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From Systems Thinking to Sustainability Awareness: Unpacking the Learning Mechanisms of Interdisciplinary STEM–ESD Education

Dida Firgiawan, Ari Widodo*, Riandi

Science Education, Universitas Pendidikan Indonesia, Bandung, Indonesia

✉* ari_widodo@upi.edu

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Abstract

Background: Developing sustainability awareness has become a major goal of science education; however, previous studies have primarily emphasized whether STEM-based instruction improves learning outcomes rather than explaining the cognitive processes through which these improvements occur. Systems thinking has been increasingly recognized as a key competency for understanding complex sustainability challenges, yet its potential role in linking interdisciplinary STEM learning and sustainability awareness remains underexplored. This study investigates how interdisciplinary STEM–ESD learning supports sustainability awareness while fostering students' systems thinking during environmental change education.
Methods: An embedded mixed-methods quasi-experimental design was employed involving 72 tenth-grade students from an Indonesian senior high school, with 36 students in the experimental group and 36 in the control group. The experimental group participated in an interdisciplinary STEM–ESD learning program centered on designing a solar-powered water purification system, integrating Biology, Sociology, and Economics through authentic environmental problem-solving. Quantitative data were collected using systems thinking and sustainability awareness instruments, while qualitative evidence was obtained through classroom observations, student worksheets, and reflective learning activities.
Results: The experimental group demonstrated greater gains in both systems thinking and sustainability awareness than the control group. For systems thinking, the experimental group increased from a pre-test mean of 50.10 to a post-test mean of 88.10, with an N-Gain of 0.77 (high), compared with 0.60 (moderate) in the control group. For sustainability awareness, the experimental group's mean increased from 143.81 to 209.67, yielding an N-Gain of 0.811 (high), whereas the control group increased from 142.25 to 184.11, with an N-Gain of 0.504 (moderate). The differences in N-Gain between groups were statistically significant for both systems thinking and sustainability awareness ($p < .05$). Qualitative findings further indicated that students increasingly connected ecological processes with social behavior and economic considerations, enabling them to evaluate environmental issues from an integrated socio-ecological perspective.

Conclusion: The findings provide evidence that interdisciplinary STEM–ESD learning can simultaneously foster systems thinking and sustainability awareness. The qualitative evidence suggests that systems thinking may function as a cognitive pathway through which students integrate ecological, social, and economic perspectives when addressing sustainability challenges. By engaging learners in authentic environmental problem-solving, interdisciplinary STEM–ESD learning can move sustainability education beyond factual knowledge toward integrated systems understanding and more informed decision-making.

INTRODUCTION

Sustainability Awareness Is More Than Environmental Knowledge

Sustainability has become one of the most important priorities in contemporary science education due to escalating global challenges, including climate change, biodiversity loss, environmental pollution, and the unsustainable exploitation of natural resources (Brundtland, 1987; United Nations, 2015; Leal Filho et al., 2019). These challenges are increasingly recognized as interconnected socio-ecological problems that require citizens capable of making informed and responsible decisions (Öhman & Öhman, 2019; Kopnina, 2020). Consequently, education is expected to equip learners not only with scientific knowledge but also with the competencies needed to understand complexity and contribute to sustainable development (United Nations, 2015; UNESCO, 2017, 2020; IPCC, 2023). UNESCO emphasizes that Education for Sustainable Development (ESD) should empower learners with the knowledge, skills, values, and attitudes to act responsibly for environmental integrity, economic viability, and social justice (UNESCO, 2014; Rieckmann, 2018).

Accordingly, sustainability awareness should not be interpreted merely as environmental knowledge. It encompasses a broader capacity to recognize the interconnectedness of environmental, social, and economic dimensions, evaluate the consequences of human activities, and develop a willingness to participate in sustainable actions (Schusler et al., 2009; Barth & Michelsen, 2013). Previous studies have shown that sustainability awareness includes cognitive, affective, and behavioral dimensions that collectively influence how individuals perceive and respond to sustainability issues (Wiek et al., 2011; Brundiers et al., 2021; UNESCO, 2020; Frisk & Larson, 2011). Therefore, environmental change education should promote transformative learning experiences that foster responsible citizenship rather than simply transmitting scientific concepts (Sterling, 2011; Mezirow, 2000; Wals, 2015).

Why Students Often Fail to Develop Sustainability Awareness

Despite growing attention to sustainability in science curricula, many students continue to struggle to translate environmental knowledge into sustainable attitudes and behaviors (Kollmuss & Agyeman, 2002; Otto & Pensini, 2017). Numerous studies have reported that students often demonstrate satisfactory conceptual understanding of environmental issues while showing limited ability to apply this knowledge in authentic decision-making situations or evaluate sustainability problems from multiple perspectives (Olsson et al., 2022; Boeve-de Pauw et al., 2015; UNESCO, 2020; Karpudewan et al., 2015). This discrepancy often referred to as the knowledge-action gap indicates that knowledge acquisition alone is insufficient to cultivate sustainability awareness (Kollmuss & Agyeman,

2002; Vicente-Molina et al., 2013). One possible explanation is that environmental learning remains predominantly disciplinary and content-oriented (Vincent & Focht, 2010). In many science classrooms, environmental change is taught primarily through biological concepts, with limited integration of social, economic, and technological dimensions (Bybee, 2013; Sadler et al., 2016). Likewise, conventional STEM education often emphasizes scientific inquiry and engineering design but pays less attention to sustainability values, ethical reasoning, and societal implications (Kelley & Knowles, 2016; English, 2016; Margot & Kettler, 2019; Roehrig et al., 2021). As a result, students may successfully solve technical problems without fully understanding the broader sustainability consequences of their proposed solutions (Stubbs & Cocklin, 2008).

