinking skills when enriched with digital learning resources and environmental contexts.

Climate awareness encompasses knowledge, attitudes, values, and behavioral tendencies regarding climate change that drive decision-making and mitigation and adaptation actions. Lestari et al. (2024), through a systematic review of sustainable physics learning, emphasize that climate change education must link scientific understanding with learning experiences that shape dispositions to act, rather than merely transferring

concepts. Similarly, Lestari et al. (2023), in a bibliometric analysis of climate literacy, affirm the role of literacy as the foundation for education, mitigation, and adaptation oriented towards sustainability. UNESCO places climate change education at the center of preparing “agents of change” with these competencies (UNESCO, 2017). In Indonesia, official guidelines emphasize climate change education as a priority curriculum issue with the aim of fostering students' awareness and concern for the impacts and solutions. In sustainable physics learning, it is emphasized that Climate Change Education (CCE) needs to link scientific understanding with learning experiences that shape dispositions to act, rather than merely transferring concepts.

At the high school level, STEM-PBL generally begins with local issues such as heat waves, school

energy consumption, or traffic emissions. Students examine data (BMKG, class carbon footprint), design solution ideas (vegetation shade, energy efficiency, electricity saving campaigns), then test and refine their designs and present evidence-based recommendations. STEM-PBL for climate awareness in high school links climate science with relevant problem-solving experiences, fostering an agentic disposition toward sustainable practices.

According to the results of a literature review of 10 scientific articles found, there were 2 articles that examined the trends and effectiveness of STEM-PBL learning on climate awareness material. The results of the study are shown in Table 2 below.

**Table 2.** Trends and Effectiveness of STEM-PBL Learning on Climate Awareness Materials

No	Author (Year)	Research Results
1	Pertiwi, Oetomo, and Sugiharto (2024)	Research results Comparing conventional PjBL vs STEM-PBL at Surakarta State High School 7. Results: environmental literacy increased significantly; STEM-PBL experimental class +16.94% vs control +10.16%. Improvements in knowledge, attitude, cognition, and environmental behavior.
2	Rizqulloh, Rusnayati, and Danawan (2024)	The results of the application of PBL learning with an ESD approach on global warming material (high school) were obtained from a one-group pre-experiment (class XI; n≈38). Results: N-gain of critical thinking is 0.524 (medium), and sustainability awareness is obtained at 73.94% (high) after learning. It can be concluded that the trend and effectiveness of STEM-PBL learning effectively raise cognitive abilities while building sustainability awareness on climate issues.

Based on the results of the analysis of the two articles, it can be concluded that the application of STEM-based PBL in climate awareness material effectively improves the cognitive and affective achievements of high school students. This effectiveness occurs because PBL-STEM places students as real problem solvers, identifying climate change issues in their environment, examining data, developing and testing solutions, and communicating evidence-based decisions. Such collaborative inquiry processes encourage scientific argumentation, systematic reasoning, and the formation of sustainable attitudes and values, rather than merely conceptual understanding. Thus, the latest research trends confirm that PBL-STEM in climate awareness material not only improves higher-order thinking skills but also fosters a sustainable behavioral orientation.

## **B. The Effectiveness Of STEM-PBL Learning In Improving Critical Thinking Among High School Students**

Critical thinking skills are an intellectual process involving the creation of concepts, application, synthesis, and/or evaluation of information obtained from observation, experience, reflection, thought, or communication as a basis for believing and taking action (Lismaya, L., 2019). According to Norris and Ennis (Stiggins, 1994), critical thinking skill indicators are a set of stages that comprise the critical thinking process, namely clarifying issues by asking critical questions, gathering information about issues, beginning to reason from different perspectives, gathering information and conducting further analysis if necessary, and making and communicating decisions. In general, the critical thinking ability (CTA) profile of high school students is in the moderate to high range but is not

yet evenly distributed across all indicators. The indicators of simple explanation and basic skills are still in the adequate category, while inference, further explanation, and strategy or tactics are relatively stronger (Ennis-based). These findings indicate an imbalance in CTH sub-skills and the need for learning that provides space for evidence-based reasoning, concept clarification, and argumentation (Santia and Hidayati, 2024). In addition to student factors, assessment problems also influence the development of KBK. A regional study in Vietnam, for example, found that the practice of multiple-choice tests/exams, which are still dominant, hinders the assessment of STEM-specific processes and products (portfolios, design artifacts, reasoning rubrics), thereby reducing opportunities for students to practice analysis, evidence evaluation, and reflection (Nguyen and Thai, 2025). Although cross-national, this lesson is relevant to the context of secondary schools in Southeast Asia that are mainstreaming STEM and HOTS.

