Interdisciplinary International Journal of Conservation and Culture
Volume 3, Issue 2, October 2025, (Page 61-74)
DOI: https://doi.org/10.25157/iijcc.v3i2.5942
ISSN 2988-2923

Green STEAM-H pedagogy with eco-mathematical literacy: a developmental framework for sustainability-oriented education

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Abstract
This study proposes a conceptual framework for Green STEAM-H Pedagogy, integrating Eco-Mathematical Literacy as an approach to sustainability-oriented education. The framework responds to the growing need for educational models that systematically connect sustainability values, interdisciplinary learning, and analytical competencies in addressing complex environmental challenges. It synthesizes three key dimensions: green pedagogy as a value-oriented foundation, STEAM-H (Science, Technology, Engineering, Agriculture, Mathematics, and Health) as an interdisciplinary structure, and eco-mathematical literacy as a central analytical component. The framework is operationalized through a developmental progression consisting of three stages: eco-awareness, eco-integration, and eco-transformation. These stages represent a structured pathway through which learners develop ecological understanding, integrate knowledge across disciplines, and apply their competencies in sustainability-oriented actions. In addition, a pedagogical model is proposed to translate the framework into classroom practice by aligning instructional strategies, learning activities, and expected outcomes. This study contributes to the literature by offering a coherent and operationalizable model that bridges the gap between sustainability theory and educational practice. The framework highlights the role of eco-mathematical literacy in supporting data-driven reasoning and decision-making within interdisciplinary learning contexts. It also provides implications for curriculum development, pedagogy, and assessment in fostering transformative and future-oriented learning.

Keywords: eco-mathematical literacy; green pedagogy; STEAM-H; sustainability education; transformative learning

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Article history
Received April 8, 2026
Revised April 14, 2026
Accepted April 20, 2026
Published Online April 21, 2026

Cite this article:
Fatimah, A. T., Isyanto, A. Y., Erlin, E., Sunaryo, Y., Zamnah, L. N., