

An Ethnobiology-Based Instructional Model Integrating Indigenous Papuan Knowledge: The Mediating Role of Systems Thinking in Enhancing Environmental Literacy

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Received: March 9, 2026

Revised: May 10, 2026

Accepted: May 27, 2026

Abstract

This study examined the effectiveness of an ethnobiology-based instructional model integrating Indigenous Papuan knowledge in improving environmental literacy through systems thinking. The study responds to the limited use of culturally contextualized learning models that explain the cognitive mechanisms linking Indigenous knowledge integration and environmental literacy outcomes. A design-based research approach combined with a one-group pretest–posttest quasi-experimental design was conducted with 72 third-year Biology Education students at STKIP PGRI Papua, Indonesia. The Ethnobiology–Systems Thinking Instructional Model (ESTIM-Papua) was developed through iterative design, validation, implementation, and evaluation stages. Data were collected using a 25-item environmental literacy questionnaire, systems thinking performance tasks, classroom observations, and semi-structured interviews. Quantitative data were analyzed using paired-sample t-tests, Cohen’s *d*, Pearson correlation, and bootstrapped mediation analysis, while qualitative data were analyzed thematically. The results showed significant improvements in environmental literacy, from $M = 62.45$ to $M = 78.63$, $t = 14.27$, $p < .001$, $d = 1.68$, and systems thinking, from $M = 58.72$ to $M = 76.15$, $t = 15.11$, $p < .001$, $d = 1.78$. Systems thinking was positively associated with environmental literacy, $r = .72$, $p < .001$, and significantly mediated the relationship between model implementation and environmental literacy (indirect effect = .38, 95% CI [.27, .51]). Qualitative findings indicated increased engagement, deeper understanding of ecological interconnections, and improved systemic environmental problem analysis. These findings suggest that integrating Indigenous Papuan knowledge into ethnobiology-based instruction can strengthen environmental literacy by developing systems thinking. However, the single-group design and context-specific sample limit generalizability; future research should employ comparative designs across multiple institutions.

Keywords: Environmental literacy; Ethnobiology; Higher education; Indigenous knowledge; Systems thinking.

INTRODUCTION

Environmental challenges, including climate change, biodiversity loss, and ecosystem degradation, are no longer isolated phenomena but systemic crises that demand transformative responses from contemporary science education. In this context, environmental literacy has emerged as a central objective, encompassing not only the acquisition of ecological knowledge but also the development of values, dispositions, and action-oriented competencies necessary for sustainable decision-making (UNESCO, 2023; OECD, 2022). Recent studies emphasize that environmental literacy should be understood as a multidimensional construct integrating cognitive, affective, and behavioral domains to support sustainability transitions (Ardoin et al., 2023). However, accumulating evidence indicates that students, including pre-service biology teachers, often struggle to translate environmental knowledge

and synchronized. Use multiple citations for key statements to strengthen the academic arguments and support them with several relevant sources.

into meaningful pro-environmental actions, revealing a persistent disconnect between cognitive understanding and behavioral engagement (Stevenson et al., 2022). This issue reflects a broader global challenge in sustainability education, where knowledge acquisition alone remains insufficient to foster transformative behavioral change.

This limitation is largely attributed to the persistence of decontextualized instructional practices that separate scientific knowledge from learners' socio-cultural and ecological realities. Contemporary studies highlight that conventional science instruction still prioritizes abstract content delivery over engagement with authentic environmental problems, resulting in fragmented knowledge structures and limited capacity to conceptualize environmental issues as interconnected systems (Sari et al., 2024). Consequently, learners often lack the integrative cognitive competencies required to address sustainability challenges. Although recent research acknowledges the effectiveness of contextual and inquiry-based approaches, it still predominantly focuses on learning outcomes without adequately explaining the cognitive processes underlying these outcomes. Emerging scholarship calls for approaches that move beyond effectiveness toward explaining how instructional processes shape sustainability competencies (Demirci et al., 2024). However, existing studies remain limited in providing causal explanations of how instructional processes translate into sustainability competencies.