Systems Thinking as a Missing Cognitive Mechanism

Systems thinking has been widely recognized as one of the core competencies for sustainable development because it enables learners to understand complex interactions, feedback relationships, and long-term consequences within socio-ecological systems (Wiek et al., 2011; Arnold & Wade, 2015; Meadows, 2008). Rather than viewing environmental issues as isolated events, systems thinking encourages students to analyze how ecological, technological, social, and economic factors influence one another, thereby supporting more comprehensive and evidence-based decision-making (Booth Sweeney & Sterman, 2007; Capra & Luisi, 2014).

Although many studies have reported positive effects of STEM-based learning on sustainability-related outcomes, relatively few have investigated the cognitive processes through which these outcomes emerge (Stohlmann et al., 2012; Thibaut et al., 2018). Most existing studies focus on whether STEM instruction improves sustainability awareness, environmental literacy, or problem-solving skills, whereas limited attention has been given to explaining how interdisciplinary learning experiences facilitate these developments (English, 2016; antzoulatos et al., 2020). Consequently, systems thinking may represent a missing explanatory mechanism linking interdisciplinary STEM learning with sustainability awareness (Sipos et al., 2008).

Research Gap

Recent studies have demonstrated the educational benefits of integrated STEM, STEM project-based learning, STEM inquiry, and STEM–ESD approaches in improving students' scientific understanding and higher-order thinking (Lou et al., 2017; Chu et al., 2017; Firman et al., 2023). However, the majority of these studies emphasize learning outcomes rather than the learning processes that produce them (Henderson et al., 2018). Moreover, interdisciplinary integration is frequently limited to STEM disciplines, with relatively little attention given to incorporating social science perspectives that are essential for understanding sustainability challenges (Bamberger & Tal, 2007; Byrne & Hadar, 2011).

This study addresses this gap by proposing a conceptual learning mechanism in which interdisciplinary STEM–ESD learning integrates Biology, Sociology, and Economics to foster students' systems thinking, which may subsequently support the development of sustainability awareness (Frisk & Larson, 2011; Sterling, 2011). Rather than statistically testing mediation effects, the study combines quantitative findings with qualitative classroom evidence to provide a theoretically grounded explanation of how sustainability awareness develops during interdisciplinary learning (Creswell & Creswell, 2018; Yin, 2018).

Purpose of the Study

This study explores how improvements in systems thinking may explain the development of sustainability awareness during interdisciplinary STEM–ESD learning on environmental change. Using evidence from an embedded mixed-methods quasi-experimental study, the research proposes a conceptual explanation of the learning processes through which interdisciplinary integration supports sustainability-oriented thinking (Creswell & Creswell, 2018). The findings are expected to contribute to the theoretical advancement of STEM–ESD research by highlighting systems thinking as a plausible cognitive pathway connecting interdisciplinary learning with sustainability awareness, while also providing practical implications for designing sustainability-oriented science education (Wiek et al., 2011; UNESCO, 2020).

Sustainability Awareness

Sustainability awareness refers to an individual's capacity to understand sustainability issues while demonstrating attitudes and behaviors that support environmentally, socially, and economically responsible actions. Rather than representing environmental knowledge alone, sustainability awareness encompasses three interrelated dimensions: knowledge, attitudes, and behavior (UNESCO, 2020; Wiek et al., 2011). Knowledge enables learners to understand sustainability concepts and global challenges; attitudes reflect values and concern toward sustainable development, whereas behavioral awareness represents the willingness to translate these understandings into responsible actions.

In science education, sustainability awareness has increasingly been recognized as a multidimensional learning outcome that supports informed decision-making in complex socio-ecological contexts. Recent reviews also indicate that sustainability awareness should be developed through authentic learning experiences that integrate scientific understanding with social responsibility and critical reflection, rather than through knowledge transmission alone.

Systems Thinking

Systems thinking is widely regarded as one of the core competencies for Education for Sustainable Development because it enables learners to recognize interactions among system components, identify causal relationships, understand feedback loops, and anticipate long-term consequences (Wiek et al., 2011; Arnold & Wade, 2015). Within science education, systems thinking supports students in moving beyond linear explanations toward understanding environmental issues as dynamic and interconnected systems.

Common indicators of systems thinking include identifying system components, recognizing relationships among variables, explaining causal interactions, predicting system behavior, and evaluating the impacts of interventions (Assaraf & Orion, 2005). Recent systematic reviews further emphasize that interdisciplinary learning environments are particularly effective in fostering systems thinking because they expose students to multiple perspectives and authentic sustainability challenges.

