Implementation of STEM Approach to Raise Students' Sustainability Awareness in Science Learning: A Systematic Study

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ABSTRACT
The STEM approach is considered relevant to integrate scientific, social, and sustainability value dimensions in science education. This study is a Systematic Literature Review (SLR) that aims to identify and analyze STEM-based learning strategies in science learning that contribute to increasing students' sustainability awareness. The analysis was conducted on 31 selected articles from 2015–2025 using the PRISMA protocol and qualitative thematic analysis. The results of the study showed five dominant strategies: Project-Based Learning (PjBL), Problem-Based Learning (PBL), Engineering Design Process (EDP), inquiry-based and interdisciplinary learning, and ESD integration in the STEM curriculum. The sustainability indicators identified include: 1) sustainability practice awareness, 2) behavioral and attitude awareness, and 3) emotional awareness. The implementation of these strategies has proven effective in increasing students' scientific literacy, emotional engagement, and reflective attitudes towards environmental issues. These findings provide insights for the development of STEM-based science education that is contextual, reflective, and transformative in supporting sustainable development goals.

Keywords: STEM, science learning, education for sustainable development, sustainability awareness.

INTRODUCTION

Sustainability issues are complex and multidimensional global challenges, encompassing environmental, social, and economic aspects. The climate crisis, ecosystem degradation, and social inequality demonstrate the importance of education that equips the younger generation not only with scientific knowledge, but also with attitudes and values that support the sustainability of the planet. The SDGs, especially SDG 4.7, emphasize the importance of ESD in shaping environmentally conscious and socially responsible global citizens (Kioupi & Voulvoulis, 2019)

In the context of education, science plays an important role in developing scientific literacy and systemic thinking. Science education must be able to foster critical awareness of the relationship between humans and the environment. To address the challenges of the 21st century, the STEM approach has emerged as an integrative pedagogical innovation to develop critical thinking skills, creativity, and problem solving (Hebebci & Usta, 2022). STEM also prepares students to become problem solvers through project-based and real-world activities (Gavari-Starkie et al., 2022; Nguyen, 2023).

When associated with ESD, the STEM approach not only transfers scientific knowledge but also fosters sustainability-related attitudes and values of sustainability through direct involvement of students in real-life contexts (Alkair et al., 2023; Wahono et al., 2021). In its implementation, STEM-based science learning can use various strategies, such as Project-Based Learning (PjBL), Problem-Based Learning (PBL), inquiry-based learning, and Engineering Design Process (EDP)(Ahsan, 2023; Chan & Nagatomo, 2022; Suryaningsih et al., 2022).

ESD itself emphasizes learning that combines real action, reflection on values, and community involvement to form individuals who are able to think systemically and act ethically in social and ecological life (Cordaro et al., 2025; Habibaturrohmah et al., 2023). When integrated into the STEM approach, learning becomes more contextual, reflective, and socially relevant.

Assessing the effectiveness of ESD implementation, (Issa et al., 2020; Raida et al., 2024) classified sustainability awareness indicators into three aspects: (1) Sustainability Practice Awareness, namely student involvement in real environmental practices; (2) Behavioral and Attitude Awareness, namely the tendency to show environmentally friendly attitudes and behavior; and (3) Emotional Awareness, namely empathy, concern, and responsibility for environmental issues.

Several studies have shown that STEM approaches contribute to fostering students' sustainability awareness. (Zhan & Niu, 2023)showed that STEM-based project learning can trigger environmental action. Wahono et al., (2021)showed that the STEM-6E model with socio-science issues builds critical attitudes towards biotechnology. (Chan & Nagatomo, 2022) developed empathetic design-based learning to address disaster-related challenges, fostering social and ethical awareness.

However, most of these studies are limited to a particular approach or level of education. Only a few systematically examine the relationship between learning strategies, sustainability indicators, and their impacts across contexts. There is no comprehensive mapping that shows how STEM strategies are used in science learning, what sustainability values are taught, and to what extent they impact students' understanding and behavior in an integrated manner (Fathurohman et al., 2023; Mahmud & Ismail, 2024).

Based on the above, this study aims to systematically identify and analyze the STEM approach in science learning that aims to increase students' sustainability awareness. This study is guided by the following four research questions: 1) What are the learning strategies integrated with the STEM approach to increase students' sustainability awareness in science learning?; 2) What are the indicators of sustainability awareness that arise in science learning with a STEM approach?;