Overall, STEM interventions have a moderate impact on learning outcomes, and are most effective in the cognitive domain at the high school level. This shows that high school age/level is very conducive to strengthening KBK through an

integrated science-technology-engineering-mathematics (STEM) approach (Cao, Lu, and Wu, 2025). In climate awareness material, the application of PBL-STEM significantly improves students' systems thinking. From a learning theory perspective, PBL practices cognitive apprenticeship teachers facilitate with guiding questions, reasoning modeling, and collaboration management; scaffolding is then faded so that students take over learning regulation and evidence evaluation. This practice has been proven to encourage higher-order thinking and transfer of reasoning strategies. STEM integration –PBL on climate awareness material is carried out through: (a) ill-structured contextual problems, multi-criteria analysis and evidence evaluation, (b) formulating needs, prototyping, testing, and revising) that encourage inference and reflection, (c) structured collaboration that elicits argumentation with evidence; and (d) authentic assessment.

According to the results of a literature review of 10 scientific articles found, there were 3 articles that examined the effectiveness of STEM-PBL learning in improving the critical thinking of high school students.

**Table 3.** Effectiveness of STEM-PBL learning to improve critical thinking of high school students

No	Author (Year)	Research Results
1	I Putu Yogi Setia Permana, I Dewa Putu Nyeneng, I Wayan Distrik (2021)	The results showed that the application of STEM approach with PBL model to high school students increased critical thinking skills significantly: the experimental class achieved N-gain = 0.73 (high category), higher than the control (0.56), with effect size $d = 1.49$ and significance test $p < 0.05$ , so it was concluded effective for strengthening critical thinking in high school physics.
2	Sheril Mahany, Fitria R. Mufida, N.Y.N. Ramadani, N.Z. Divanissa, S.D. Saputro, Setyo Admoko (2025)	Bibliometric analysis of 124 articles (2010-2025) and concluded that PBL strategies, including PjBL-STEM, were repeatedly reported to improve aspects of critical thinking (analysis, evaluation, reflection) in physics learning; the publication trend of the last five years also increased sharply, indicating the consistency of effectiveness and research attention.
3	Putri, Sukmono, and Wicaksana (2023)	The implementation of STEM-PBL in high school biology is proven to significantly improve critical thinking skills, significant in critical thinking (ANOVA), N-Gain 51 (experimental) vs 48 (control). It can be concluded that it is proven effective in improving students' critical thinking skills, with significant differences between experimental and control classes.

Based on the analysis of the three articles reviewed, it can be concluded that the application of STEM-PBL has proven to be effective in improving the critical thinking skills of high school

students, especially in the subject of climate awareness. The application of STEM-PBL learning at the high school level has a real effectiveness in improving students' critical thinking skills. This

model presents a learning process that emphasizes problem identification, evidence analysis, and contextual solution finding, thereby encouraging students to develop higher-order thinking skills. The characteristics of PBL, which focuses on solving real problems, when combined with STEM integration, provide a more authentic, collaborative, and reflective learning experience. Thus, STEM-PBL plays an important role not only in strengthening cognitive aspects but also in shaping analytical, evaluative, and creative mindsets, which are at the core of critical thinking in 21st-century education.

In practice, teachers can utilize the STEM-PBL approach as a more meaningful learning strategy by presenting contextual issues, such as environmental problems and climate change, to directly train students' critical thinking skills. Schools can also incorporate this model into curriculum innovation, for example through cross-curricular project integration, provision of simple laboratory facilities, and strengthening collaboration among teachers in designing problem scenarios. These implications emphasize that the effectiveness of STEM-PBL extends beyond academic achievement to the development of a culture of critical and creative learning that supports the achievement of sustainable education goals.