Interdisciplinary STEM–ESD

Interdisciplinary STEM–ESD combines the problem-solving orientation of STEM education with the values and competencies promoted by Education for Sustainable Development. Unlike conventional STEM approaches that often emphasize scientific

inquiry and engineering design, interdisciplinary STEM–ESD intentionally integrates scientific, social, and economic perspectives when addressing authentic sustainability problems (Kelley & Knowles, 2016; UNESCO, 2020).

The integration of Biology, Sociology, and Economics enables students to examine environmental issues as complex socio-ecological systems rather than isolated scientific phenomena. Through interdisciplinary inquiry, learners are encouraged to analyze ecological processes, human behavior, and economic consequences simultaneously, thereby creating opportunities to construct more comprehensive explanations of sustainability challenges. Recent reviews similarly conclude that integrating sustainability with interdisciplinary STEM strengthens higher-order thinking and better prepares learners to address real-world environmental problems.

Proposed Learning Mechanism

Building upon these theoretical perspectives, this study proposes a conceptual learning mechanism to explain how interdisciplinary STEM–ESD learning may foster sustainability awareness. Rather than testing a statistical mediation model, the mechanism provides a theoretical explanation supported by quantitative findings and qualitative classroom evidence from the present study. The proposed mechanism assumes that interdisciplinary STEM–ESD learning engages students in authentic inquiry across Biology, Sociology, and Economics. These interdisciplinary learning experiences encourage students to develop systems thinking by identifying relationships, interactions, and feedback within environmental systems. As students gain a more integrated understanding of complex socio-ecological problems, they become better able to reflect on the environmental, social, and economic consequences of their decisions, ultimately supporting the development of sustainability awareness. This conceptual pathway is consistent with recent evidence highlighting systems thinking as a foundational competency linking interdisciplinary learning and sustainability education.

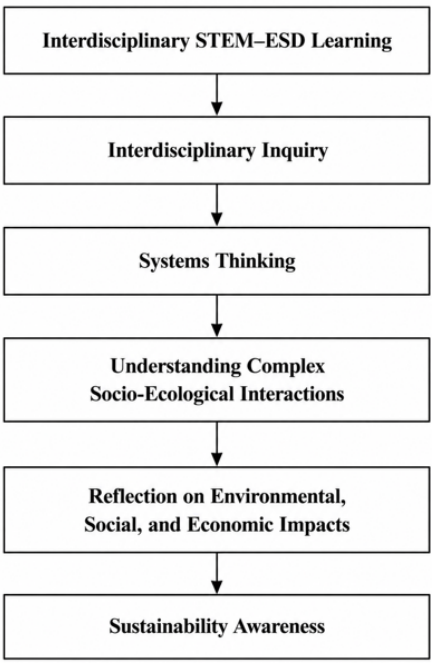


Figure 1. Proposed Conceptual Learning Mechanism

Figure 1 illustrates a conceptual learning mechanism rather than a statistical mediation model. The proposed pathway is intended to explain, from a theoretical and pedagogical perspective, how interdisciplinary STEM–ESD learning may foster sustainability awareness through the development of systems thinking. This mechanism is informed by the quantitative findings and supported by qualitative classroom evidence, but it is not presented as a tested causal model.

METHODS

Research Design

This study employed an embedded mixed-methods quasi-experimental design to explore how interdisciplinary STEM–Education for Sustainable Development (STEM–ESD) learning may foster sustainability awareness through the development of students' systems thinking. The quantitative component was designed to examine changes in students' systems thinking and sustainability awareness, while the qualitative component was embedded to provide explanatory evidence regarding the learning processes underlying these changes. This design enabled the integration of numerical outcomes with classroom evidence to develop a conceptual interpretation of the proposed learning mechanism.

The study adopted a non-equivalent pretest–posttest control group design, in which the experimental group participated in interdisciplinary STEM–ESD learning and the control group received conventional STEM instruction on the same environmental change topic. It should be noted that the present study does not aim to test a statistical mediation model. Instead, quantitative and qualitative findings were interpreted collectively to explain how systems thinking may function as a conceptual pathway supporting the development of sustainability awareness.

Participants and Learning Context

The participants were 72 tenth-grade students from a public senior high school in Bandung, Indonesia. Two intact classes were selected using purposive sampling, with 36 students assigned to the experimental group and 36 students to the control group. Both groups studied the same environmental change topic over the same instructional period; however, the learning approaches differed in their degree of interdisciplinary integration and sustainability orientation. The experimental group participated in an interdisciplinary STEM–ESD learning program that explicitly integrated Biology, Sociology, and Economics through an authentic environmental project involving the design of a solar-powered water purification system. Students were also engaged in sustainability-oriented reflection concerning the environmental, social, and economic implications of their proposed solutions. In contrast, the control group learned the same scientific concepts through a conventional STEM approach without explicit integration of Biology, Sociology, and Economics or structured sustainability-oriented reflection. Thus, the distinguishing characteristic of the experimental treatment was the explicit integration of multiple disciplinary perspectives and sustainability considerations within authentic environmental problem-solving.

