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Research Article

Keywords: Environmental literacy, Pre-service biology teachers, Socio-scientific issues, STEAM education, Environmental education

Posted Date: July 21st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10338696/v1

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Additional Declarations: No competing interests reported.

Environmental Literacy Profile of Pre-Service Biology Teachers Through SSI-STEAM Integrated Learning

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ABSTRACT

Environmental literacy is a foundational competence for pre-service biology teachers, encompassing the ability to understand ecological phenomena, critically evaluate socio-scientific environmental issues, and engage in responsible environmental action. This study examined the environmental literacy profile of Biology Education students at Universitas Muhammadiyah Makassar who participated in SSI-STEAM integrated learning in an Environmental Education course. A mixed methods explanatory sequential design was employed with 40 students recruited through total sampling. Quantitative data were collected using a 40-item environmental literacy questionnaire covering five dimensions: environmental knowledge, environmental awareness and concern, SSI-based critical thinking, STEAM based problem solving and decision making, and pro environmental behavior and participation. Semi-structured interviews provided qualitative data. Overall environmental literacy was very high (M = 4.39; 87.7%). Environmental awareness and concern and pro environmental behavior and participation achieved the highest scores (M = 4.72 and M = 4.79 respectively), both in the very high category. SSI-based critical thinking obtained the lowest score (M = 3.93; 78.6%), classified as high indicating that deliberative argumentation remained the most challenging dimension to develop within a single course-based intervention. The findings support SSI-STEAM integration as a productive pedagogical model while identifying scientific argumentation as the priority area for future curricular strengthening.

KEYWORDS: Environmental literacy; Pre-service biology teachers; Socio-scientific issues; STEAM education; Environmental education

1. INTRODUCTION

Contemporary environmental problems, including water pollution, soil contamination, climate change, and biodiversity loss, are inherently multidimensional phenomena that intersect scientific, technological, social, economic, and ethical domains simultaneously. These challenges demand citizens equipped not merely with ecological knowledge but with the competence to evaluate scientific evidence, reason through value laden controversies, and translate their understanding into responsible action (Tijani & Adeduyigbe, 2026). Environmental literacy, broadly understood as the integrated capacity to understand environmental systems, develop informed concern, exercise critical environmental judgment (Sorensen et al., 2016), and engage in pro-environmental behavior, has consequently emerged as a central goal of science

education at all levels (Kinslow et al., 2019). Cultivating environmental awareness from an early age is essential for reducing pollution (Yuliani et al., 2023). Within the higher education sector, this mandate is especially pressing, given that universities are widely regarded as pivotal institutions for cultivating the knowledge, attitudes, and competencies required to advance the global sustainability agenda articulated in the Sustainable Development Goals (SDGs), particularly SDG 4 on quality education and SDG 6 on clean water and sanitation (Escoz-Roldán et al., 2020). Water and soil pollution represent particularly salient topics for environmental literacy education in Indonesia: both issues are directly experienced by students in their daily lives, both have well documented consequences for human health and ecosystem integrity, and both lend themselves naturally to cross disciplinary analysis and community-oriented problem solving (Forbes et al., 2018).

Pre-service biology teachers occupy a uniquely strategic position within this global environmental education agenda. They are not simply students developing their own environmental literacy; they are simultaneously prospective educators who will shape the environmental values, knowledge, and action competence of the next generation of citizens. (Herro & Quigley, 2017) have demonstrated that teachers' perceptions and professional preparation for integrated, context relevant science education have a direct bearing on the quality and coherence of the learning experiences they subsequently design. Within this framework, socio-scientific issues (SSI) have attracted considerable attention as a pedagogical approach that situates science learning within complex (Romine et al., 2020), authentic social dilemmas requiring both scientific reasoning and ethical reflection (Kinslow et al., 2019). At the same time, STEAM education integrating Science, Technology, Engineering, Arts, and Mathematics has gained traction as a framework for translating analytical competence into creative, cross disciplinary problem solving and design (Mang et al., 2021). Recent empirical evidence has reinforced the utility of both approaches: (Purwasih et al., 2025) demonstrated that SSI grounded in local environmental potential strengthened students' ecological literacy, while (Rahmawati et al., 2025) showed that STEAM project based learning combined with design thinking enhanced environmental literacy through authentic engagement with real world environmental problems.

Despite growing recognition of the pedagogical value of both SSI and STEAM approaches, significant challenges continue to limit the effectiveness of environmental education in higher education. A fundamental tension persists between the dominant emphasis on conceptual knowledge transmission and the affective, deliberative, and action-oriented dimensions that translate environmental awareness into durable behavioral change (Kellberg et al., 2023). (Arif et al., 2022) have documented that environmental literacy, particularly its behavioral dimension, is shaped not only by individual knowledge and attitudes but also by contextual and institutional conditions, including the availability of supporting infrastructure and the normative expectations of peer communities. A second challenge concerns the capacity for socioscientific reasoning itself: students at all levels tend to develop concern and behavioral intention more readily than the analytical competencies required to evaluate competing evidence, weigh multiple perspectives, and construct data grounded arguments about controversial issues (Romine et al., 2020). (Türk & Çam, 2025) have specifically demonstrated that argumentation based instructional approaches are necessary

prerequisites for building students' capacity to reason through SSI, and that such capacity does not emerge from incidental exposure to controversial topics alone. (Tangio et al., 2026) further document that even among prospective chemistry and science teachers, social scientific reasoning competencies frequently remain underdeveloped in the absence of deliberate, structured instructional attention.

The literature has proposed two general classes of pedagogical response to these challenges. The first draws on the SSI tradition, emphasizing the deliberate embedding of authentic, locally relevant socioscientific dilemmas within science learning to motivate both conceptual engagement and ethical reflection. (Lubis et al., 2022) found that problem-based learning oriented toward local wisdom and SSI significantly improved students' socioscientific reasoning, while (da Silva Fonseca & da Costa, 2025) demonstrated that investigative analysis of SSI related to water issues in a teacher education program deepened prospective teachers' understanding of both scientific content and social responsibility. The second class of response draws on STEAM integration, emphasizing the creation of cross disciplinary (Asilturk et al., 2026), design-oriented learning experiences that give learners the opportunity to apply scientific knowledge to authentic problems through engineering design, artistic communication, and mathematical analysis (Hariyono et al., 2026). SSI-STEAM integrated learning, these skills are essential for enabling students to analyze environmental issues, evaluate evidence, and design responsible solutions (Diep et al., 2026). (Syamsudin et al., 2026) demonstrated that a problem and design process-based learning model incorporating STEAM significantly improved students' problem-solving skills, while (Keum & Baek, 2025) found that a STEAM climate change education program enhanced environmental competence in elementary learners.