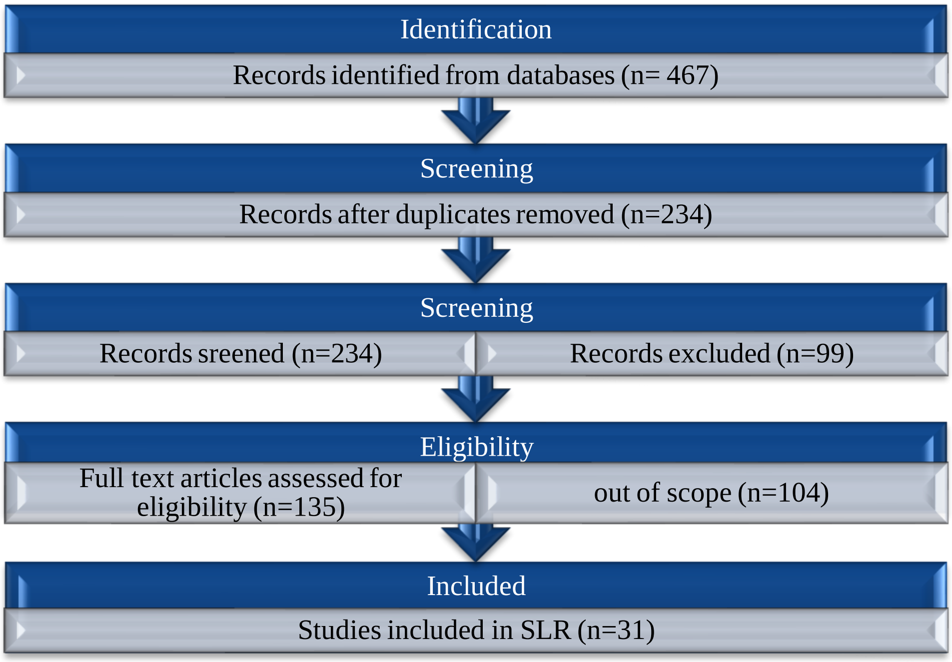
METHOD

This study is a Systematic Literature Review (SLR) that aims to identify, analyze, and synthesize scientific articles that discuss the use of the STEM approach in science learning to increase awareness and behavior toward sustainability. This method was designed to address the two explicitly formulated research questions.

This study was conducted in accordance with the principles and stages of the PRISMA protocol, which includes the stages of identification, screening, eligibility, and inclusion of articles. A literature search was conducted across several reputable academic databases, namely: Scopus, Web of Science, ERIC, Google Scholar, SpringerLink, ScienceDirect. The search focused on articles published between 2015–2025, using the following keyword combinations: “STEM education” OR “STEM approach” OR “STEM-based learning” AND “science education” AND “sustainability” OR “sustainability awareness” OR “ESD” OR “environmental literacy”. The eligibility criteria are presented in Table 1.

From the initial search results, a number of articles were summarized in a spreadsheet, then filtered based on title and abstract. This selection stage resulted in n = 31 that met the criteria, which were then further analyzed through full reading to assess suitability to the research questions. The analysis was carried out using qualitative thematic analysis techniques to extract research questions. Article selection using the PRISMA diagram is shown in Figure 1.

Figure 1: Article selection through the PRISMA diagram



FINDINGS AND DISCUSSION

1. The learning strategies integrated with the STEM approach to increase students' sustainability awareness in science learning

Based on a systematic analysis of the articles included in the eligible criteria, several strategies were found in STEM-approach science learning that contributed to increasing students' sustainability awareness. Several studies integrated several learning strategies. In Table 1. The studies are grouped into each learning strategy.

Table 1: Learning Strategies Integrated with the STEM Approach

Author and Year	Science Focus / Sustainability Context	Sustainability Achievements
Project-Based Learning (PjBL)		
(Ahsan, 2023)	Clean energy, clean water, sustainable agriculture	Increased conceptual understanding, reflection of sustainability values
(Winarni et al., 2022)	Biology: life cycles, wildlife conservation	Scientific literacy increased, students' environmental awareness
(Suryaningsih et al., 2022)	Chemistry: titration, natural indicators	High creativity through e-posters, digital reflection
(Shahali et al., 2017)	Energy, infrastructure, transportation, ecology	Interest in STEM increased, understanding of renewable energy
(Chan & Nagatomo, 2022)	Product design, material engineering, shelter	Empathy for victims, sustainable design

Author and Year	Science Focus / Sustainability Context	Sustainability Achievements
(Sahin, Alpaslan and Top, 2015)	Physics (impulse, waves, energy), Chemistry, Mathematic	Self-confidence, collaboration, students' social empathy
(AlAli, 2024)	Physics, Technology, Communication	High collaboration, digital literacy, spirituality slightly decreased
(Bascopé & Reiss, 2021)	Local ecology: medicinal plants, water, biodiversity, traditional agriculture	Community participation, socio-ecological resilience
Problem-Based Learning (PBL)		
(Ahsan, 2023)	Clean energy, clean water, sustainable agriculture	Collaborative strategies, increased social responsibility
(Li, 2025)	Climate mathematics, energy, biodiversity	Empathy, positive perceptions of mathematics in sustainability
(Smith et al., 2022)	Secondary school science context	Collaborative, flexible, PBL-STEM principles applied
(AlAli, 2024)	Physics, Technology, Communication	High productivity, collaboration, increased motivation
(Funa et al., 2025)	Pili tree conservation, local economy	Reflection of cultural values, contextual sustainability action
(Chan & Nagatomo, 2022)	Product design, material engineering, shelter	Reflection of values, socio-ecological design skills
ESD		
(Ahsan, 2023)	Clean energy, clean water, sustainable agriculture	Strengthening sustainability values in learning strategies
(Loh et al., 2019)	Sustainable consumption, air pollution	SDGs-based challenges, curriculum integration
(Bascopé & Reiss, 2021)	Local ecology: medicinal plants, water, biodiversity, traditional agriculture	Socio-ecological resilience and community action
(Odell, 2024)	Inquiry school model, local SDGs	Student reflection on local environmental issues
(Vilmala et al., 2022)	Prospective science teachers' perceptions of ESD-STEM	Positive perception, implementation is still limited
(Amos & Levinson, 2019)	SDGs-based SSIBL	Social action based on reflection and inquiry
(Alkair et al., 2023)	Problem-solving based E-STEM	Concrete environmental projects, increased understanding & creative solutions
(Wahono et al., 2021)	Biotechnology and social issues	Critical attitudes and social awareness increased
Engineering Design Process (EDP)		
(Shahali et al., 2017)	Solar cars, smart cities	Technical design encourages STEM interest