Table 1. Distinguishing Characteristics of the Experimental and Control Groups

Aspect	Experimental Group	Control Group
Learning approach	Interdisciplinary STEM–ESD	Conventional STEM
Disciplinary integration	Biology, Sociology, and Economics integrated within the learning activities	Primarily focused on the scientific concepts within the STEM learning context
Learning context	Authentic environmental problem-solving	Classroom-based learning of the same environmental change topic
Learning project	Design of a solar-powered water purification system	No equivalent interdisciplinary environmental design project
Problem-solving orientation	Students considered environmental, social, and economic dimensions in developing solutions	Students focused on understanding and applying scientific concepts through conventional STEM activities
Sustainability reflection	Explicit reflection on the environmental, social, and economic implications of proposed solutions	No structured sustainability-oriented reflection
Expected learning process	Connecting disciplinary perspectives to construct integrated solutions to an authentic problem	Developing understanding of environmental change through conventional STEM learning

Instruments and Data Collection

Data were collected using both quantitative and qualitative instruments to obtain a comprehensive understanding of students' learning experiences. Quantitative data consisted of a Systems Thinking Test and a Sustainability Awareness Questionnaire administered before and after instruction. The systems thinking instrument measured students' ability to identify system components, recognize relationships, explain causal interactions, and predict system behavior. Sustainability awareness was assessed across three dimensions: knowledge, attitudes, and behavior.

Prior to implementation, the research instruments were subjected to both content validity and internal consistency reliability testing to ensure that they accurately and consistently measured the intended constructs. Content validity was established through expert judgment involving three experts in science education and STEM education. Each expert evaluated the instruments based on theoretical relevance, construct representation, contextual appropriateness, language clarity, scoring procedures, and overall feasibility using a four-point rating scale. The degree of agreement among the experts was quantified using Aiken's V.

The Systems Thinking Test demonstrated excellent content validity, with Aiken's V coefficients ranging from 0.667 to 1.000 and an average coefficient of 0.875. The highest validity indices were obtained for the alignment between the indicators and the theoretical framework of systems thinking, language clarity, and completeness of the test instructions (V = 1.000). Slightly lower values were found for the scoring rubric (V = 0.667), leading to minor revisions to improve scoring consistency and clarify the assessment criteria based on the experts' recommendations.

Similarly, the Sustainability Awareness Questionnaire demonstrated excellent content validity, with Aiken's V coefficients ranging from 0.667 to 1.000 and an average

coefficient of 0.944. The questionnaire adequately represented the three constructs of sustainability awareness knowledge, attitudes, and behaviours across the environmental, social, and economic dimensions adapted from the Sustainability Consciousness Questionnaire (Gericke et al., 2019). Based on the experts' suggestions, several statements were refined to improve the balance between positively and negatively worded items while maintaining the conceptual framework of the instrument.

Following expert validation, the internal consistency reliability of both instruments was examined using Cronbach's Alpha. The Systems Thinking Test, consisting of 15 items, obtained a Cronbach's Alpha coefficient of 0.901, indicating excellent internal consistency. Likewise, the Sustainability Awareness Questionnaire, consisting of 45 items, achieved a Cronbach's Alpha coefficient of 0.891, indicating high internal consistency. According to Hair et al. (2019), Cronbach's Alpha values above 0.70 indicate acceptable reliability, whereas values approaching or exceeding 0.90 reflect excellent internal consistency. Therefore, both instruments demonstrated satisfactory reliability and were considered appropriate for measuring students' systems thinking skills and sustainability awareness.

Overall, the results of the content validity and reliability analyses indicate that the research instruments possess strong psychometric properties. The high Aiken's V coefficients confirm that the instruments adequately represent the intended theoretical constructs, while the Cronbach's Alpha coefficients demonstrate consistent measurement across the instrument items. Consequently, the instruments were considered both theoretically valid and empirically reliable for evaluating the effectiveness of the proposed interdisciplinary STEM–ESD learning framework.

Table 2. Summary of Instrument Validity and Reliability

Instrument	Number of Items	Content Validity (Aiken's V)	Reliability (Cronbach's Alpha)	Interpretation
Systems Thinking Test	15	0.875	0.901	Excellent content validity and excellent internal consistency
Sustainability Awareness Questionnaire	45	0.944	0.891	Excellent content validity and high internal consistency

The expert validation and reliability analyses confirmed that the developed instruments possessed strong psychometric quality. The Systems Thinking Test achieved an average Aiken's V coefficient of 0.875 and a Cronbach's Alpha coefficient of 0.901, indicating excellent content validity and internal consistency. Likewise, the Sustainability Awareness Questionnaire obtained an average Aiken's V coefficient of 0.944 and a Cronbach's Alpha coefficient of 0.891, demonstrating excellent content validity and high reliability. These findings indicate that both instruments consistently measured the intended constructs and were therefore appropriate for evaluating the effectiveness of the proposed interdisciplinary STEM–ESD learning framework. High-quality instruments are essential for ensuring that improvements in students' systems thinking and sustainability awareness can be attributed to the instructional intervention rather than to measurement error.