Studies that have operationalized SSI or STEAM in relationship to environmental literacy offer more specific evidence regarding pedagogical mechanisms. (Mang et al., 2021) developed an SSI based STEAM program framework and demonstrated its utility for integrating socioscientific reasoning with cross disciplinary design competencies. (Mang et al., 2023) subsequently developed an evaluation rubric for planning and assessing SSI based STEAM programs, providing a methodological contribution that strengthens the empirical base for this integrated approach. (Rahmawati et al., 2023) documented that embedding ethical dilemma story pedagogy within STEAM projects on environmental sustainability fostered students' chemical literacy, critical thinking, and awareness of environmental responsibility. (Rahmawati et al., 2024) extended this to pre service teacher education, showing that an ethical dilemma STEAM teaching model strengthened chemical literacy in addressing real life environmental problems. (Natalya et al., 2021) further documented improvements in students' engagement with both scientific content and ethical dimensions of environmental issues through STEAM integrated dilemma stories. (Herman, 2018) provided complementary evidence from place-based SSI instruction, showing that grounding SSI in specific, observable local contexts shaped students' environmental views, compassion toward affected communities, and intentions to act.

A systematic review of the literature reveals three persistent gaps. First, the majority of existing studies examine SSI and STEAM as conceptually and methodologically separate strands, rarely investigating their deliberate integration within a single, coherent learning experience. (Hariyono et al., 2026) have specifically

identified the integration of SSI within STEAM education as an underexplored factor in explaining variance in problem solving outcomes. Second, existing empirical evidence on environmental literacy within SSI-STEAM contexts is largely limited to secondary education and to specific subject domains such as chemistry (Kinslow et al., 2019); evidence from biology teacher education programs in Indonesian higher education is markedly absent (Purwasih et al., 2025). Third, most environmental literacy studies measure individual dimensions in isolation rather than profiling learners across the full spectrum of cognitive (Sorensen et al., 2016), affective, competence, and behavioral dimensions simultaneously (Romine et al., 2020). This gap constitutes the central justification for the present study.

Building on this rationale, the present study aims to: (1) analyze the environmental literacy profile of pre-service biology teachers engaged in SSI-STEAM integrated learning across five dimensions environmental knowledge, environmental awareness and concern, SSI based critical thinking skills, STEAM based problem solving and decision making skills, and pro environmental behavior and participation; and (2) explain how these students interpret and make meaning of their environmental literacy within the context of water and soil pollution topics. The study addresses two research questions: (1) What is the environmental literacy profile of pre-service biology teacher students across the five dimensions in SSI STEAM integrated learning on water and soil pollution? and (2) How do pre-service biology teacher students interpret and make meaning of their environmental knowledge, awareness and attitudes, SSI based critical thinking, STEAM based problem solving and decision making, and pro environmental behavior within this integrated learning experience?

2. METHODS

This study employed a mixed methods approach using an explanatory sequential design, in which quantitative data were collected and analyzed first, followed by the collection of qualitative data intended to elaborate and contextualize the quantitative findings. This design was selected because a comprehensive profile of pre-service biology teachers' environmental literacy across five dimensions required two complementary sources of evidence: numerical data capable of characterizing the distribution and magnitude of literacy across dimensions, and narrative data capable of illuminating the meanings, reasoning processes, and experiential interpretations underlying those numerical patterns.

The participants were 40 students enrolled in the Biology Education program at Universitas Muhammadiyah Makassar who were taking the Environmental Education course during the study semester. A total sampling technique was employed, including all students participating in the SSI-STEAM integrated learning activities. The learning context was organized around two topics, water pollution and soil pollution which were selected for their direct relevance to students' daily lives and salience as locally observable environmental problems in the Makassar urban and peri urban context. These topics afforded students opportunities to design simple, feasible solutions within the SSI-STEAM framework. Locally grounded environmental problems consistently produce stronger affective engagement (Condeza-Marmentini, 2020), deeper conceptual understanding, and greater behavioral motivation than abstract or decontextualized topics (Forbes et al., 2018).