### C. The Effectiveness Of STEM-PBL Learning In Increasing Sustainability Consciousness Among High School Students

In general, the level of Sustainability Consciousness (SC) among high school students in Indonesia is still in the moderate category, with a tendency to be more prominent in the cognitive aspect than in the affective and behavioral aspects. Ardoin, Bowers, and Gaillard (2020) found that adolescents have a fairly good understanding of environmental issues, but their awareness to act sustainably is still limited, especially in daily

practices. A similar finding was reported by Hidayati (2022), who studied high school students in Central Java, where knowledge about climate change was quite high, but the dimensions of sustainable attitudes and behavior had not developed optimally. This condition indicates a gap between knowledge and willingness to act, thus requiring a more contextual and applicable learning approach to strengthen SC as a whole.

The integration of STEM-PBL has proven to be relevant in increasing Sustainability Consciousness because this model connects scientific concepts with real-world, cross-disciplinary problem solving. According to Bybee (2020), problem-based STEM learning allows students to relate academic concepts to sustainability issues such as renewable energy, waste management, and climate change mitigation. This is in line with the research by Saputri and Suryadi (2024), which found that the application of STEM-PBL to global warming material in high school significantly improved students' systems thinking skills, which is an important indicator in the development of sustainability awareness. Musahal, Rahmawati, Purwanto, and Mardiah (2024) also showed that when students were invited to design STEM-based solutions to household waste issues, they not only mastered environmental chemistry concepts but also showed an increase in environmental awareness and sustainability awareness. This reinforces UNESCO's (2023) opinion that problem-based learning that integrates sustainability issues will encourage the emergence of a young generation with pro-environmental awareness, attitudes, and actions.

According to the results of a literature review of 10 scientific articles found, there were 3 articles that examined the effectiveness of STEM-PBL learning in increasing the sustainability consciousness of high school students.

**Table 4.** The effectiveness of STEM-PBL learning in increasing sustainability awareness among high school students

No	Author (Year)	Research Results
1	Maulina, D., Priadi, M. A., Gustina, M., and Rakhmawati, I. (2025)	Quasi-experimental design (NECG) in two high school classes with a climate change theme oriented towards SDGs. Results: An average SA of 81.42% (category "often/always done") shows that PBL has a positive effect on students' sustainability awareness.
2	Ramandani, R., Lestari, N. A., Budiarto, E., and Uulaa, R. F. R. (2024).	Development of PBL-based modules integrated with environmental education on the topic of climate change. R&D study (ADDIE) with excellent validity results; module design explicitly trains "environmental awareness" character alongside problem-solving skills

		in line with the affective dimension of sustainability consciousness.
3	Abdurrahman, Maulina, Nurulsari, Sukanto, Umam, and Mulyana (2023)	STEM-PBL and Engineering Design Process (EDP) on renewable energy material (11th grade high school) significantly improved systems thinking, with the treatment class outperforming the control class on all systems reasoning indicators. The study confirms the relevance of ESD and the strengthening of engineering-based sustainability awareness.

#### D. The Effectiveness Of STEM-PBL Learning In Improving Critical Thinking And Sustainability Consciousness Among High School Students

High school students' critical thinking skills improved after participating in STEM-PBL-based learning. Students were able to ask analytical questions, identify real problems related to environmental issues, and construct arguments based on relevant data. This ability is in line with Ennis' (2018) findings, which emphasize that critical thinking includes analytical, evaluative, and inferential skills that can be developed through contextual learning activities. This improvement was also marked by increased student participation in group discussions and the ability to make decisions based on evidence, which, according to Facione (2020), are key indicators of the success of critical thinking-based learning. There is a positive correlation between critical thinking and students' sustainability consciousness. Students who are trained in critical thinking tend to have a higher awareness of sustainability issues, in terms of knowledge, attitude, and behavior. This is in line with the opinion of Gericke et al. (2019), who stated that Sustainability Consciousness includes cognitive, affective, and conative dimensions that are interrelated with critical thinking skills in

understanding the complexity of environmental and social issues. These findings indicate that strengthening critical thinking can encourage students to be more caring and reflective towards sustainability.

The integration of STEM-PBL learning has been proven effective in improving both aspects. This model provides a learning experience that challenges students to solve authentic problems, such as climate change and energy sustainability issues, thereby encouraging them to think critically while fostering sustainability awareness. These results are in line with Qiroah (2024) research, which found that the application of STEM-PBL can improve problem-solving skills while shaping a sustainability mindset in high school students. Similarly, research by Capraro et al. (2022) shows that the integration of STEM-PBL encourages students to connect scientific concepts with real-life contexts, which ultimately fosters environmental awareness and social responsibility.