Recent scholarship has increasingly emphasized the integration of Indigenous Knowledge (IK) and local wisdom within culturally responsive and sustainability-oriented pedagogies. This integration has been shown to enhance engagement, deepen conceptual understanding, and promote higher-order thinking by situating learning within culturally meaningful contexts (McKinley & Stewart, 2022). Furthermore, recent studies highlight that Indigenous knowledge plays a critical role in linking local ecological understanding with global sustainability agendas (Akinsemolu, 2025). Despite these advances, existing research often treats Indigenous knowledge as an additive component rather than embedding it within systematically designed instructional frameworks. As a result, its potential as a core driver of cognitive development and transformative learning remains underexplored. Within biology education, ethnobiology has emerged as a promising interdisciplinary framework for bridging scientific knowledge with Indigenous ecological systems by emphasizing the relationships among humans, culture, and biological environments. Recent empirical evidence demonstrates that contextual and ethnoscience-based learning approaches significantly enhance environmental literacy and higher-order thinking skills (Sari et al., 2024). However, despite these contributions, current research has largely failed to explicate the causal pathways through which such approaches influence environmental literacy outcomes. In particular, limited attention has been given to understanding how higher-order cognitive processes—specifically systems thinking—mediate the relationship between culturally contextualized instruction and environmental learning outcomes.

Systems thinking has been widely recognized as a critical competency for understanding complex environmental systems, as it enables learners to analyze interconnections, feedback loops, and dynamic relationships across ecological and social dimensions (Wals & Benavot, 2022). Recent studies further emphasize its central role in sustainability education for addressing complex global challenges (Demirci et al., 2024). Despite its strong theoretical relevance, its mediating role within ethnobiology-based instructional contexts remains underexplored. This represents a significant theoretical gap, particularly in higher education, where future educators are expected to develop advanced competencies for sustainability-oriented teaching capable of addressing complex environmental challenges through contextual and transformative learning approaches (Ardoin et al., 2023). This gap is particularly salient in Papua, Indonesia, where Indigenous communities possess rich ecological knowledge systems developed through long-term interactions with their natural environment (McKinley & Stewart, 2022). These knowledge systems reflect sophisticated understandings of

biodiversity conservation, ecosystem balance, and sustainable resource management, which are increasingly recognized as valuable foundations for culturally responsive sustainability education (UNESCO, 2023). sophisticated understandings of biodiversity, ecosystem balance, and sustainable resource management. However, such knowledge remains underutilized in formal education, resulting in a disconnect between local ecological realities and classroom learning. This condition highlights the need for instructional models that not only integrate Indigenous knowledge but also systematically transform it into structured learning processes that support higher-order cognitive development.

In response to these challenges, this study proposes the Ethnobiology–Systems Thinking Instructional Model (ESTIM-Papua), a structured instructional framework that systematically integrates Indigenous Papuan knowledge into ethnobiology-based learning processes. This study advances the field in three key ways. First, it develops a theoretically grounded instructional model that positions Indigenous knowledge as a central component within a structured pedagogical design. Second, it empirically validates systems thinking as a mediator linking instructional processes and environmental literacy outcomes, thereby providing a clear explanation of how learning occurs. Third, it contributes empirical evidence from higher education teacher education contexts, which remain underrepresented in sustainability education research. Therefore, this study seeks to advance sustainability education by (1) developing and validating the ESTIM-Papua instructional model, (2) examining its effectiveness in enhancing environmental literacy, and (3) analyzing the mediating role of systems thinking within the proposed framework. By positioning systems thinking as a cognitive mediator, this study provides a theoretically robust explanation of how culturally contextualized instructional processes translate into meaningful environmental literacy outcomes. This perspective offers a significant contribution to bridging Indigenous knowledge systems and contemporary sustainability education in both local and global contexts.