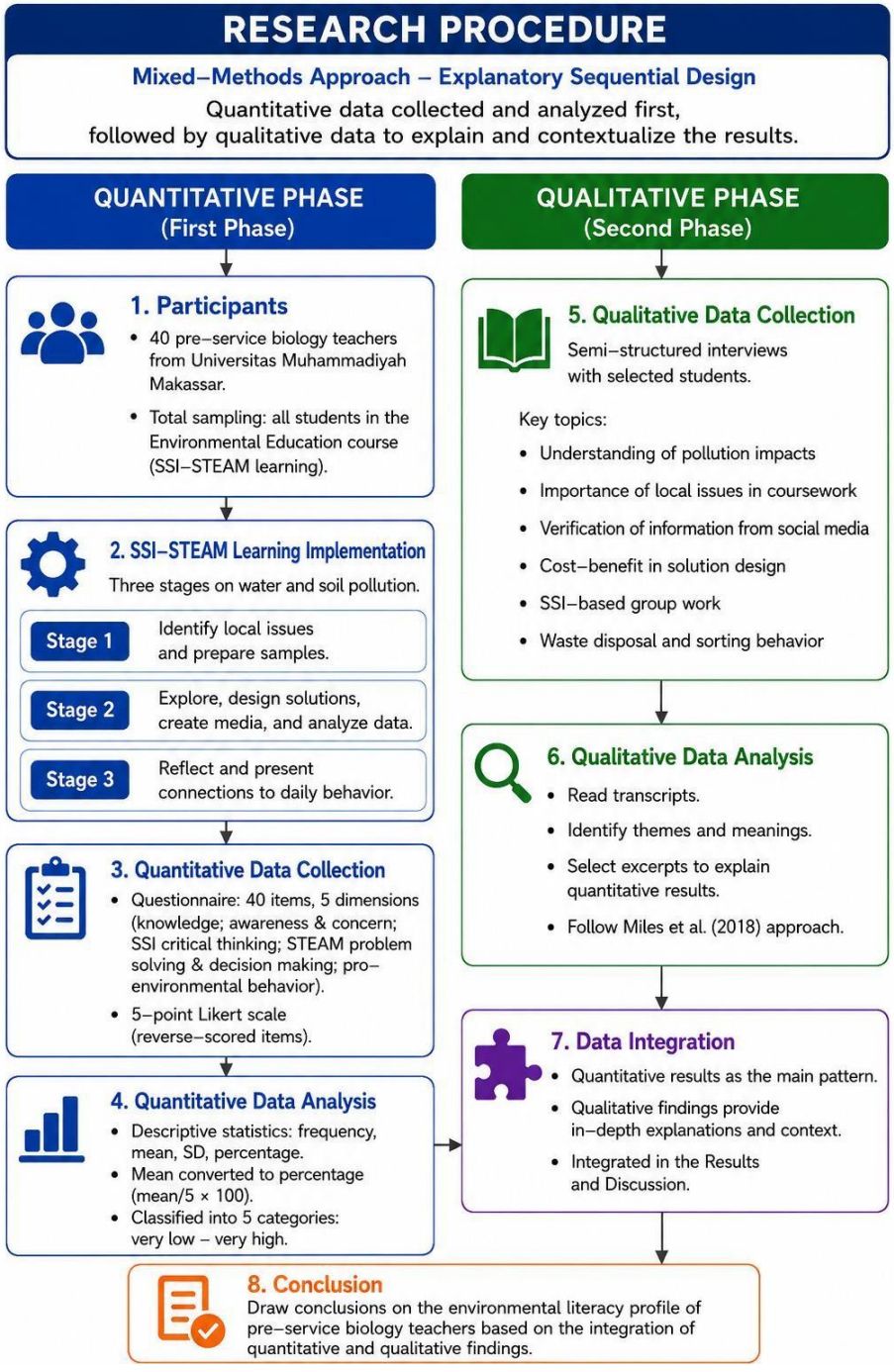


Figure 1. Mixed methods approach; explanatory sequential design

The SSI-STEAM integrated learning was implemented across three sequential stages. In the first stage, students identified local environmental issues and collected practical materials, including water samples from multiple sources (pond water, drainage water, lake water, and rice field water) and contaminated soil samples from

waste disposal sites, oil contaminated areas, and household waste contaminated drainage channels (Lubis et al., 2022). The issues were framed explicitly as socio scientific issues encompassing biological, ecological, community behavioral, policy, cost benefit, and moral responsibility dimensions (Estigarribia et al., 2022).



Figure 2. Students making a simple water filter

In the second stage, students engaged in scientific exploration through laboratory activities and solution design organized around all five STEAM components. The science component involved water quality testing, soil contamination analysis, and biological indicator interpretation. The technology component encompassed digital information searches, source verification, and educational media development. The engineering component was operationalized through the design and construction of a simple water filtration device made from a 1,500 ml plastic bottle layered with cotton, activated charcoal, small stones, coconut fiber, gravel, and sand. The arts component was applied in the creation of environmental campaign posters and infographics, while the mathematics component provided tools for interpreting quantitative data. Data based argumentation activities were deliberately integrated, requiring students to construct claims, assemble evidence (Baran et al., 2021), and articulate reasoning about pollution issues and proposed solutions a necessary condition for developing SSI based critical thinking (Türk & Çam, 2025).

The third stage was structured as a collective reflection phase in which students shared their designed solutions, campaign materials, and conclusions through group presentations, fostering awareness of the relationship between environmental knowledge and everyday behavior ((Romero-Ariza et al., 2021); (Kim et al., 2021)).



Figure 3. Practical activities using a simple water filtration tools

Quantitative data were collected using a 40-item environmental literacy questionnaire developed with reference to established frameworks, encompassing five dimensions of 8 items each. Students responded using a five-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree), with negatively worded items reverse scored. Mean scores were converted to percentages and classified into five interpretive categories, as presented in Table 1. Qualitative data were collected through semi structured interviews covering all five questionnaire dimensions. Data were analyzed descriptively (quantitative) and through iterative thematic coding (qualitative), integrated at the interpretation stage with quantitative findings establishing the primary pattern and qualitative findings providing elaboration and grounding.

Table 1. Environmental literacy classification categories

Score Range	Percentage	Category	Interpretation
4.21 – 5.00	84.1% – 100%	Very high	Excellent environmental literacy
3.41 – 4.20	68.1% – 84.0%	High	Good environmental literacy
2.61 – 3.40	52.1% – 68.0%	Moderate	Adequate environmental literacy
1.81 – 2.60	36.1% – 52.0%	Low	Limited environmental literacy
1.00 – 1.80	20.0% – 36.0%	Very low	Minimal environmental literacy

3. RESULTS

3.1 Overall Environmental Literacy Profile

Overall, pre-service biology teacher students demonstrated a very high level of environmental literacy (M = 4.39; SD = 0.69; 87.7%), as presented in Table 2. This

aggregate outcome suggests that SSI-STEAM-integrated learning provided a productive pedagogical context for developing environmental literacy across its cognitive, affective, and behavioral dimensions simultaneously. The result is consistent with the multidimensional framework advanced by which holds that genuine environmental literacy encompasses not merely factual knowledge but also affective dispositions, competency-based skills, and responsible behavioral orientations that reinforce one another in practice(Romine et al., 2020) further affirm that socioscientific reasoning, when developed within authentic problem contexts, produces multidimensional literacy gains spanning declarative knowledge, analytical competence, and dispositional commitment.