Author and Year	Science Focus / Sustainability Context	Sustainability Achievements
(Loh et al., 2019)	Sustainable consumption, design challenges	Social reflection and technical solutions
(Chan & Nagatomo, 2022)	Product design, material engineering, shelter	Empathy, social responsibility, design innovation
(Indahwati et al., 2023)	Renewable energy, digital teaching tools	Critical thinking scores increase, positive student responses
(Ling et al., 2019)	Recycling projects	Creativity increases, despite limited implementation
(Suryaningsih et al., 2022)	Chemistry: titration, natural indicators	Innovative digital projects, high environmental awareness
Interdisipliner & Inquiry-Based		
(Amos & Levinson, 2019)	SDGs-based SSIBL	Reflection on values, local action on global issues
(Mylvaganam et al., 2021)	microplastics, food	Social awareness through reflective projects
(Bascopé & Reiss, 2021)	Local ecology: medicinal plants, water, biodiversity, traditional agriculture	Transdisciplinary and action-based
(Chan & Nagatomo, 2022)	Product design, material engineering, shelter	Cross-disciplinary projects & design ethics
(Odell, 2024)	Inquiry, 5E model, STEM school	Student reflection on local environmental impacts
(Funa et al., 2025)	Pili tree conservation, local economy	Socio-cultural reflection in local conservation projects
(Ješková et al., 2022)	Biology, Physics, Chemistry, Mathematics, Geography	Experimentation, inquiry-based decision making
Other Learning Strategies		
(Hsiao & Su, 2021)	Renewable energy, local culture, conservation	Motivation and self-efficacy increased through immersive learning
(Mikhailova et al., 2021)	Soil science, ecosystems, environmental services	Perception of environmental values increased after digital learning
(Abu Khurma et al., 2023)	Ecosystems, pollution, learning strategies	Students' metacognition and independent exploration were honed
(Wahono et al., 2021)	Biotechnology (GMOs, DNA)	Critical attitudes increased, reflective action towards socio-science issues
(Hiğde, 2022)	Renewable energy (wind, solar, biomass)	Positive attitudes increased, but not emotionally significant
(Pilotti, 2021)	High STEM – social & gender sustainability ethics	Female representation increased, social sustainability was raised

Author and Year	Science Focus / Sustainability Context	Sustainability Achievements
(Syahmani et al., 2021)	Wetlands, biodiversity, science vs environmental literacy	Environmental & science literacy increased, emotional impact not explicit

a. Project-Based Learning (PjBL)

In the context of sustainability education, PjBL allows students to directly explore environmental issues, analyze their impacts, and create solutions that can be applied in real life (Nagamalla et al., 2024). This model provides space for students to build deep meaning and awareness of sustainability issues through reflective and action-oriented engagement (Stokes & Harmer, 2018). Several studies have shown that the application of PjBL in STEM-based science learning can improve understanding of science concepts while fostering concern for the environment.

Ahsan (2023) in their research used a combination of STEM with PjBL, PBL, and IBL learning models in science learning on the topics of clean energy, clean water, and sustainable agriculture. The results of the study showed that the combination could significantly improve students' conceptual understanding compared to traditional methods. This can be seen in the results of statistical tests (t-test, ANOVA) showing an increase in all levels of student ability in all STEM domains. In addition, these projects not only strengthen conceptual understanding but also foster social and emotional responsibility towards sustainability issues.

Research by Winarni et al. (2022) integrated STEM with PjBL in the form of making dioramas of animal life cycles and environmental conservation. In their research, the integration of PjBL-STEM increased students' scientific literacy and environmental awareness. Students expressed their concern for animals through slogans and diorama projects. Students not only showed increased scientific understanding but also developed an attitude of caring for environmental sustainability through slogans and personal reflections.

A study by Suryaningsih et al. (2022) combined STEAM learning with PjBL through digital creation (e-posters) on social media. This study was proven to increase students' curiosity (87.6%) and support (88.6%) for green chemistry-based conservation projects and can encourage students' interest in natural indicators and environmental issues in chemistry lessons. In addition, in the context of engineering, Shahali et al. (2017) developed the "Smart City" project and solar-powered cars within the STEM PjBL framework based on the EDP. The results showed a significant increase in students' interest in STEM careers, from 42% to 69%. This approach successfully increased students' interest in STEM careers and understanding of the concepts of renewable energy, sustainable transportation, and green infrastructure.

Furthermore, research by Chan & Nagatomo (2022) applied the STEM-DDIF (Double-Diamond Innovation Framework) model in a post-disaster shelter design project. Students were involved in a design process based on social and ecological needs, producing prototypes of sustainable products such as furniture and emergency buildings made from cardboard. Through this, students demonstrated empathy, social awareness, and critical thinking skills in the context of sustainability. Project-based and design-based learning has been shown to be effective in building capabilities for sustainable action.

Sahin, Alpaslan and Top (2015) study also emphasized the role of PjBL in strengthening students' personal and social dimensions through the STEM SOS model. In this approach, students are given the freedom to choose project themes according to their interests and present them in various media such as videos, websites, and STEM Expo presentations. These projects not only increase self-confidence and motivation to learn, but also form social responsibility and awareness of the role of STEM in facing real challenges in society.