METHODS

This study employed a design-based research (DBR) approach integrated with a quasi-experimental one-group pretest–posttest design to develop, implement, and evaluate the Ethnobiology–Systems Thinking Instructional Model (ESTIM-Papua). The DBR approach enabled iterative refinement of the instructional model within an authentic educational context while generating theoretical insights into learning processes. The study was conducted through two iterative cycles: (1) design and development, including needs analysis, conceptual framework construction, instrument development, expert validation, and initial model design; and (2) implementation and evaluation, involving classroom application, quantitative and qualitative data collection, thematic analysis, and model refinement. The first cycle produced a prototype informed by theoretical synthesis and contextual analysis, followed by pilot testing and formative evaluation involving two environmental education experts and one instructional design expert. The research instruments consisted of 25 environmental literacy questionnaire items, 10 systems thinking performance tasks, and classroom observation sheets. Environmental literacy indicators included ecological knowledge, environmental attitudes, cognitive awareness, and pro-environmental behavior, while systems thinking indicators included causal relationship analysis, feedback loop identification, system interconnection, and problem-solving ability. Feedback from the validation phase informed revisions to instructional sequencing, integration of Indigenous knowledge, and systems thinking activities. Qualitative data were analyzed using thematic coding procedures consisting of data reduction, initial coding, category development, theme identification, and interpretation. The second cycle involved full implementation of the refined model and summative evaluation of its effectiveness. An example of the systems thinking assessment rubric included students' ability to identify relationships among environmental components, explain causal interactions, and propose sustainable solutions based on systemic analysis. Figure 1 presents the conceptual framework of the ESTIM-Papua model, illustrating how Indigenous Papuan knowledge is systematically integrated into ethnobiology-based

instructional processes across four phases and how these processes foster systems thinking as a mediating mechanism in enhancing environmental literacy. This framework guided the operationalization of variables and the analytical procedures employed in this study.