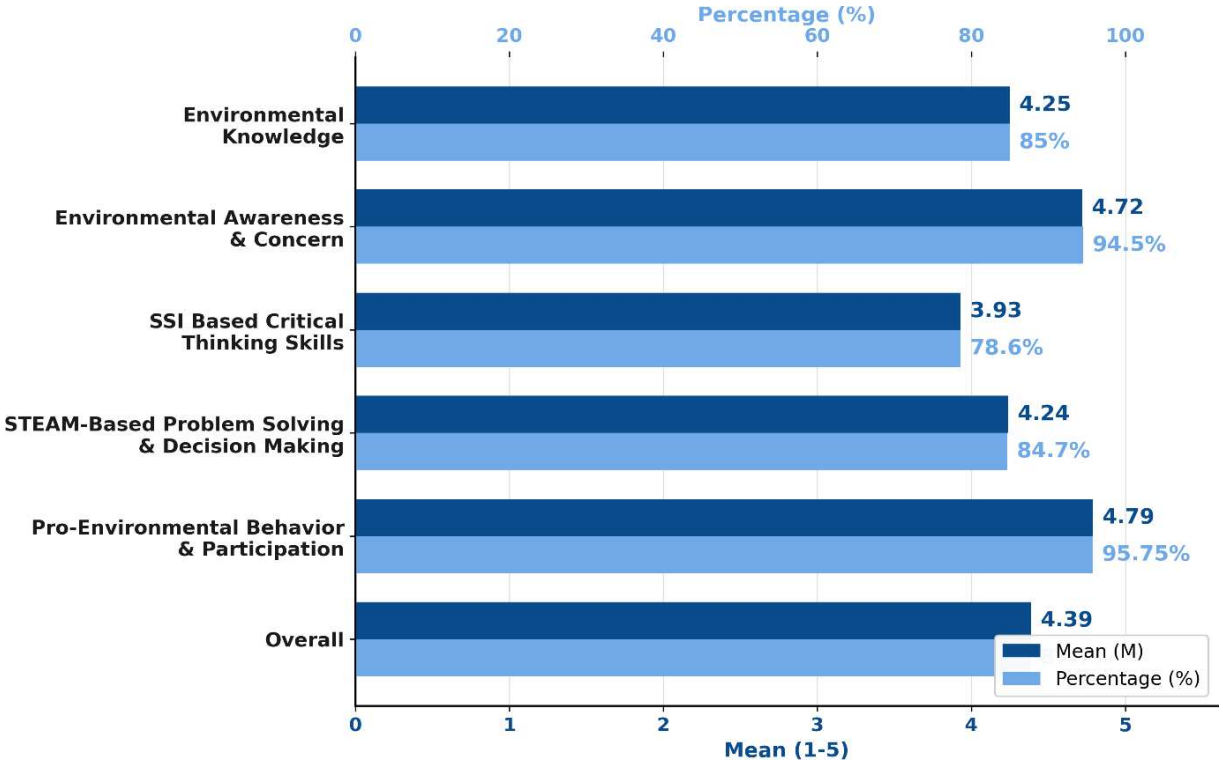


Figure 4. Environmental literacy profile of pre-Service biology teacher students by dimension

As shown in Figure 4, four of the five dimensions were classified within the very high category, while the SSI-based critical thinking skills dimension attained a high category score (M = 3.93; 78.6%). The pro-environmental behavior and participation dimension obtained the highest score (M = 4.79; 95.75%), followed by environmental awareness and concern (M = 4.72; 94.5%), environmental knowledge (M = 4.25; 85.0%), STEAM based problem solving and decision-making skills (M = 4.24; 84.7%), and SSI-based critical thinking skills (M = 3.93; 78.6%). The finding that SSI-based critical thinking fell below the very high threshold while all other dimensions reached it is theoretically significant. (Kellberg et al., 2023) have demonstrated that identity oriented SSI approaches produce stronger affective and behavioral outcomes than cognitive-analytical ones, which may help explain the divergence between behavioral

intention and critical reasoning observed here. (Türk & Çam, 2025) specifically emphasize that argumentation-based scaffolding is a prerequisite for elevating the critical thinking dimension, and that such competency does not emerge from SSI exposure alone. These considerations point to a clear pedagogical priority: future implementations of SSI-STEAM learning should incorporate more structured argumentation scaffolding to bridge the gap between the high and very high categories in this dimension.

3.2 Environmental Knowledge

The environmental knowledge dimension was rated in the very high category (M = 4.25; SD = 0.81; 85.0%). Among the eight items, the highest mean score was recorded for the environmental damage and lifestyle relationship item (M = 4.72), followed by the ecosystem balance item (M = 4.68) and the biodiversity-conservation connection and conservation actions items (both M = 4.50). These results indicate that students had developed strong understanding of ecological interdependencies and the human dimensions of environmental degradation. Student responses across all eight items are presented in Table 2.

Table 2. Student responses on the environmental knowledge dimension

No	Statement	SA	A	N	D	SD	M	SD
1	I understand that ecosystem balance is influenced by the relationship between biotic and abiotic components.	30	7	3	0	0	4.68	0.61
2	I can explain the impacts of water, soil, and air pollution on human health and other living organisms.	20	8	10	2	0	4.15	0.98
3	I understand that climate change is related to increased greenhouse gas emissions from human activities.	10	10	15	5	0	3.63	1.00
4	I know examples of conservation actions that can be applied in campus and community environments.	20	20	0	0	0	4.50	0.51
5	I can connect the concept of biodiversity with environmental conservation efforts.	24	12	4	0	0	4.50	0.68
6	I understand that waste management must consider the principles of reduce, reuse, and recycle.	20	5	5	10	0	3.88	1.28
7	In my view, environmental damage has a direct relationship with human daily lifestyles.	29	11	0	0	0	4.72	0.45
8	I find it difficult to distinguish between scientific facts and opinions when reading information about environmental issues. (-)	0	3	6	11	10	3.92	0.98

The item level data in Table 2 reveal an important pattern of variance within the dimension. While items relating to ecosystem balance, biodiversity, and the relationship between environmental damage and lifestyles attracted predominantly strongly agree responses, items concerning climate change and greenhouse gas emissions (M = 3.63) and the 3R waste management principles (M = 3.88) received more distributed responses, indicating partial rather than secure conceptual understanding on these topics. Notably, the item on distinguishing scientific facts from opinions (M = 3.92) also registered a more moderate score (Tal & Ginosar, 2024), suggesting that epistemological differentiation a foundational competency for SSI-based reasoning remains an area requiring more deliberate instructional attention (Sorensen et al., 2016). (Forbes et al., 2018) documented a comparable pattern in their interdisciplinary water literacy course, where students showed stronger gains in relational ecological knowledge than in the capacity for critical epistemic evaluation. (Sjöström et al., 2017) argue that the Bildung tradition in science education demands precisely this kind of epistemological self-awareness, and that its underdevelopment represents a meaningful limitation in otherwise strong science literacy profiles.

Interview data corroborate and extend the quantitative findings. Students articulated context embedded understandings of pollution that integrated biological, health-related, and ecological reasoning:

"Water pollution can cause health problems such as diarrhea, skin irritation, or poisoning if contaminated water is used in daily life. Soil pollution can also interfere with soil fertility, plant growth, and the life of soil organisms. Therefore, biology education students need to understand its impacts in order to explain the relationship between pollution, health, and ecosystem balance." (S1)"

"Soil pollution can affect human, plant, and animal life because soil containing chemical waste, excessive pesticides, plastics, or heavy metals can disrupt plant growth. Plants growing in contaminated soil can also absorb harmful substances, which ultimately affects human and animal health when consumed. In addition, soil animals such as earthworms and microorganisms can also be disturbed, so that the decomposition of organic matter becomes suboptimal." (S2)"

These narratives illustrate that students had moved beyond surface-level recall to a relational understanding that connects pollution to cascading effects across ecological and social systems. (Kinslow et al., 2019) documented a comparable pattern in their field-based ecology course, where SSI engagement produced environmental knowledge that was both scientifically grounded and socially contextualized. The strong performance on most items in this dimension thus provides the necessary conceptual foundation for all subsequent dimensions of environmental literacy development, while the more moderate scores on climate change and 3R items point to topics requiring greater instructional depth in future course iterations.