According to the results of a literature review of 10 scientific articles found, there were 2 articles that examined the effectiveness of STEM-PBL learning in improving critical thinking and sustainability consciousness among high school students.

**Table 5.** The effectiveness of STEM-PBL learning in improving critical thinking and awareness of sustainability among high school students

No	Author (Year)	Research Results
1	Agusti, K. A., Wijaya, A. F. C., and Tarigan, D. E. (2019).	The results of a one-group pretest and posttest design study on high school students showed that ESD-based PBL improved students' critical thinking skills and increased their sustainability awareness on the issue of global warming. This is in line with the indicators of critical thinking and sustainability consciousness.
2	Maulina, D., Priadi, M. A., Gustina, M., and Rakhmawati, I. (2025).	A quasi-experimental design (NECG) was used in two high school classes, with climate change material oriented towards SDGs. Results: N-gain CT = 0.52 (moderate), effect size = 2.88 (large), average SA 81.42% (category "often/always done"). The findings confirm that PBL is effective in improving CT and influencing students' SA.

Based on two studies reviewed, the application of STEM-PBL in climate awareness material at the high school level has been proven effective in strengthening critical thinking while encouraging students' sustainability consciousness (SC). A consistent pattern can be seen in the increase in analysis, evaluation, and inference indicators, as well as the strengthening of the cognitive dimension of SC through systems thinking, which then attracts attitudes and intentions to act towards pro-environmental practices. This effect occurs because students are confronted with real problems such as global warming or renewable energy and go through the engineering design cycle of formulating needs, designing, prototyping, testing, and revising, which forces data-based decision making, consideration of socio-environmental impacts, and reflection on values. Critical thinking (CT) functions as a “connector” that translates knowledge into action orientation. When students analyze causes and effects, weigh conflicting evidence, and construct accountable arguments, they simultaneously develop systems thinking. The essence of SC is the ability to map components, interrelationships, feedback, and the short- and long-term consequences of human choices on the earth-society system. In other words, CT provides the cognitive tools to evaluate claims, assess risks, and make ethical decisions, while SC provides the direction of values and action orientation so that these decisions are in favor of sustainability.

STEM-PBL integration brings these two skills together in an operational way. Deliberately unstructured climate awareness issues (greenhouse gas emissions, renewable energy, plastic waste) require students to formulate problems, identify relevant information, and test alternative solutions through the engineering design cycle of designing, prototyping, testing, and revising. This process forces the use of critical thinking skills (analysis, evaluation, inference, self-regulation) while fostering a dimension of sustainability consciousness in students who are aware of the ecological, economic, and social trade-offs of each choice, reflect on their values, and then form a stronger intention to behave in an environmentally friendly manner. The effectiveness of STEM-PBL is not only evident in increased cognitive scores, but also in the formation of agency that gives students the confidence and willingness to design solutions and implement sustainable practices in their schools and communities.

## Conclusion

The integration of STEM-PBL in high school climate awareness materials is relevant to addressing research issues while strengthening

critical thinking skills and shaping sustainability consciousness. Through problem-based inquiry, the engineering design process, and climate data reading, students practice constructing evidence-based arguments, causal reasoning, and sustainable decision-making. PBL also fosters efficacy and action intentions that are in line with SDG 13, so that learning does not stop at knowledge but leads to a disposition to act (Lestari, Jatmiko, et al., 2023). At the same time, low climate awareness among students reinforces the urgency of contextual climate education, including the theme of disaster mitigation linked to climate change, to enrich students' interest, agency, and participation in evidence-based climate action.

Limitations of the study include limited sample coverage, heterogeneity of designs and instruments, dominance of short-term evaluations, and reliance on self-reports, meaning that real behavioral changes have not been strongly measured. Future directions for development include comparative, cross-school and cross-regional longitudinal studies; standardization and validation of contextual CT and SC instruments; measurement of behavioral and agency indicators (e.g., energy conservation, waste management); and testing of mediation mechanisms (such as systems thinking and argumentation) and moderating factors (school support, teacher experience, socioeconomic context). Cross-subject collaboration and community partnerships, for example with disaster preparedness agencies, need to be strengthened to ensure the sustainability of learning impacts inside and outside of school.

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