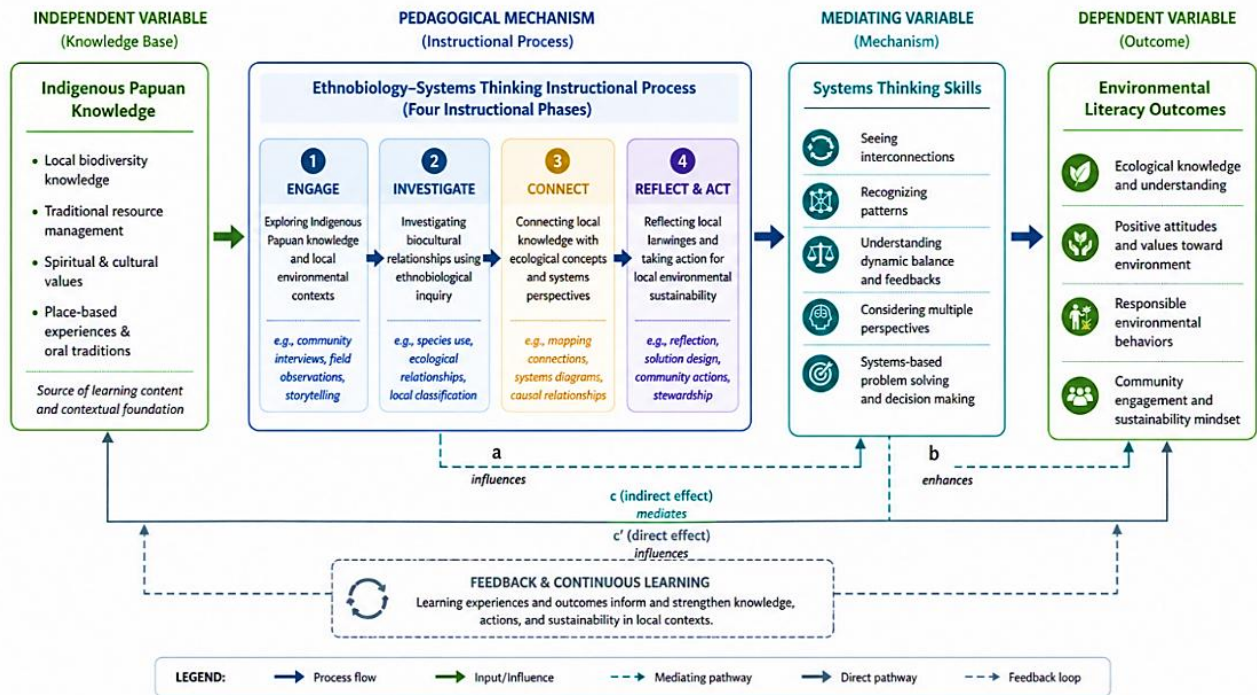


Figure 1. Conceptual Model

The participants consisted of 72 undergraduate students enrolled in the Biology Education program at STKIP PGRI Papua, Indonesia. Participants were selected using purposive sampling, targeting third-year (semester 5) pre-service biology teachers with prior exposure to ecological concepts. Ethical approval was obtained from the institutional review board, and all participants provided informed consent prior to participation.

The ESTIM-Papua model is grounded in three interconnected theoretical foundations: ethnobiology, Indigenous knowledge integration, and systems thinking. The instructional process consists of four sequential phases: contextual ethnobiology exploration (engage), biocultural investigation (investigate), systems integration (connect), and reflection and sustainability action (reflect and act). These phases are designed to develop systems thinking competencies, including identifying system components, analyzing interrelationships, and understanding feedback mechanisms. Consistent with the conceptual framework (Figure 1), this study assumes a mediated causal pathway in which the implementation of the ESTIM-Papua instructional model (X) enhances systems thinking (M), which subsequently improves environmental literacy (Y). This operationalization aligns with the hypothesized mediation structure, positioning systems thinking as the key cognitive mechanism linking instructional processes to learning outcomes.

Data were collected using a mixed-methods approach, combining quantitative and qualitative instruments. Environmental literacy was measured using a structured questionnaire encompassing cognitive, affective, and behavioral dimensions, using a 5-point Likert scale. The instrument demonstrated high internal consistency (Cronbach's $\alpha = 0.89$). Systems thinking skills were assessed through performance-based tasks requiring students to construct system maps, identify causal relationships, and analyze feedback loops. Scoring was conducted using an analytic rubric, and inter-rater reliability was confirmed (Cohen's $\kappa = 0.84$). Qualitative data were obtained through classroom observations and semi-structured interviews to capture student engagement, conceptual understanding, and the integration of Indigenous knowledge during the learning process.

The intervention was conducted over one academic semester. A pretest was administered to assess baseline levels of environmental literacy and systems thinking, followed by the implementation of the ESTIM-Papua model through structured learning sessions incorporating ethnobiological content and systems-based analytical activities. A posttest was subsequently administered to evaluate learning outcomes. Quantitative data were analyzed using paired sample t-tests to examine pre–post differences and effect size calculations (Cohen’s *d*) to determine the magnitude of change. Pearson correlation analysis was conducted to examine the relationship between systems thinking and environmental literacy. To examine the mediating role of systems thinking, mediation analysis was conducted using PROCESS macro (Model 4) with 5,000 bootstrap samples. In this model, the implementation of the ESTIM-Papua instructional model (operationalized as a pre–post intervention condition) was treated as the independent variable (X), systems thinking as the mediator (M), and environmental literacy as the dependent variable (Y). The indirect effect was considered statistically significant when the 95% confidence interval (CI) did not include zero.

Qualitative data were analyzed using thematic analysis, involving coding, categorization, and identification of patterns related to student engagement, conceptual understanding, and systems thinking development. The integration of quantitative and qualitative findings enabled a comprehensive interpretation of how the instructional model enhances environmental literacy through systems thinking.

To ensure methodological rigor, several strategies were employed, including expert validation of instruments, internal consistency testing, inter-rater reliability assessment, and triangulation of multiple data sources. The iterative nature of the DBR approach strengthened ecological validity by aligning instructional design with authentic classroom contexts. It should be noted that the use of a single-group pretest–posttest design without a control group may limit causal generalization; however, the combination of large effect sizes and mediation analysis provides robust evidence supporting the effectiveness and underlying instructional processes of the ESTIM-Papua model.

RESULT AND DISCUSSION

Changes in Environmental Literacy and Systems Thinking

The effectiveness of the ESTIM-Papua model was examined by comparing pre-test and post-test scores of environmental literacy and systems thinking skills. Preliminary analyses confirmed that the assumptions of normality and homogeneity were met. The results of the paired sample t-test are presented in Table 1.