3.3 Environmental Awareness and Concern

The environmental awareness and concern dimension attained the second-highest score among all five dimensions (M = 4.72; SD = 0.51; 94.5%), placing it firmly within the very high category. Student responses across the eight items in Table 4 reveal a strong and consistent affective orientation toward environmental responsibility, personal accountability, and the social and moral dimensions of environmental care.

Table 3. Student responses on the environmental awareness and concern dimension

No	Statement	SA	A	N	D	SD	M	SD
9	I feel I have personal responsibility for maintaining the environment.	32	7	1	0	0	4.78	0.48
10	I feel concerned when I see littering behavior in the campus environment.	30	8	2	0	0	4.70	0.56
11	I believe that biology education students need to be role models in environmentally responsible behavior.	33	7	0	0	0	4.83	0.38
12	I am willing to change personal habits if those habits have a negative impact on the environment.	33	6	1	0	0	4.80	0.46
13	In my view, environmental issues need to be a primary concern in biology education.	27	12	1	0	0	4.65	0.53
14	I feel that local environmental issues such as waste, flooding, and pollution need to be discussed in lectures.	26	10	3	0	0	4.59	0.64
15	I consider environmental conservation to be part of social and moral responsibility.	31	8	1	0	0	4.75	0.49
16	I am less interested in joining discussions about environmental problems because they do not affect my life. (-)	0	0	1	10	29	4.70	0.52

The item asserting that biology education students need to serve as role models in environmentally responsible behavior received the highest score within this dimension (M = 4.83), closely followed by willingness to change personal habits with negative environmental impact (M = 4.80) and consideration of environmental conservation as a social and moral responsibility (M = 4.75). These high scores across all eight items, with no item falling below M = 4.59, suggest that affective engagement with environmental issues was both strong and broadly distributed across the student group. (Kellberg et al., 2023) specifically identify identity-oriented SSI instruction as a mechanism for producing strong, durable affective engagement with environmental issues, since learners who connect environmental responsibility to their professional self-concept tend to demonstrate more sustained motivational orientations than those engaging with environmental issues purely as academic content. The item on the relevance of local environmental issues to coursework (M = 4.59) confirmed that the course design anchoring learning in water and soil pollution problems directly visible in students' daily environments was pedagogically effective.

"Local environmental issues need to be discussed because they are very close to students' lives. Waste, flooding, water pollution, and soil pollution are often found in the surrounding environment. When those issues are brought into lectures, the material

does not feel distant from real life and students find it easier to understand the relationship between biological concepts and environmental problems." (S3)"
"The local environmental issues closest to my life are waste and water pollution. Waste that is not properly managed can block drainage channels and cause flooding. In addition, household waste that is disposed of haphazardly can contaminate water and disturb community health. In my view, these issues should be discussed through case-based discussions, environmental observations, simple practicum activities, or SSI-STEAM projects such as creating campaigns to reduce waste, designing simple filtration devices, or producing educational media about water and soil pollution." (S4)"

These interview responses demonstrate that students have developed contextually embedded environmental concern that recognizes local pollution issues as simultaneously personal, professional, and scientifically significant. (Widhiastuti et al., 2019) have specifically documented that environmental education cultivating a sense of personal responsibility mediates the development of pro-environmental behavioral intentions among university students in Indonesia, a mechanism that the SSI-STEAM learning design in this study appears to have successfully activated.

3.4 SSI Based Critical Thinking Skills

The SSI based critical thinking skills dimension obtained the lowest mean score among all five dimensions (M = 3.93; SD = 0.90; 78.6%), falling within the high rather than very high category. This represents the most notable differentiation in the study's overall environmental literacy profile, and warrants careful analysis. Table 4 presents the distribution of responses across the eight items comprising this dimension.

Table 4. Student responses on the SSI-based critical thinking skills dimension

No	Statement	SA	A	N	D	SD	M	SD
17	I can analyze environmental issues by considering scientific evidence and their impact on society.	5	10	20	5	0	3.38	0.87
18	I am able to compare various viewpoints on environmental issues that generate debate.	15	13	12	0	0	4.08	0.83
19	I can provide arguments based on data when discussing environmental issues.	10	9	10	11	0	3.45	1.15
20	I consider ethical aspects when evaluating solutions to environmental problems.	20	10	2	8	0	4.05	1.18
21	I usually verify the truth of environmental information from social media before accepting it.	29	8	2	1	0	4.62	0.70
22	I can identify the parties affected by a socio-scientific environmental issue.	15	15	10	0	0	4.13	0.79
23	I am able to draw conclusions based on discussion results, data, and social considerations on environmental issues.	13	14	13	0	0	4.00	0.82

No	Statement	SA	A	N	D	SD	M	SD
24	I find it difficult to explain the scientific reasons behind decisions I make regarding environmental issues. (-)	0	0	20	11	9	3.73	0.82

The item level data in Table 4 reveal substantial variation in performance across the dimension's constituent competencies. The highest score was recorded for the digital information verification item (M = 4.62), while the ability to analyze environmental issues by considering scientific evidence and their societal impact obtained the lowest mean (M = 3.38), followed closely by the ability to provide data-based arguments in environmental discussions (M = 3.45). This pattern is theoretically consistent with (Romine et al., 2020) characterization of SSI-based reasoning as a developmental progression of competencies, in which verification of sources represents a more accessible entry point than the more demanding tasks of evidence analysis and data-based argumentation. (Cha et al., 2022) similarly found that undergraduate students engaging with socioscientific chemical issues were more readily able to identify ethical dimensions of controversies than to construct and defend evidence based argumentative positions. (Tangio et al., 2026) underscore that this developmental gap is particularly common among pre-service science teachers and requires deliberate, structured instructional attention to close. (Türk & Çam, 2025) further demonstrate that argumentation-based instruction is a necessary not merely supplementary condition for building this capacity, confirming that the design of future SSI-STEAM courses must prioritize explicit argumentation scaffolding.