Meanwhile, AlAli (2024) developed a Project-Oriented Problem-Based Learning (PoPBL) approach through four thematic modules focusing on energy, infrastructure, transportation, and communication issues. The results showed that PoPBL successfully improved students' collaboration, decision-making, and digital literacy skills. This contextual learning also helps shape positive attitudes towards sustainability issues and strengthens students' active involvement in developing STEM-based solutions.

Finally, a study by Bascopé & Reiss (2021) adopted the Place-Based STEM Education (STEM4S) model, which combines PjBL, inquiry, and local knowledge approaches. Through community projects in elementary schools in Chile, students participated in medicinal plant conservation, water management, and sustainable agriculture based on local wisdom. These activities strengthen students' emotional ties to the surrounding environment, build collective responsibility, and strengthen socio-ecological resilience in line with educational values for sustainable development.

In general, PjBL allows students to experience a holistic learning process—combining cognitive, affective, and psychomotor aspects—with a direct orientation to the application of sustainability values. Through these projects, students not only learn about sustainability, but also for sustainability and through sustainability, as emphasized in the ESD framework.

b. Problem-Based Learning (PBL)

PBL is an inquiry-based pedagogical approach in which students are confronted with complex and meaningful contextual problems. In the context of STEM-based science learning, PBL positions students as active problem solvers on sustainability issues such as climate change, environmental degradation, resource conservation, and energy transition. PBL encourages the development of critical, collaborative, and reflective thinking skills, which are highly relevant in shaping sustainability awareness.

Although some studies have been discussed in the PjBL framework, in this subsection the PBL approach is viewed from the perspective of the process of scientific inquiry and problem-based decision-making, not just the final project outcome. A study by Ahsan (2023) used a combination of PBL, PjBL, and IBL to explore sustainability issues such as clean water, clean energy, and sustainable agriculture. In their PBL approach, students not only built projects but also went through a process of problem exploration, data analysis, and reflection on the solutions they designed based on the principles of the SDGs.

Li (2025) developed a theme-based interdisciplinary PBL approach in STEMS programs, such as biodiversity and renewable energy. This study emphasized the role of mathematics as a critical thinking tool in understanding sustainability challenges. Thhuirough contextual quantitative problem solving, students showed increased understanding and concern for global issues. Meanwhile, Smith et al., (2022) did not implement PBL directly, but proposed PBL-based pedagogical principles such as flexibility of knowledge, intrinsic collaboration, and active reflection. This study shows the importance of STEM learning designs that allow students to deal with open-ended problems reflectively in the context of sustainability education.

Research by AlAli (2024) applied Project-Oriented PBL (PoPBL) based on energy, transportation, and communication modules. In addition to project outcomes, learning emphasized discussions and data-based decision-making relevant to the SDGs. This approach was also effective in increasing digital literacy and student engagement in topics with global impacts. In a local context, a study by Funa et al. (2025) used I-STEM-PBL-ESD to engage students in a Pili tree-based conservation project in the Philippines. Students were asked to assess the ecological and economic value of the local resource and reflect on sustainable solutions for the community. Although the project raised awareness and understanding, the actual behavioral impact was limited due to the lack of direct community involvement.

Finally, (Chan & Nagatomo, 2022) presented the application of design-based PBL in a post-disaster shelter project. Students explored the social and ecological needs of disaster victims, then designed solutions based on recycled materials. This approach builds empathy, social awareness, and design skills in a sustainable context.

Overall, the PBL approach in STEM learning not only strengthens scientific understanding, but also forms attitudes of social responsibility, critical awareness of environmental issues, and higher-order thinking skills that are essential to support sustainable development..

c. Integrating ESD into STEM Curriculum

Integrating ESD into the STEM curriculum is not only about implementing certain teaching strategies, but also reflects a more fundamental transformation in the goals, content, and values that science and technology education seeks to achieve. In this context, ESD demands a STEM curriculum that does not simply emphasize cognitive and technical skills, but also forms critical awareness, social responsibility, and concern for ecological sustainability and local communities (Pitt, 2009).

Several studies in this review show how ESD has been explicitly integrated into STEM curriculum design. A study by (Ahsan, 2023), integrated four main SDGs (SDG 4 – quality education, SDG 6 – clean water, SDG 7 – clean energy, and SDG 13 – climate action) into PjBL, PBL, and IBL-based science learning. The curriculum was designed so that students not only understand science concepts but also assess and create solutions to sustainability problems in their environment.

A more structured approach is seen in research by Loh et al. (2019) who designed a STEM curriculum using the Engineering Design Process (EDP) with an emphasis on the SDGs context. This curriculum incorporates challenges such as air pollution, food security, and sustainable consumption into the learning design, allowing students to design solutions by integrating science, mathematics, and engineering concepts in an integrated manner. The values instilled include innovation, environmental responsibility, and awareness of the relationship between science and social needs.

Locally-based curriculum has also emerged as an important approach to integrating ESD into STEM. Bascopé & Reiss (2021) developed the Place-Based STEM4S model that integrates local knowledge—such as medicinal plant conservation practices, water management, and traditional agriculture—into elementary science learning. Here, sustainability values are embedded not only through scientific content but also through students' direct experiences in interacting with their communities and the natural world. The result is a strengthening of social-ecological resilience and student engagement in concrete actions for sustainability.