Qualitative evidence was collected through classroom observations, student worksheets (LKPD), and semi-structured interviews. Classroom observations documented

students' participation during interdisciplinary inquiry and collaborative problem-solving. Student worksheets provided evidence of how learners connected biological, social, and economic perspectives while analyzing environmental issues. Interviews were conducted with selected students to explore their reasoning processes, reflections, and perceptions of sustainability throughout the learning activities.

Data Analysis & Quantitative Data Analysis

Quantitative and qualitative data were analyzed separately and subsequently integrated following the embedded mixed-methods design. The quantitative data were analyzed using descriptive statistics and inferential statistics. Descriptive statistics were employed to summarize students' performance on each research variable, including mean, standard deviation, minimum score, maximum score, percentage, and normalized gain (N-Gain) for the Systems Thinking Test and Sustainability Awareness Questionnaire.

Inferential statistics were conducted to examine the effectiveness of the interdisciplinary STEM–ESD learning framework. Prior to hypothesis testing, data normality was assessed using the Shapiro–Wilk test, while homogeneity of variance was examined using Levene's test. Depending on the distributional assumptions, differences between the experimental and control groups were analyzed using an independent-samples t-test for normally distributed data or the Mann–Whitney U test for non-normally distributed data. Statistical significance was determined at $p < .05$. All quantitative analyses were performed using IBM SPSS Statistics version 27.

Qualitative Data Analysis

Qualitative data obtained from classroom observations, student worksheets (LKPD), interviews, and field notes were analyzed using thematic analysis. The analysis involved data reduction, coding, categorization, theme development, and interpretation to identify patterns of systems thinking, interdisciplinary reasoning, collaborative learning, and sustainability-oriented decision-making emerging throughout the learning process.

Integration of Quantitative and Qualitative Findings

Finally, quantitative and qualitative findings were integrated during the interpretation stage in accordance with the embedded mixed-methods design. Quantitative results explained the effectiveness of the interdisciplinary STEM–ESD learning framework, whereas qualitative findings provided explanatory evidence regarding how students developed systems thinking, integrated interdisciplinary perspectives, and constructed sustainability-oriented solutions during authentic problem-solving activities.

RESULT AND DISCUSSION

Interdisciplinary STEM–ESD Learning Enhanced Students' Systems Thinking

The quantitative findings indicated that students who participated in the interdisciplinary STEM–ESD learning program demonstrated substantially greater improvements in systems thinking than those receiving conventional STEM instruction. Before the intervention, both groups showed comparable systems thinking performance. Following instruction, however, the experimental group achieved significantly higher post-test scores and learning gains than the control group.

Table 3. Students' Systems Thinking Scores

Group	Pre-test Mean ± SD	Post-test Mean ± SD	N-Gain	Category
Experimental	50.10 ± 6.40	88.10 ± 7.75	0.77	High
Control	49.90 ± 4.30	80.10 ± 3.07	0.60	Moderate

Further statistical analysis demonstrated that the improvement was statistically significant (Mann–Whitney U = 36, p = .012), indicating that interdisciplinary STEM–ESD learning was more effective in promoting systems thinking than conventional STEM instruction. Beyond the numerical improvement, classroom observations suggested qualitative differences in students' reasoning processes. During the initial learning activities, many students explained environmental change primarily from biological perspectives. As learning progressed, students increasingly recognized interactions among ecological processes, community behavior, and economic activities when discussing environmental problems. This shift reflected movement from linear explanations toward systems-oriented reasoning.

Sustainability Awareness Improved Through Interdisciplinary Learning

Prior to instruction, both groups exhibited comparable levels of sustainability awareness. Shapiro–Wilk tests confirmed that pretest scores were normally distributed in both the experimental group (p = 0.376) and the control group (p = 0.817), and Levene's test indicated homogeneity of variance (p = 0.717). An independent-samples t-test found no significant difference between the experimental (M = 63.92, SD = 1.66) and control groups (M = 63.22, SD = 1.91) at pretest, t(70) = 1.66, p = 0.105 > 0.05, confirming that the two groups began the study with an equivalent level of sustainability awareness. Following instruction, students in the experimental group demonstrated substantially greater improvement in sustainability awareness than those in the control group. Table 4 summarizes the pretest and posttest scores, gain, and N-Gain for both groups.

Table 4. Students' Sustainability Awareness Scores

Group	Pre-test Mean ± SD	Post-test Mean ± SD	N-Gain	Category
Experimental	63.92 ± 1.66	93.19 ± 1.13	0.811	High
Control	63.22 ± 1.91	81.83 ± 1.49	0.504	Moderate

Posttest scores were likewise normally distributed (experimental: p = 0.357; control: p = 0.664) with homogeneous variances (p = 0.111), satisfying the assumptions for parametric comparison. The experimental group's posttest mean (93.19) exceeded that of the control group (81.83) by 11.36 points, a difference confirmed as statistically significant by an independent-samples t-test, t(70) = 36.44, p = 0.000 < 0.05. The experimental group also achieved a substantially higher N-Gain (0.811, high category) than the control group (0.504, moderate category), and this difference was likewise statistically significant, t(70) = 31.62, p = 0.000 < 0.05.