Interview data illuminate how students have begun developing environmental digital literacy, even as their broader analytical argumentation skills remain in development:

"I usually verify the truth of environmental information through trusted sources, such as scientific journals, official government websites, environmental institutions, news from credible media, or expert opinions in the field of the environment. If the content consists only of personal opinions, has an exaggerated headline, or does not cite a clear source, I will be more cautious." (S4)"

"When I find environmental information that turns out to be incorrect, I do not immediately share it with others. I will look for more trustworthy comparative sources, then explain to those around me that the information needs to be checked again so as not to be misleading." (S5)"

These responses indicate that students are developing meaningful practices of source triangulation and credibility assessment (Oliver & Adkins, 2020), competencies integral to SSI based reasoning in digitally mediated environments (Tal & Ginosar, 2024). However, the markedly lower scores on items requiring students to analyze issues using scientific evidence (M = 3.38) and construct data grounded arguments (M = 3.45) signal that information verification, while necessary, is not sufficient for full SSI based critical thinking. These findings collectively indicate that the SSI-STEAM course has successfully initiated the development of digital information literacy while identifying formal scientific argumentation as the dimension requiring the most targeted instructional investment in future iterations.

3.5 STEAM Based Problem Solving and Decision-Making Skills

The STEAM based problem solving and decision-making skills dimension was rated in the very high category (M = 4.24; SD = 0.80; 84.7%). The distribution of student responses across the eight items in Table 6 indicates that students perceived themselves as capable of integrating science, technology, engineering, arts, and mathematics in the design and evaluation of authentic environmental solutions, although the scores reveal meaningful variation across specific competencies.

Table 5. Student responses on the STEAM based problem solving and decision-making skills dimension

No	Statement	SA	A	N	D	SD	M	SD
25	I can propose environmental solutions by integrating science and technology concepts.	20	8	12	0	0	4.20	0.88
26	I am able to use simple data, such as waste quantities or energy use, to assess environmental problems.	19	8	13	0	0	4.15	0.89
27	I can design product ideas, posters, media, or creative campaigns to increase environmental awareness.	20	18	2	0	0	4.45	0.60
28	I consider cost feasibility, materials, and benefits when designing environmental solutions.	18	10	10	2	0	4.10	0.96
29	I feel that arts/design approaches have no role in conveying environmental conservation messages. (-)	0	0	13	7	20	4.18	0.90
30	I can collaborate in a group to design solutions to SSI-based environmental problems.	11	17	12	0	0	3.98	0.77
31	I can choose the most appropriate environmental solution based on evidence, community needs, and its impact.	21	10	9	0	0	4.30	0.82
32	I am able to use digital technology to search for information or create solutions related to the environment.	22	17	1	0	0	4.53	0.55

The highest scoring items within this dimension were the ability to use digital technology to search for information or create environment related solutions (M = 4.53) and the ability to design product ideas, posters, media, or creative campaigns to increase environmental awareness (M = 4.45). These results reflect the productive integration of the technology and arts components of STEAM within the course design, consistent with (Mang et al., 2021) finding that SSI based STEAM programs are particularly effective in developing competencies that require both analytical reasoning and creative design. The item on choosing the most appropriate environmental solution based on evidence, community needs, and anticipated impacts also scored relatively

high (M = 4.30), reflecting students' developing capacity for evidence informed, stakeholder sensitive decision making. (Syamsudin et al., 2026) found comparable results in their problem and design process-based STEAM learning model, where the connection between socioscientific problem contexts and design processes produced meaningful improvements in students' problem-solving skills.

The relatively lower scores on the data interpretation item (M = 4.15), the cost feasibility and benefits item (M = 4.10), and the group collaboration item (M = 3.98) indicate that mathematical reasoning, practical design constraint analysis, and collaborative problem management represent areas within the STEAM dimension where students' competence is developing but has not yet reached the same level as their digital and creative design competencies. (Baran et al., 2021) specifically documented that 21st century collaborative skills require sustained, structured practice within project-based contexts, suggesting that a single course-based intervention may be insufficient to fully develop these competencies.

"In group work, each member can share ideas, gather data, design solutions, create campaign media, and compile reports. When discussing water or soil pollution, group work helps us see the problem from many perspectives so that the designed solution becomes more comprehensive." (S4)"

"Cost, materials, and benefits need to be considered so that environmental solutions are not only sound in theory but can also be applied in practice. For example, a simple water filtration device can be made from used bottles, sand, gravel, charcoal, and cotton — making it affordable, easy to build, and useful as an educational medium for learning about water pollution." (S5)"

These excerpts confirm that students have begun internalizing the principle of contextual feasibility as a criterion for evaluating environmental solutions, a disposition particularly consequential for prospective biology teachers who must design activities within the resource constraints of Indonesian secondary school settings. (Hidaayatullaah et al., 2026) specifically identify practical feasibility assessment as a key competency produced by well-designed SSI-STEAM programs, and the present data confirm that this competency was cultivated within the course.

3.6 Pro Environmental Behavior and Participation

The pro environmental behavior and participation dimension obtained the highest overall score among all five dimensions (M = 4.79; SD = 0.44; 95.75%), placing it firmly within the very high category. The item-level distribution across the eight statements in Table 6 reveals a consistently high level of reported pro-environmental conduct and participatory intention, with no item scoring below M = 4.67.

Table 6. Student responses on the pro environmental behavior and participation dimension

No	Statement	SA	A	N	D	SD	M	SD
33	I habitually dispose of waste in its proper place and sort waste when facilities are available.	34	6	0	0	0	4.85	0.36
34	I try to reduce the use of single-use plastics in daily activities.	32	8	0	0	0	4.80	0.41
35	I conserve electricity and water at home, on campus, or in public places.	32	8	0	0	0	4.80	0.41

No	Statement	SA	A	N	D	SD	M	SD
36	I am willing to be involved in campus or community activities related to environmental conservation.	33	7	0	0	0	4.83	0.38
37	I rarely reprimand or remind friends when I see behavior that harms the environment. (-)	0	0	3	7	30	4.67	0.62
38	I use biological knowledge to explain the importance of maintaining the environment to others.	33	6	1	0	0	4.80	0.46
39	I am motivated to take real action after participating in SSI-STEAM-based learning.	30	10	0	0	0	4.75	0.44
40	I feel the need to participate in solving environmental problems.	33	6	1	0	0	4.80	0.46

The highest scoring item was habitual waste disposal and sorting when facilities are available (M = 4.85), followed closely by willingness to participate in campus or community environmental conservation activities (M = 4.83). Multiple items scored at M = 4.80, including reduction of single-use plastics in daily activities, conservation of electricity and water, and use of biological knowledge to explain environmental importance to others. The item on motivation to take real action after SSI-STEAM learning (M = 4.75) is particularly noteworthy as direct evidence that the learning experience translated into behavioral intention a critical outcome in environmental education, where the gap between knowledge and action is a persistent challenge (Kellberg et al., 2023). (Widhiastuti et al., 2019) have documented that responsibility based environmental education in Indonesian university contexts effectively mediates the development of pro environmental behavioral intentions, a finding corroborated by the present results.