A study by (Odell, 2024)suggests that integrating ESD into the school curriculum can be done through an interdisciplinary approach and project-based learning that aligns STEM with local issues. In their model, projects are designed to solve community problems such as waste and energy use. This curriculum not only builds scientific understanding but also instills values of collaboration, social empathy, and awareness of the impact of technological decisions on society.

From the teacher education perspective, (Vilmala et al., 2022) showed that the curriculum for science teacher education has begun to incorporate ESD-STEM principles. However, although students showed positive perceptions of sustainability values and the potential of STEM to support the SDGs, they still had difficulty in designing effective learning. This shows the importance of ESD integration not only in content, but also in teacher training and pedagogical reinforcement.

Amos & Levinson (2019) offer a unique approach through the Socio-scientific Inquiry-Based Learning (SSIBL) model that combines the principles of ESD, inquiry-based learning, and social engagement. The curriculum in this study is designed to encourage students to ask, investigate, and act on issues such as healthy food, energy, and vaccination. Values such as empathy, participation, and awareness of personal and collective responsibility are at the heart of the learning process. Furthermore, Alkair et al., (2023) developed a PBL-based E-STEM curriculum model at the elementary school level, with topics covering waste management, water crisis, and global warming. This curriculum not only teaches science contextually but also instills values of sustainable action through simple projects such as drip irrigation systems and wastewater treatment.

Overall, these studies show that integrating ESD into STEM curricula not only results in more meaningful and contextual learning, but also shapes students who are not only able to understand science and technology, but also responsible global citizens who are aware of sustainability.

d. Engineering Design Process (EDP)

Engineering Design Process (EDP) is a systematic approach to STEM learning that positions students as designers of solutions to real-world problems through a series of iterative steps: identifying problems, envisioning solutions, designing, testing, and refining. In the context of sustainability-based science learning, EDP plays an important role in fostering systemic, innovative, and action-oriented thinking on environmental and social issues.

Several studies in this review demonstrate how EDP is explicitly used to equip students with engineering skills relevant to sustainability challenges. Shahali et al., (2017) developed the Bitara-STEM model based on the five-stage EDP (Ask–Imagine–Create–Test–Improve) in the "Smart City" and solar-powered car projects. Through this approach, students not only understood the concepts of physics and energy but also began to think about how technology design can support sustainable living. This study showed a significant increase in students' interest in STEM careers and their understanding of the role of science in solving real-world problems.

A similar approach was adopted by (Chan & Nagatomo, 2022), who applied STEM-DDIF—an EDP-based design innovation framework—to a post-disaster shelter project. Students designed prototypes from recycled materials and considered sustainability aspects and the socio-ecological needs of the affected community. Through ethical and contextual design, this learning fosters empathy, social awareness, and values of environmental responsibility, positioning STEM as a tool for social action and reflection.

On the curriculum planning side, Loh et al., (2019) designed EDP-based STEM learning by emphasizing the contextualization of SDGs such as food security and air pollution. This curriculum is designed for students to design engineering solutions to environmental issues through project-based challenges, which instill design skills, cross-disciplinary thinking, and reflection on the social impacts of technology. The implementation of EDP in the classroom was also found in a study by (Ling et al., 2019)who developed STEM projects for junior high school students. Projects such as making recycled products and sustainable consumption systems encouraged creativity and environmental awareness, despite being limited by minimal motivation and school facilities.

The use of EDP was also found in a study by Indahwati et al. (2023), which integrated EDP with the STEAM-PjBL approach. Students were asked to design digital teaching tools related to renewable energy. This project not only strengthened science understanding and critical thinking skills but also formed a caring attitude towards environmentally friendly technological solutions.

Suryaningsih et al. (2022) applied the EDP principle in a digital-based chemistry project through the design of an e-poster for the conservation of natural indicator plants. Although simple, this project involves the process of identifying environmental problems, planning visual messages, and delivering solutions through social media, which combines creativity, scientific thinking, and sustainability literacy.

e. Interdisciplinary Approach and Inquiry

STEM-based science learning designed to increase sustainability awareness does not only rely on project learning strategies or engineering design, but also requires an interdisciplinary and inquiry-based approach. This approach allows students to explore real-world problems from multiple perspectives (scientific, social, cultural, and ecological), and to actively engage in the process of asking, investigating, reflecting, and acting on the results of their investigations. One model that explicitly combines aspects of inquiry and interdisciplinarity is SSIBL (Socio-scientific Inquiry-Based Learning), as developed by (Amos & Levinson, 2019). SSIBL emphasizes three stages of the inquiry process: Ask–Find Out–Act, which encourages students to question socio-scientific issues such as vaccination, energy, and healthy food, investigate scientifically and socially, and take real action. Through this model, students not only improve scientific literacy, but also develop value reflection, empathy, and social participation in the context of the SDGs.

The STEAM+ model as described by Mylvaganam et al. (2021) also integrates inquiry and cross-disciplinary approaches by engaging students in projects that touch on sustainability issues such as microplastics, clean air, and healthy food. This project-based learning is enriched with social and personal reflection activities, resulting in deeper affective engagement and a more contextual understanding of environmental issues.