These quantitative findings indicate that interdisciplinary STEM–ESD learning supported the development of sustainability awareness more effectively than conventional STEM instruction. Students in the experimental group not only demonstrated a stronger grasp of sustainability concepts but also expressed greater concern for environmental issues and a stronger willingness to consider sustainable actions. Importantly, this improvement extended beyond cognitive achievement alone.

Classroom discussions revealed that students increasingly evaluated environmental problems by weighing environmental protection alongside social responsibility and economic feasibility, reflecting a broader, more integrated understanding of sustainable development.

Classroom Evidence Supporting the Proposed Learning Mechanism

Qualitative findings provided further evidence explaining how sustainability awareness developed during interdisciplinary STEM–ESD learning. Classroom observations, student worksheets (LKPD), and interviews consistently showed that students gradually integrated biological, social, and economic perspectives while solving authentic environmental problems. During the early stages of learning, many students proposed technological solutions without considering their broader implications. However, after participating in interdisciplinary inquiry activities, students increasingly discussed how environmental problems involved interactions among ecological conditions, community behavior, and economic activities. This progression suggested the development of systems thinking that extended beyond disciplinary knowledge. Specifically, students shifted from single-cause explanations toward multi-causal reasoning that explicitly linked ecological, social, and economic factors within the same problem, a pattern consistent with the conceptualization of systems thinking as the ability to recognize interconnections and feedback among components of a system (Assaraf & Orion, 2005; Mehren et al., 2018).

Analysis of students' worksheets also demonstrated this transition. Initially, students identified pollution primarily as a biological issue affecting ecosystems. In later learning activities, they expanded their explanations by connecting water pollution with household waste management, community participation, public awareness, production costs, and the long-term sustainability of technological solutions. Such responses indicated that students were constructing integrated explanations rather than isolated scientific descriptions. Classroom observations further revealed that collaborative discussions encouraged students to justify their proposed solutions from multiple perspectives. Rather than focusing solely on technical effectiveness, students evaluated whether their designs were environmentally sustainable, socially acceptable, and economically feasible.

In the initial interviews, before the interdisciplinary inquiry activities, students consistently framed the water pollution problem in narrow technical terms, describing the solution mainly as a matter of improving filtration technology without reference to community behavior, affordability, or long-term environmental consequences. Following participation in interdisciplinary STEM–ESD learning, subsequent interviews indicated a marked shift toward integrated reasoning that incorporated social and economic considerations alongside the technical dimension. One student's reflection illustrates this shift in thinking:

> *"At first, we thought that solving water pollution only required better technology. After discussing the biological, social, and economic aspects, we realized that clean water cannot be sustained unless people also change their behavior and communities are willing to support environmentally responsible practices."*

Another student explained:

> *"Designing the water purification system was not only about making it work. We also had to consider whether people could afford it, whether they would use it, and whether it would reduce environmental impacts in the long term."*

This shift is best explained by the repeated exposure to biological, social, and economic perspectives during interdisciplinary inquiry, which prompted students to reconsider the scope of the problem before proposing a solution, rather than by maturation or repeated testing alone (Repko & Szostak, 2021). These qualitative findings complement the quantitative improvements in systems thinking and sustainability awareness. Together, they suggest that interdisciplinary STEM–ESD learning encouraged students to understand environmental change as a complex socio-ecological system. As students became more capable of identifying relationships, feedback, and multiple perspectives, they increasingly reflected on the environmental, social, and economic consequences of their decisions. This pattern provides empirical support for the proposed conceptual learning mechanism, in which the development of systems thinking helps explain how interdisciplinary STEM–ESD learning fosters sustainability awareness.

Systems Thinking as the Cognitive Pathway to Sustainability Awareness

The findings suggest that the development of sustainability awareness was not solely a consequence of acquiring environmental knowledge, but rather of students' increasing ability to understand environmental issues as interconnected socio-ecological systems. Throughout the interdisciplinary STEM–ESD learning process, students gradually shifted from viewing environmental change as an isolated scientific phenomenon to recognizing the complex interactions among ecological processes, human behavior, technological innovation, and economic activities. This progression indicates that systems thinking provided the cognitive foundation through which students interpreted sustainability problems more holistically.

The classroom evidence supports this interpretation. Students initially focused on technological solutions for water pollution but later recognized that sustainable solutions also depended on community participation, environmental responsibility, and economic feasibility. This conceptual shift suggests that interdisciplinary inquiry encouraged students to integrate multiple perspectives before making sustainability-related judgments. These findings are consistent with previous studies identifying systems thinking as a key competency for understanding complex sustainability challenges (Wiek et al., 2011; Arnold & Wade, 2015; Brundiers et al., 2021). However, whereas these earlier studies primarily established systems thinking as an outcome or predictor of sustainability-related competencies, the novelty of the present study lies in providing mixed-methods empirical evidence that specifies how systems thinking functions as a cognitive pathway linking interdisciplinary STEM learning experiences to the development of sustainability awareness, rather than only inferring this association statistically.