"I always try to dispose of waste in its proper place because it is a simple habit for maintaining environmental cleanliness and making the learning environment more comfortable. When facilities are available, I will sort organic waste, inorganic waste, and recyclable waste so that waste is more easily managed." (S6)"

"Campus needs to provide separated waste bins that are easy to find, clearly color-coded and labeled, and equipped with examples of waste types so that students are not confused when disposing of waste." (S7)"

The interview data introduce an important structural qualification: waste sorting behavior was explicitly conditioned on the availability of appropriately labeled and accessible facilities on campus. (Atutxa et al., 2025) have documented a comparable pattern in their study of pro environmental action on air quality, noting that behavioral participation depends critically on accessible engagement tools and supportive infrastructure. (Tan et al., 2023) similarly found that structural and institutional factors are significant predictors of sustainability behaviors in developing country contexts. These findings collectively indicate that the very high behavioral scores represent individual readiness that requires institutional investment to sustain, and that SSI-

STEAM environmental education initiatives must be accompanied by corresponding institutional commitments to campus sustainability infrastructure.

4. DISCUSSION

The overall environmental literacy profile of pre-service biology teacher students (M = 4.39; 87.7%; very high) produced by SSI-STEAM integrated learning is a substantively meaningful finding, particularly given that the five dimensions reflect qualitatively distinct aspects of environmental literacy knowledge, affect, deliberative reasoning, creative problem solving, and behavioral agency that are rarely developed to this level simultaneously within a single course-based intervention (Sorensen et al., 2016). Environmental literacy frameworks consistently emphasize that genuine literacy cannot be reduced to any single dimension (Kinslow et al., 2019), and the broad distribution of high scores across all five dimensions in this study confirms that SSI-STEAM integration successfully created a coherent, mutually reinforcing developmental context. This finding is consistent with (Rahmawati et al., 2025) evidence that STEAM project-based learning combined with design thinking produces comprehensive environmental literacy gains, and extends that evidence to a specifically SSI grounded pedagogical context focused on locally relevant pollution issues. This indicates that contextual and project-oriented learning experiences can strengthen students' environmental literacy by connecting scientific concepts with real-life sustainability prantices (Thahir et al., 2026). The high level of environmental literacy observed in this study is particularly important because effective plastic-pollution mitigation requires not only regulatory and rechnological interventions but also sustained public awareness, stakeholder engagement (Alemayehu et al., 2026).

The most theoretically significant finding in this study is the categorical divergence between the SSI based critical thinking dimension (M = 3.93; 78.6%; high) and the remaining four dimensions, all of which reached the very high category. This divergence directly reflects the theoretical structure of SSI competence as described by (Romine et al., 2020) who characterize SSI based reasoning as a developmental progression in which source verification and ethical consideration represent more accessible early competencies, while systematic evidence analysis and data grounded argumentation represent advanced capacities that require extended, structured practice to develop. The item level data confirm this interpretation: students scored highest on digital information verification (M = 4.62) and lowest on analyzing environmental issues using scientific evidence (M = 3.38) and constructing data-based arguments (M = 3.45). (Türk & Çam, 2025) have empirically demonstrated that this gap cannot be closed without deliberate argumentation instruction that makes the epistemic norms of evidence evaluation and claim warrant backing reasoning explicit; (Tangio et al., 2026) similarly document that pre-service science teachers are particularly vulnerable to this developmental gap given the competing demands of their professional preparation. Future implementations of SSI-STEAM courses should therefore incorporate structured argumentation scaffolding as a central, not peripheral, element of the design.

The finding that SSI and STEAM function as genuinely complementary rather than competing frameworks is substantiated by the distribution of scores across the five dimensions. SSI contributed most visibly to students' affective engagement and their willingness to take environmental positions reflected in the very high awareness and concern scores as well as to their developing information evaluation practices. STEAM

contributed most visibly to students' creative and technological competencies, reflected in the very high scores on the digital technology and campaign design items within the problem-solving dimension, and to their understanding of practical feasibility constraints, reflected in their articulation of cost material benefit reasoning. The integration of both within a single learning experience appears to have produced a breadth of literacy development that neither framework would have generated independently, consistent with (Mang et al., 2021) SSI-STEAM program framework and evaluation rubric, which specifically anticipate these synergistic outcomes. (Hariyono et al., 2026) similarly identify the combination of SSI's deliberative orientation with STEAM's design orientation as the factor most likely to explain variance in environmental problem-solving outcomes.

The very high scores on the pro environmental behavior and participation dimension (M = 4.79) and environmental awareness and concern dimension (M = 4.72) merit interpretation in terms of the specific learning mechanisms activated by the SSI-STEAM design. Both dimensions reflect motivational and identity related aspects of environmental literacy that (Kellberg et al., 2023) specifically associate with identity oriented SSI instruction: when students perceive environmental responsibility as part of their professional identity as prospective biology teachers as evidenced by the highest scoring item in the awareness dimension (M = 4.83, biology students as role models) their affective engagement and behavioral intention tend to be stronger and more durable. The SSI-STEAM context reinforced this professional identity framing by situating students as designers of educational solutions to local pollution problems, rather than merely consumers of environmental information. This repositioning from learner to designer appears to have strengthened students' sense of agency and perceived behavioral control, which (Baran et al., 2021) identify as critical determinants of sustainable behavioral intention.

The finding related to environmental digital literacy students' emerging practices of verifying the credibility of environmental information before accepting or sharing it represents a meaningful contribution to twenty first century science education that partially offsets the relatively lower performance on formal argumentation items. Oliver and (Oliver & Adkins, 2020) have documented that scientific literacy and environmental awareness are strongly shaped by engagement with credible scientific sources, while (Tal & Ginosar, 2024) have demonstrated that SSI frameworks can be applied effectively to the critical analysis of media content. The students in this study independently described consulting scientific journals, official government websites, and credible media outlets, and articulated specific criteria for evaluating online environmental content. While this competency does not substitute for the formal analytical argumentation that scored lower in this study, it represents a practically important form of environmental citizenship competency that future courses should build upon through more structured connections to evidence analysis and scientific reasoning.

The environmental knowledge dimension (M = 4.25; 85.0%) demonstrated that students had developed relational understanding of pollution extending beyond declarative recall. However, the more moderate scores on climate change (M = 3.63) and 3R waste management (M = 3.88) items within this dimension suggest that topical depth was uneven, with conceptually accessible ecological relationships attracting stronger understanding than more abstract systemic and policy- oriented content.