In the context of local-based learning, Bascopé & Reiss (2021) through the Place-Based STEM4S model show how the inquiry approach can be strengthened by integrating local knowledge. Students are directly involved in observing, exploring, and analyzing local community practices related to sustainable agriculture, medicinal plants, and water management. This approach forms students' emotional attachment to their environment, as well as strengthening socio-ecological resilience.

The design-based inquiry approach is also evident in the STEM-DDIF model developed by (Chan & Nagatomo, 2022). Students are challenged to design post-disaster emergency shelters from recycled materials, taking into account technical and social aspects. The design process begins with an exploration of community needs and ethical reflection on proposed solutions, making the learning process a vehicle for strengthening empathy and ecological responsibility.

At the elementary and middle school levels, Odell (2024) describe an interdisciplinary STEM school model that combines inquiry, PBL, and the 5E model. Students are invited to investigate environmental issues in their communities, such as waste or energy consumption, and design solutions that can be implemented in the local context. This approach positions inquiry as a tool for empowering students to understand and contribute to sustainability in real ways.

The I-STEM-PBL-ESD model by Funa et al. (2025) combines science learning with local economics and SDGs. Students explore local cultural potentials such as Pili tree conservation and its impact on biodiversity and community well-being. Inquiry is conducted through community reflection, socio-economic analysis, and discussion of sustainability values.

Based on the above description, the interdisciplinary and inquiry approach provides an important contribution in connecting science content with sustainability values. This approach not only enhances cognitive understanding, but also builds emotional awareness, social concern, and the desire to act, which are the core of education for sustainable development.

f. Other Learning Strategies

In addition to mainstream approaches such as PjBL, PBL, EDP, and IBL, several studies have shown the existence of other STEM learning strategies that are thematic, digital, culture-based, or focused on psychosocial aspects. These strategies, although not always explicitly categorized into standard pedagogical models, still make significant contributions in shaping students' understanding, attitudes, and actions towards sustainability issues.

One emerging approach is the use of digital technology and interactive media. A study by Hsiao & Su (2021) developed STEAM learning that combines virtual reality (VR) and game-based learning based on local Taiwanese culture. In this context, technology is used not only to enhance scientific understanding but also to foster students' motivation and concern for cultural values and environmental issues.

A digital approach was also used by Mikhailova et al. (2021) who integrated reusable learning objects in the context of soil ecosystem services. Students studied the impacts of carbon, soil pH, and ecosystem quality through real data simulated online. Although the learning was distance learning, the results showed an increase in awareness of human-environment relationships.

Another prominent strategy is the metacognitive approach and learning autonomy, as reviewed by Abu Khurma et al., (2023). Through the Learning How to Learn (LHTL) framework, students are trained to design their own learning strategies, conduct problem-based explorations, and reflect on their learning process in the context of STEM and sustainability. This approach strengthens the personal dimension in learning and fosters students' learning independence in dealing with complex issues.

In the socio-scientific realm, Wahono et al. (2021) used the STEM-6E approach combined with Socio-scientific Issues (SSI), especially in biotechnology topics such as GMOs and DNA. This learning not only emphasizes mastery of scientific concepts but also develops students' abilities to analyze the social, ethical, and sustainability impacts of these issues critically and reflectively.

Meanwhile, a study by Hiğde (2022)focused on the influence of the STEM approach on attitudes and behaviors towards renewable energy, although it did not adopt a specific pedagogical model. The strategies used were more content-based and contextual design, with an emphasis on reducing energy consumption and efficiency as indicators of sustainability.

Other studies have raised contributions from a broader social perspective. Pilotti (2021) examined the role of gender in STEM education in Saudi Arabia and how differences in academic experiences between men and women affect sustainability outcomes and perceptions. While not a direct learning strategy, this study highlights the importance of an inclusive and equitable approach to STEM education for sustainability.

Syahmani et al. (2021) explored the relationship between science and environmental literacy in a wetland ecosystem-based STEM approach. Although not using explicit strategies such as PjBL or IBSE, their approach was rooted in contextual exploration and field observation, which nevertheless strengthened students' awareness of sustainability.

In general, these strategies show that sustainability learning in STEM does not always have to follow a single pedagogical approach, but can be developed flexibly and contextually, according to the characteristics of students, materials, and local culture. Learning innovations such as the use of technology, emphasizing metacognition, and strengthening the social and ethical dimensions open up new opportunities to expand the impact of STEM education in forming a generation that is aware of and responsible for sustainability.

2. Sustainability Awareness Indicators Emerging in STEM-Approach Science Learning

Integration of sustainability into STEM learning is not only seen from the teaching methods or strategies, but also from the content and indicators presented to raise awareness of environmental and social issues. In this section, indicators of sustainability awareness are divided into three main categories, namely practice, behavioral & attitude, and emotional. The depth and breadth of ESD content in the STEM-Science curriculum are examined by understanding the most frequently appearing indicators and the concrete forms of their implementation

a. Sustainability Practice Awareness

The sustainability practice awareness indicator refers to students' ability and awareness to engage in real and sustainable practices related to environmental protection and resource management. In the context of STEM education, this indicator is often realized through project-based activities that encourage students to create, observe, and maintain solutions to environmental problems repeatedly and integrated into everyday life.