Why Interdisciplinary Learning Strengthened Systems Thinking

A central characteristic of the proposed interdisciplinary STEM–ESD approach is the integration of Biology, Sociology, and Economics within authentic environmental problem solving. Rather than learning these disciplines independently, students were encouraged to examine environmental change through complementary perspectives. Biological concepts explained ecological processes, sociology highlighted community behavior and

social responsibility, while economics introduced considerations of resource use, cost, and sustainability. Deliberately combining these three domains rather than limiting interdisciplinarity to STEM subjects alone or pairing Biology with only one social discipline constitutes one of the novel contributions of this study, as it explicitly positions economic reasoning alongside ecological and social considerations as a core dimension of sustainability problem solving, responding to calls in the literature for broader interdisciplinary integration within STEM–ESD education (Bamberger & Tal, 2007; Byrne & Hadar, 2011; Repko & Szostak, 2021).

This interdisciplinary inquiry appeared to promote systems thinking by encouraging students to identify relationships among multiple variables instead of focusing on isolated disciplinary concepts. During classroom discussions and worksheet activities, students increasingly connected pollution with waste management, human behavior, public participation, technological accessibility, and economic sustainability. Such reasoning reflects a transition from fragmented knowledge toward systems-oriented understanding, supporting previous research suggesting that interdisciplinary learning provides favorable conditions for developing systems thinking in sustainability education (Repko & Szostak, 2021; UNESCO, 2020).

Reflection as the Bridge Between Systems Thinking and Sustainability Awareness

The findings also suggest that reflection played an essential role in transforming systems thinking into sustainability awareness. While systems thinking enabled students to recognize interactions and feedback within socio-ecological systems, reflective activities encouraged them to evaluate the environmental, social, and economic consequences of their proposed solutions. During reflection sessions, students discussed not only whether the solar-powered water purification system functioned technically, but also whether it would be accessible to local communities, economically feasible, and environmentally sustainable over time. Such reflective processes encouraged learners to consider trade-offs among competing sustainability objectives rather than seeking single technical solutions. These findings align with UNESCO's Education for Sustainable Development framework, which emphasizes critical reflection as a prerequisite for developing sustainability competencies. Reflection allows learners to transform scientific understanding into responsible judgment and informed decision-making by connecting knowledge with values and real-world contexts (UNESCO, 2017, 2020).

A Conceptual Explanation of the Learning Mechanism

Based on the integration of quantitative and qualitative findings, this study proposes a conceptual explanation of how interdisciplinary STEM–ESD learning may foster sustainability awareness. Authentic environmental problems first stimulated students to investigate environmental change through interdisciplinary inquiry. By integrating biological, social, and economic perspectives, students progressively developed systems thinking that enabled them to recognize interactions, feedback relationships, and long-term consequences within socio-ecological systems. Reflection activities subsequently encouraged learners to evaluate the sustainability implications of alternative solutions, ultimately supporting the development of sustainability awareness.

Importantly, this explanation should not be interpreted as a statistically tested mediation model. Rather, it represents a theory-informed conceptual mechanism grounded in empirical evidence obtained through an embedded mixed-methods design.

The quantitative findings demonstrated significant improvements in systems thinking and sustainability awareness, whereas classroom observations, student worksheets, and interviews provided complementary evidence illustrating how these developments occurred during learning. The proposed mechanism therefore contributes to the literature by shifting attention from the question of whether interdisciplinary STEM–ESD learning improves sustainability awareness toward understanding how such learning experiences facilitate its development.

Implications for Sustainability-Oriented Science Education

The findings have several implications for science education. First, sustainability awareness should not be considered a direct outcome of environmental knowledge alone. Instead, instructional design should deliberately cultivate systems thinking by engaging students in interdisciplinary inquiry and authentic problem solving. Second, integrating Biology, Sociology, and Economics within STEM learning provides opportunities for students to understand sustainability challenges from multiple perspectives. Such integration moves beyond traditional disciplinary boundaries and encourages learners to evaluate environmental issues as dynamic socio-ecological systems.

Finally, the study suggests that Education for Sustainable Development (ESD) should function not as an additional curriculum component but as the pedagogical orientation guiding STEM learning. Embedding reflection on environmental integrity, social responsibility, and economic feasibility throughout the learning process enables students to develop sustainability awareness that extends beyond conceptual understanding toward informed and responsible decision-making.

Conceptual Learning Mechanism

Figure 2 presents the conceptual learning mechanism proposed in this study. Rather than representing a statistical mediation model, the framework illustrates the pedagogical process through which interdisciplinary STEM–ESD learning may foster sustainability awareness. The mechanism is derived from the integration of quantitative findings, classroom observations, student worksheets, and interview data.

Authentic environmental problems serve as the entry point for learning by engaging students in interdisciplinary inquiry. Within this process, students integrate knowledge from Biology, Sociology, and Economics to investigate environmental issues from multiple perspectives. This interdisciplinary reasoning supports the development of systems thinking by enabling learners to recognize relationships, feedback loops, trade-offs, and long-term consequences within socio-ecological systems.