(Rahmawati et al., 2024) documented that STEAM integrated dilemma stories fostered the depth of contextual understanding evident in this study's strongest items, while the less developed items point to the need for more explicit instruction on climate systems and waste management policy in future iterations. (Forbes et al., 2018) similarly found that interdisciplinary water literacy courses produced stronger gains in relational ecological understanding than in the systemic and policy dimensions of environmental literacy. Students engangement in sustainable waste management may be shaped by environment knowledge, socio-behavioural factors, including cultural norms, social influence, educational background and local characteristics (Uali et al., 2026).

The STEAM based problem solving dimension (M = 4.24; 84.7%), while classified in the very high category, showed internal variation that is instructive for future course design. Digital and creative design competencies scored markedly higher than mathematical data interpretation, cost benefit analysis, and collaborative problem solving. (Baran et al., 2021) both document that the mathematical reasoning and collaborative dimensions of STEAM require the most sustained, structured practice to develop within project-based contexts. Holistic learning ecosystem in which cognitive, affective, and social dimensions reinforce one another. In the present study, this holistic character was reflected in student environmental knowledge, awareness, SSI based critical thinking, and STEAM based problem solving (Golestaneh et al., 2026). Future SSI-STEAM course iterations should incorporate more explicit attention to data analysis tasks, collaborative design protocols, and feasibility assessment frameworks to strengthen these relatively underdeveloped STEAM competencies. Learning environment that accommodates diverse perspectives may foster creativity and facilitate the development of sustainability-oriented innovations (Shzu et al., 2026).

Taken together, these findings make several contributions to the existing literature. Theoretically, they provide nuanced empirical support for SSI-STEAM integration as a pedagogical model that produces differentiated not uniformly high literacy gains, with the pattern of differentiation (high SSI-critical thinking, very high for all others) reflecting the well documented hierarchical structure of SSI competence development (Romine et al., 2020). Practically, they identify specific, evidence grounded curricular priorities: deliberate argumentation instruction, strengthened climate and waste policy content, mathematical data reasoning tasks, and collaborative design scaffolding. Methodologically, they demonstrate the utility of a mixed methods explanatory sequential design for revealing the mechanisms underlying the quantitative profile. The study extends prior work by (Rahmawati et al., 2025) into pre-service biology teacher education in Indonesia, fills a documented gap in SSI-STEAM environmental literacy research, and generates a differentiated, actionable agenda for future course development. (Ayodeji et al., 2026) emphasized that STEAM education has become a major priority in contemporary educational reform because of it connection to scientific literacy, technological competence, innovation, employabilitu, and national development. This supports the relevance of SSI-STEAM integrated learning in strengthening pre-service biology teacher’s environmental literacy as part of broader scientific and future oriented competencies.

5. CONCLUSION

This study demonstrates that SSI-STEAM integrated learning in the Environmental Education course produced a very high overall environmental literacy profile (M = 4.39; 87.7%) among pre-service biology teachers at Universitas

Muhammadiyah Makassar. Environmental awareness and concern (M = 4.72; 94.5%) and pro-environmental behavior and participation (M = 4.79; 85.7%) achieved the highest scores, both in the very high category. Environmental knowledge (M = 4.25; 85.0%) and STEAM based problem solving and decision-making skills (M = 4.24; 84.7%) also reached the very high category. The SSI-based critical thinking skills dimension obtained the lowest score (M = 3.93; 78.6%), classified as high rather than very high a theoretically important distinction indicating that deliberative argumentation, evidence analysis, and data-based reasoning remain the most challenging competencies to develop within a single course-based SSI-STEAM intervention. Qualitative interview findings corroborated and enriched these quantitative results: students demonstrated relational pollution knowledge linking ecological processes to human health, strong professional identity grounded environmental concern, emerging digital information credibility assessment practices, experience grounded design reasoning incorporating practical feasibility considerations, and strong behavioral intentions contingent on institutional supporting infrastructure. These findings collectively demonstrate that SSI-STEAM integration creates a productive and broadly effective pedagogical context for developing multiple, mutually reinforcing dimensions of environmental literacy within a single course.

Several limitations warrant consideration. Reliance on self-report questionnaire data introduces potential social desirability bias, and the absence of a pretest posttest design with a comparison group limits causal attribution of the observed literacy profile to the SSI-STEAM intervention. The single-institution sample constrains generalizability. Future research should employ quasi experimental designs incorporating control groups, pretest posttest measurements, and direct behavioral observation, and should extend inquiry to broader populations, institutions, and environmental topics. Despite these limitations, this study makes three substantive contributions to the literature. First, it contributes to the limited empirical multidimensional environmental literacy profile of pre-service biology teachers within a deliberately integrated SSI-STEAM learning context in Indonesia. Second, it demonstrates that SSI based critical thinking represents the most challenging dimension for course-based development, generating a targeted, evidence grounded agenda for curricular strengthening centered on explicit argumentation instruction. Third, it affirms SSI-STEAM integration as a pedagogically productive framework for connecting scientific knowledge, social reasoning, and creative environmental action in biology teacher education a contribution with direct implications for Environmental Education course design across Indonesian higher education institutions.

DECLARATIONS

Ethical Approval

This study involved human participants. Ethical approval was granted by the Institutional Review Board (IRB) of the Institute for Research, Development, and Community Service (Lembaga Penelitian, Pengembangan dan Pengabdian kepada Masyarakat [LP3M]), Universitas Muhammadiyah Makassar. All procedures were conducted in accordance with applicable ethical standards and the principles of the Declaration of Helsinki (Approval No. 109A/LP3M/05/A.4-VIII/VIII/47/2025).

Consent to Participate

All participants provided informed consent to participate in this study.

Consent to Publish

Not applicable

Competing Interests

The authors declare no competing interests.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author Contributions

Conceptualization: All authors; Methodology: Rahmatia Thahir, Hartono Bancong and Nurlina; Formal analysis: Nurlina, Agustan and Rahmatia Thahir; Visualization: Rahmatia Thahir and Eny Syatriana; Writing - original draft preparation: Rahmatia Thahir and Hartono Bancong; Writing - review and editing: Hartono Bancong, Nurlina, Agustan, Eny Syatriana, and Rahmatia Thahir; Supervision: Hartono Bancong.

Availability of Data and Materials

The data supporting the findings of this study are available within the article. Additional materials are available from the corresponding author upon reasonable request.

Acknowledgements

The authors declare that there are no acknowledgements for this manuscript.

Clinical Trial Number

Not applicable

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