Table 2: Sustainability Practice Awareness in STEM learning

No	Author and Year Education Level	Education Level	Continued Practice Activities
1	(Alkair et al., 2023)	Elementary School	Drip irrigation, waste management, water conservation projects
2	(Bascopé & Reiss, 2021)	Early Childhood Education–Elementary School	Conservation of medicinal plants, traditional agriculture, rainwater harvesting

3	(Suryaningsih et al., 2022)	Senior High School	Recycling of natural indicators, environmental campaign e-posters
4	(Indahwati et al., 2023)	Vocational School	Design of digital teaching tools for renewable energy
5	(Chan & Nagatomo, 2022)	Higher Education	Design of post-disaster shelters from recycled materials
6	(Winarni et al., 2022)	Elementary School	Diorama of animal life cycles, environmental conservation slogans
7	(Funa et al., 2025)	Senior High School	Pili tree conservation, biodiversity-based local economy

Several studies have shown how STEM approaches can directly foster awareness of these sustainability practices. For example, Shahad Alkair et al. (2023) developed an E-STEM model at the elementary school level that allowed students to design a drip irrigation system, create a recycling tool, and evaluate the water crisis through collaborative projects. These activities were conducted in a local context and were sustainable, showing that students not only understood environmental issues but also actively participated in solution-oriented actions.

Similarly, in the context of locally-based education, Bascopé & Reiss (2021) implemented place-based STEM education for preschool and elementary school students to practice medicinal plant conservation, rainwater harvesting, and traditional agriculture. These projects were developed with the community and repeated every season, demonstrating that sustainable practices are not only taught but also cultivated.

At the high school level, Suryaningsih et al. (2022)combined chemistry experiments with digital campaigns through a natural indicator e-poster project. Although carried out in one learning cycle, this activity still shows a form of sustainability practice because it involves exploring natural materials and spreading conservation messages through social media.

At the vocational education level, Indahwati et al. (2023) integrated the design of digital teaching tools based on renewable energy in the STEAM-PjBL project. Although the practical activities were not stated to be repeated, this project showed that students developed prototypes that were directly related to sustainable solutions in the energy sector.

In the context of higher education, (Chan & Nagatomo, 2022) developed a post-disaster shelter design project using recycled materials, combining design techniques with reflection on sustainability ethics. Students participated in an Engineering Design Process (EDP) that encouraged them to create concrete solutions based on recycling principles and socio-ecological resilienc

In addition, two other studies also strengthen this indicator. Winarni et al., (2022)involved elementary school students in making dioramas of animal life cycles and environmental conservation slogans, which although limited in scale, still show forms of ecological practice. Funa et al., (2025) encourage local tree conservation (Pili) and exploration of biodiversity-based community economy, which brings together environmental and social issues in one project framework.

Based on the description above, practice awareness indicators tend to come in the form of real projects, exploratory activities, and local context-based designs. The articles that are most successful in developing these indicators are those that combine cross-disciplinary learning with concrete action within the student community. Integration of iterative and meaningful sustainability practices appears to be a key factor in shaping sustainable environmental behavior.

b. Behavioral and Attitude Awareness

Behavioral and attitude awareness indicators refer to the extent to which students demonstrate positive attitudes, habits, and tendencies to act consciously towards environmental sustainability issues. This includes students' involvement in environmentally friendly habits, participation in socio-ecological activities, and changes in attitudes and values towards the environment as a result of the learning process.

Table 3: Behavioral and Attitude Awareness in STEM learning

No	Author and Year Education Level	Education Level	Continued Practice Activities
1	(Ahsan, 2023),	Junior High School	ttitudes towards clean water, renewable energy, SDGs
2	(Winarni et al., 2022)	Elementary School	Conservation slogans, animal care
3	(Wahono et al., 2021)	Junior High School	Critical attitudes towards socio-science issues
4	(Ješková et al., 2022)	Senior High School	Reflective, collaborative, metacognitive attitudes
5	(Indahwati et al., 2023)	Vocational High School	Self-confidence, teamwork, enthusiasm
6	(Funa et al., 2025)	Senior High School	Social reflection, community awareness

Several studies in this SLR indicate that STEM-based learning can significantly increase awareness of behavior and attitudes towards sustainability. A study by Ahsan (2023), students showed changes in attitudes towards the importance of clean water, renewable energy, and sustainable consumption, after being involved in project-based learning focused on the SDGs. This increase was measured through pre-post attitude tests and reflective interviews, which showed that STEM learning not only changed understanding, but also habits of thinking and assessing sustainability issues.

Similarly, Winarni et al. (2022) reported that elementary school students who participated in the animal life cycle diorama project also produced conservation slogans and showed concern for species preservation. This activity triggered students' awareness that small actions (not littering) have an impact on animal and environmental sustainability. Wahono et al. (2021)used the STEM-6E approach combined with Socio-scientific Issues (SSI) and showed that students were more critical and reflective of social science issues such as GMOs (genetically modified organisms). Students not only understood the material but also developed a critical and responsible attitude in assessing the benefits and risks of applying biotechnology technology.

Ješková et al. (2022) study assessed high school students' inquiry skills and science attitudes after participating in 5E model-based learning and scientific inquiry. Although the main focus was on understanding, this study also showed that students became more reflective and collaborative, which is a form of change in attitude towards the learning process and science issues. At the vocational high school level, Indahwati et al. (2023) found that students were more confident and enthusiastic in completing renewable energy projects, and showed increased interpretation, inference, and teamwork—all of which are indicators of active learner attitudes and behaviors and concern for sustainability issues. Funa et al., (2025) also reported that students showed social reflection and engagement in discussions about their role in local conservation, although the long-term behavioral impacts were not yet significant.