Table 1. Pre-test and Post-test Comparison of Environmental Literacy and Systems Thinking

Variable	Pre-test Mean (SD)	Post-test Mean (SD)	t-value	p-value	Cohen’s <i>d</i>
Environmental Literacy	62.45 (8.12)	78.63 (7.45)	14.27	< .001	1.68
Systems Thinking	58.72 (7.95)	76.15 (8.03)	15.11	< .001	1.78

From a theoretical perspective, these results suggest that integrating Indigenous knowledge within a systems-oriented instructional framework can effectively enhance both cognitive understanding and higher-order thinking processes related to environmental issues. These findings are fully aligned with the proposed conceptual framework of ESTIM-Papua, which emphasizes the role of contextualized and systems-based learning in improving environmental competencies.

Relationship Between Systems Thinking and Environmental Literacy

Pearson correlation analysis was conducted to examine the relationship between systems thinking and environmental literacy.

Table 2. Correlation Analysis

Variables	1	2
1. Systems Thinking	—	

2. Environmental Literacy	0.72	—
p < .001		

The results reveal a strong positive correlation ($r = 0.72$, $p < .001$), indicating that higher levels of systems thinking are associated with higher levels of environmental literacy. This finding supports the theoretical assumption that systems thinking is a critical cognitive competency for understanding complex environmental systems and fostering environmentally responsible behavior.

Mediation Analysis

To examine the mediating role of systems thinking, mediation analysis was conducted using PROCESS macro Model 4 with 5,000 bootstrap samples. In this model, the independent variable (X) represents the implementation of the ESTIM-Papua instructional model (pre-post intervention condition), the mediator (M) is systems thinking, and the dependent variable (Y) is environmental literacy.

Table 3. Mediation Analysis Results

Path	Coefficient (β)	SE	t-value	p-value
X → M (Instruction → Systems Thinking)	0.65	0.07	9.28	< .001
M → Y (Systems Thinking → Environmental Literacy)	0.58	0.08	7.21	< .001
X → Y (Direct Effect)	0.29	0.09	3.22	.002

Table 4. Indirect Effect (Bootstrapping)

Effect	Value	Boot SE	95% CI Lower	95% CI Upper
Indirect Effect (X → M → Y)	0.38	0.06	0.27	0.51

The mediation analysis demonstrates that systems thinking significantly mediates the relationship between the ESTIM-Papua instructional model and environmental literacy. The indirect effect is statistically significant, as the 95% confidence interval does not include zero (CI = [0.27, 0.51]). This indicates that the instructional model enhances environmental literacy not only directly but also indirectly through the development of systems thinking skills. Furthermore, the direct effect remains significant ($\beta = 0.29$, $p = .002$), indicating a partial mediation model. This finding strengthens the causal interpretation of the proposed instructional mechanism, demonstrating that systems thinking functions as a key cognitive pathway through which ethnobiology-based instructional processes influence environmental literacy outcomes. These results provide strong empirical support for the conceptual framework underlying the ESTIM-Papua model.

Qualitative Findings

Thematic analysis revealed three major themes: (1) increased student engagement through culturally relevant learning, (2) deeper conceptual understanding of ecological interconnections, and (3) enhanced ability to analyze environmental problems using systems perspectives. Students demonstrated improved capacity to identify causal relationships, feedback loops, and dynamic interactions within environmental systems. As one participant noted, *"This learning approach helped me understand how human activities and environmental changes are interconnected, rather than seeing them as separate issues."* These qualitative insights further validate the quantitative findings and illustrate the learning processes underlying the observed improvements in systems thinking and environmental literacy.

Research Design Consideration

It should be noted that this study employed a single-group pre-test-post-test design without a control group. This approach is consistent with the principles of design-based research, which emphasize iterative development and validation of instructional models in authentic educational settings. Therefore, the findings are interpreted within the context of

instructional design effectiveness rather than controlled experimental comparison.

Discussion

The findings demonstrate that the Ethnobiology–Systems Thinking Instructional Model (ESTIM-Papua) was associated with substantial improvements in both environmental literacy and systems thinking among pre-service biology teachers. Environmental literacy increased from a pre-test mean of 62.45 to a post-test mean of 78.63, with a large effect size ($d = 1.68$), while systems thinking increased from 58.72 to 76.15, also with a large effect size ($d = 1.78$). Moreover, systems thinking showed a strong positive relationship with environmental literacy ($r = .72$, $p < .001$). The mediation analysis further indicated that systems thinking partially mediated the association between the ESTIM-Papua intervention and environmental literacy, as indicated by a significant indirect effect of .38, 95% CI [.27, .51]. These results suggest that the instructional model supported environmental literacy not only through direct exposure to ecological content and Indigenous Papuan knowledge, but also through students' improved capacity to recognize interrelationships, causal pathways, feedback mechanisms, and sustainability consequences.

The results align with global scholarship positioning systems thinking as a central competence for sustainability education. Systems thinking enables learners to move beyond fragmented knowledge by identifying interactions among ecological, social, cultural, and economic dimensions of environmental problems (Elsawah et al., 2022; Green et al., 2022; McBride et al., 2021). In higher education, sustainability-oriented instruction is more likely to be effective when students engage with authentic problems, interdisciplinary perspectives, and structured opportunities to analyse complex relationships rather than merely memorize environmental concepts (Mokski et al., 2023). The large improvement in systems thinking observed in this study is consistent with evidence that explicit systems-oriented activities, including causal mapping, model construction, simulation, and inquiry into real-world challenges, can strengthen students' ability to understand environmental complexity (Demssie et al., 2023; Karaarslan Semiz & Teksöz, 2024; Kurent & Avsec, 2024).

The present findings also correspond with studies showing that climate-change and sustainability instruction becomes more meaningful when systems thinking is intentionally embedded in the learning design. Karayol and Umdü Topsakal (2025) found that a global climate-change module strengthened students' systems-thinking performance by engaging them with interconnected environmental processes. Similarly, Lorenzo-Rial et al. (2025) reported that systems-thinking instruction supported students' capacity to analyse climate change beyond isolated causes and consequences. Peretz (2025) further argued that sustainability education requires educators to make system boundaries, interactions, delays, and feedback loops visible to learners. In the present study, the ethnobiology investigation, systems-integration activities, and reflection-and-action phase provided a comparable pedagogical structure. However, ESTIM-Papua differs from many international systems-thinking interventions because it is grounded in Indigenous Papuan ecological knowledge rather than relying primarily on abstract case studies, simulation models, or universalized climate scenarios.

The relevance of Indigenous knowledge is particularly important because environmental literacy cannot be reduced to scientific knowledge alone. Indigenous knowledge systems often embody long-term observations of biodiversity, local resource management, social responsibility, and human–nature relationships. International research has shown that integrating Indigenous perspectives into science education can strengthen learners' ecological understanding, cultural identity, and sustainability-oriented reasoning when such knowledge is positioned as an epistemic resource rather than as an illustrative cultural addition (Cajete, 2020; Demssie et al., 2020; Zidny et al., 2020). In a similar vein, Zidny and Eilks (2020) demonstrated that the integration of Indigenous and Western scientific perspectives can support contextualized science learning when teachers explicitly address the relationships and differences between knowledge systems. Systematic reviews also indicate that Indigenous and local knowledge may strengthen sustainability education when it is linked to authentic

community practices, place-based inquiry, and ethical environmental action (Druker-Ibáñez & Cáceres-Jensen, 2022; Latip et al., 2024).

Nevertheless, the present results should not be interpreted as implying that Indigenous knowledge automatically produces environmental literacy. The effectiveness of ESTIM-Papua appears to arise from the deliberate instructional transformation of Indigenous Papuan knowledge into structured learning experiences involving exploration, investigation, systems integration, reflection, and sustainability action. This interpretation is supported by Datta et al. (2025), who emphasized that land-based and Indigenous education becomes transformative when learners engage directly with local ecological practices and community realities. Thus, the contribution of Indigenous Papuan knowledge in this study was not merely cultural relevance; it functioned as an entry point for analysing ecological interdependence, environmental responsibility, and sustainable decision-making.

The findings are also consistent with Indonesian studies demonstrating the value of local wisdom, ethnoscience, and contextual environmental problems in science education. Suryawati et al. (2020) found that local environmental problem-based worksheets strengthened students' environmental literacy by connecting scientific content with nearby ecological issues. Likewise, Sumarni and Kadarwati (2020) reported that Ethno-STEM project-based learning improved critical and creative thinking by integrating local culture into scientific problem-solving. Parmin and Fibriana (2020) further demonstrated that reconstructing Indigenous knowledge within science learning can support prospective teachers' scientific literacy and conservation awareness. These findings collectively reinforce the argument that local knowledge is most educationally powerful when it is systematically linked to scientific concepts, inquiry activities, and reflective reasoning.

The ESTIM-Papua findings extend this Indonesian evidence by explaining a possible cognitive mechanism through which contextualized instruction affects environmental outcomes. Previous Indonesian research has commonly focused on the effectiveness of local-wisdom-based materials in improving critical thinking, scientific literacy, or environmental awareness. For example, Ramdani et al. (2021) found that local-wisdom-integrated science materials supported critical thinking among junior secondary students, while Sumarni et al. (2022) demonstrated that Indigenous medicinal knowledge could be meaningfully incorporated into STEM learning. However, these studies did not explicitly test whether systems thinking mediated the relationship between culturally contextualized instruction and environmental literacy. The current study therefore contributes more than evidence of effectiveness by demonstrating that systems thinking may act as a cognitive bridge between Indigenous ecological knowledge and students' environmental literacy.

Recent Indonesian studies further support this interpretation. Ekselsa et al. (2023) showed that project-based learning integrated with Education for Sustainable Development strengthened students' systems-thinking skills. Martawijaya et al. (2023) reported that Ethno-STEM project-based learning enhanced higher-order thinking and reduced misconceptions in local-context physics learning. Similarly, Wibowo et al. (2024) found that project-based science instruction contributed to critical thinking, collaboration, and environmental awareness. These studies are consistent with the ESTIM-Papua model because all of them position contextual problems as a vehicle for deeper cognitive engagement. However, ESTIM-Papua provides a more explicit instructional sequence linking Indigenous knowledge exploration with systems analysis and sustainability action.

The study also complements more recent research concerning culturally embedded sustainability education in Indonesia. Khairati et al. (2025) identified uneven systems-thinking competence among students in ESD-oriented learning, indicating that systems thinking requires intentional instructional support rather than incidental exposure to sustainability topics. Atmojo et al. (2025) found that ethnoscience-integrated STEM learning strengthened critical thinking and cultural literacy, while Rati et al. (2025) demonstrated that Tri Hita Karana-integrated science learning enhanced both computational thinking and environmental awareness.

Furthermore, Pada et al. (2025) reported that an SDG-oriented Ethno-STEM approach improved environmental awareness in elementary education. Taken together, these studies indicate that Indonesian cultural frameworks can strengthen environmental learning when they are connected with structured cognitive tasks. The present study adds evidence from Papua, a context that remains underrepresented in sustainability education research, and highlights the importance of recognizing Indigenous Papuan knowledge as an instructional foundation rather than peripheral content.

The novelty of this study lies in the development and empirical testing of ESTIM-Papua as a culturally grounded instructional model that integrates ethnobiology, Indigenous Papuan knowledge, systems thinking, and environmental literacy within a unified pedagogical framework. Unlike previous studies that primarily assess instructional effectiveness, this study tests the mediating role of systems thinking and therefore provides a more explanatory account of how contextualized learning contributes to environmental literacy. The partial mediation result is particularly important because it indicates that systems thinking is a major, although not exclusive, pathway through which the intervention supports environmental literacy. Other mechanisms may include cultural identification, emotional engagement with local ecological issues, environmental values, and collaborative learning experiences. The study also contributes to assessment development by operationalizing systems thinking through performance tasks involving system maps, causal relationships, feedback loops, and sustainable problem-solving. This approach is consistent with recent Indonesian efforts to develop systems-thinking-based environmental-literacy instruments for sustainability contexts (Taufik et al., 2026).