As students engage in reflective discussions about the environmental, social, and economic implications of their proposed solutions, they gradually develop a broader understanding of sustainability. Consequently, sustainability awareness emerges not simply as the acquisition of environmental knowledge but as the result of systems-oriented reasoning supported by interdisciplinary inquiry and critical reflection.

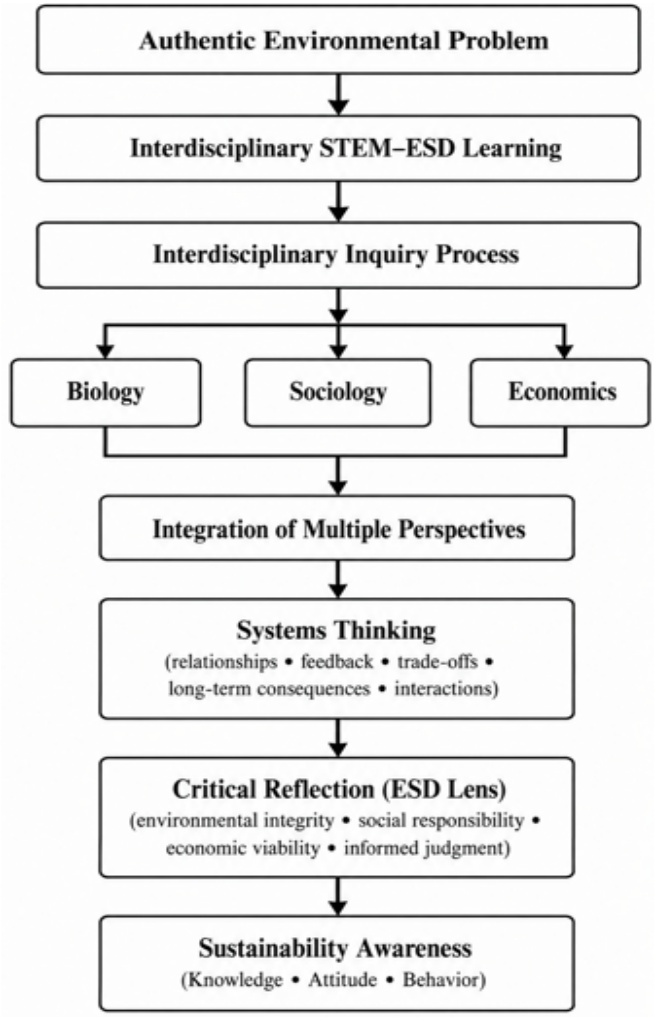


Figure 2. Proposed Conceptual Learning Mechanism of Interdisciplinary STEM–ESD Learning

Figure 2 illustrates a conceptual learning mechanism, providing a theoretical explanation of how interdisciplinary STEM–ESD learning may promote sustainability awareness rather than presenting a statistically tested causal pathway.

CONCLUSION

In line with the objective of explaining how, rather than merely whether, interdisciplinary STEM–ESD learning supports sustainability awareness, this study developed and tested a conceptual explanation in which systems thinking functions as a cognitive pathway connecting interdisciplinary learning experiences to sustainability awareness. This study developed and evaluated an interdisciplinary STEM–Education for Sustainable Development (STEM–ESD) learning framework to enhance students' systems thinking and sustainability awareness through authentic sustainability problem solving. The findings indicate that integrating Biology, Sociology, and Economics within an interdisciplinary STEM–ESD approach enables students to understand sustainability from interconnected environmental, social, and economic perspectives rather than as isolated concepts. The framework also demonstrated positive effects on students' systems

thinking and sustainability awareness. An important contribution of this study is the identification of the Engineering Design Process (EDP) as a key pedagogical mechanism supporting sustainability learning. Throughout the stages of problem identification, investigation, design, prototype construction, testing, and redesign, students continuously evaluated environmental, technological, social, and economic consequences of their decisions. This iterative process encouraged systems thinking and reflective decision-making, thereby strengthening students' sustainability awareness beyond merely developing technical design skills. The proposed interdisciplinary STEM–ESD learning procedure consists of sequential stages: (1) introducing authentic sustainability challenges, (2) integrating interdisciplinary knowledge from Biology, Sociology, and Economics, (3) engaging students in the Engineering Design Process, (4) facilitating reflection through Education for Sustainable Development (ESD) principles, and (5) evaluating sustainability-oriented solutions. This sequence provides a practical and replicable framework for educators and researchers seeking to implement interdisciplinary STEM–ESD learning in secondary education. Overall, the proposed framework contributes to the growing literature on interdisciplinary STEM education by demonstrating how systems thinking can serve as a bridge between interdisciplinary learning and sustainability awareness. Future research should examine the framework in different educational contexts and employ longitudinal or structural equation modeling approaches to further investigate the relationships among interdisciplinary STEM–ESD learning, systems thinking, and sustainability awareness.

DECLARATION OF GENERATIVE AI

During the preparation of this work, the author used ChatGPT to check grammar and spelling. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

CONFLICTING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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