In general, behavioral and attitude awareness indicators emerged most strongly in approaches that emphasized social discussions, community-based projects, and value reflection. While most studies showed an increase in positive attitudes toward sustainability, only a small number measured long-term habit changes, indicating the need for further action in integrating sustainability as part of school culture and continuous learning.

c. Emotional Awareness

Emotional awareness in the context of sustainability education refers to students' emotional awareness of environmental and social issues, including empathy, responsibility, concern, and personal involvement that emerge in response to sustainability issues. This aspect is important because it forms a deep affective dimension that is the foundation of sustainable attitudes and actions. Although this indicator is often more difficult to measure quantitatively, many studies have shown that STEM approaches can generate positive emotional responses in students towards sustainability issues.

Table 3: Emotional Awareness in STEM Learning

No	Author and Year Education Level	Education Level	Continued Practice Activities
1	(Bascopé & Reiss, 2021)	PAUD–SD	Empathy towards nature, local attachment
2	(Chan & Nagatomo, 2022)	Higher Education	Ethical reflection, empathy towards disaster victims
3	(Wahono et al., 2021)	Junior High School	Social awareness and moral values
4	(Funa et al., 2025)	High School	Local cultural pride, social empathy
5	(Mylvaganam et al., 2021)	Higher Education	Personal reflection, sustainability values
6	Odell (2024)	Primary School–Senior High School (K–12)	Motivation, reflection on community
7	(Winarni et al., 2022)	Primary School	Concern for animals and habitat

One prominent study is Bascopé & Reiss (2021), which involved preschool–elementary school students in place-based STEM with a focus on local ecosystems. Through activities such as medicinal plant conservation, rainwater observation, and local agricultural practices, students demonstrated an emotional attachment to nature, as well as a sense of responsibility for the sustainability of local resources. This suggests that emotions can develop along with personal and direct engagement with the environment.

At the tertiary level, Bascopé & Reiss (2021) showed that design students who developed post-disaster shelter prototypes from recycled materials experienced ethical reflection and empathy for disaster victims. This design-based project not only fostered technical skills but also a strong social awareness. Wahono et al., (2021) reported that junior high school students who participated in STEM-6E and Socio-scientific Issues (SSI) learning showed concerns and ethical opinions on GMO and biotechnology issues. Student reflections showed the involvement of moral values in assessing the risks and benefits of technology.

Similar attitudes were also found in a study by (Funa et al., 2025), where high school students showed pride in local culture and social empathy in a local tree conservation project and community economic development. Student reflections reflected personal involvement in preserving local resources, which strengthened the emotional dimension of sustainability awareness. Students in the study by Mylvaganam et al. (2021)who followed the STEAM+ model expressed personal reflection on environmental issues such as microplastics and clean air. Through real projects and reflection sessions, students realized the connection between personal actions and global impacts.

A study by Odell (2024) showed that at various levels of education (elementary to high school), students in interdisciplinary STEM schools showed motivation and concern for the local community, especially in environmental projects that were linked to real contexts. Finally, Winarni et al. (2022)showed that even elementary school students can develop emotional concern for animals and their habitats, through diorama projects and conservation campaigns. Students' expressions in this project showed emotional involvement in the importance of animal conservation.

Overall, indicators of emotional awareness emerged in learning contexts that provided space for personal reflection, direct engagement, and social values. The studies that were most successful in fostering emotional awareness were those that actively engaged students in personally relevant local or global issues, and provided space for expressing their values and empathy for the environment and society.

It is interesting to note that only a few studies in this review explicitly integrated all three categories of sustainability awareness at once: sustainability practice awareness, behavioral and attitude awareness, and emotional awareness. Among all the articles analyzed, at least three studies demonstrated a holistic approach to sustainability learning in the STEM context.

The research of Alkair et al. (2023), not only involved students in real environmental projects (practice), but also succeeded in fostering attitudinal changes and active participation in conservation activities (behavioral), as well as emotional involvement through awareness of the water and waste crisis (emotional). Similarly, research by Funa et al. (2025) integrated local tree conservation and community economy as a sustainable project, while encouraging students' social reflection on individual and collective responsibilities for sustainability. At the same time, students showed pride in local culture and social empathy for the surrounding community.

Winarni et al. (2022) also showed strong integration at the elementary level through the creation of dioramas, conservation slogans, and students' emotional expressions towards animals and their habitats. Although limited in scale, this learning shows that a STEM approach designed with a local context and project orientation can cover all dimensions of sustainability awareness, even from an early age.

These three studies show that the integration of sustainability indicators is possible, especially when learning is contextual, reflective, and provides space for real action. This can be an important reference for the development of STEM-based science curricula that are oriented towards social and ecological transformation

CONCLUSION

This systematic review reveals that the STEM approach in science learning has great potential in shaping students' sustainability awareness and behavior. (1) The most widely used strategies are PjBL and PBL, followed by EDP inquiry-based learning, and integration of ESD, especially when applied in real contexts and local issues. (2) Most studies integrate sustainability indicators in the form of practices and attitudes explicitly, but emotional dimensions such as empathy and value reflection have not been systematically touched upon. Suggestions for further research are that research needs to be conducted to evaluate the long-term impact of STEM learning on changes in student behavior, as well as developing learning models that are adaptive to cultural diversity and local-global challenges.

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