Theoretically, the findings support the proposition that environmental literacy is strengthened when learners develop the ability to interpret environmental problems as interconnected socio-ecological systems. ESTIM-Papua extends ethnobiology and Indigenous knowledge integration by positioning systems thinking as a cognitive mechanism rather than treating it as a separate learning outcome. This perspective suggests that culturally contextualized knowledge supports environmental literacy most effectively when students are guided to analyse causal relationships, feedback loops, interdependence, and long-term consequences. The partial mediation effect also refines the model by showing that systems thinking should not be considered the sole explanatory mechanism. Environmental literacy is likely shaped simultaneously by cognitive understanding, cultural identity, place attachment, environmental values, and opportunities for sustainability action.

Pedagogically, biology educators should incorporate local biodiversity, community practices, oral traditions, and Indigenous environmental knowledge into structured inquiry rather than presenting them as supplementary examples. Lecturers can use ecosystem mapping, causal-loop diagrams, field observations, community interviews, reflective journals, and local conservation projects to help students connect scientific concepts with lived ecological realities. At the policy level, teacher education institutions should provide curriculum space, ethical protocols, and partnerships that enable respectful engagement with Indigenous communities and community-held knowledge. Policies should protect Indigenous intellectual and cultural rights, ensure community participation in content selection, and avoid the extraction or decontextualization of Indigenous knowledge. This study did not measure students' online behaviour, identity formation, psychological well-being, or mental-health outcomes; therefore, policy implications should remain focused on sustainability education, cultural responsiveness, and ethical knowledge integration rather than extending to unmeasured social or psychological domains.

Several limitations should be considered when interpreting the findings. First, the study used a single-group pre-test–post-test design without a comparison group; therefore, the observed gains cannot be attributed exclusively to ESTIM-Papua because maturation, testing effects, prior coursework, or other contextual influences may have contributed to the results. Second, the sample consisted of 72 pre-service biology teachers from one institution in Papua, limiting the generalizability of the findings across disciplines, regions, educational levels, and

Indigenous communities. Third, the mediation model was estimated from a pre-post intervention condition, which provides preliminary evidence of an explanatory pathway but does not establish definitive causal mediation. Fourth, the study was conducted within one academic semester and did not assess the long-term retention of systems thinking, environmental literacy, or sustainability-oriented behaviour. Future research should employ multi-site quasi-experimental or randomized designs, longitudinal follow-up assessments, multilevel modelling, and comparisons across Indigenous and non-Indigenous learning contexts. Further studies should also examine the roles of cultural identity, environmental values, place attachment, collaboration, and pro-environmental action as additional mediators or moderators of environmental literacy outcomes.

CONCLUSION

This study concludes that the Ethnobiology-Systems Thinking Instructional Model (ESTIM-Papua) shows promising effectiveness in enhancing environmental literacy and systems thinking among pre-service biology teachers through the structured integration of Indigenous Papuan knowledge, ethnobiological inquiry, systems analysis, and sustainability-oriented reflection. The significant increases in environmental literacy and systems thinking, accompanied by large effect sizes, indicate that culturally contextualized learning can support students' ability to understand environmental problems as interconnected socio-ecological systems. Moreover, the significant partial mediating role of systems thinking demonstrates that the model supports environmental literacy not only through direct exposure to contextual ecological knowledge but also through students' enhanced capacity to identify causal relationships, feedback loops, interdependence, and sustainable solutions. The study contributes to sustainability education by positioning Indigenous knowledge as a central pedagogical and cognitive resource rather than as supplementary cultural content. Nevertheless, because the study employed a single-group pretest-posttest design within one higher education institution, the findings should be interpreted cautiously. Future studies should involve larger and more diverse samples, comparison groups, longitudinal designs, and cross-cultural implementation to strengthen causal inference and examine the long-term impact of ESTIM-Papua on sustainability-oriented knowledge, values, and environmental action..

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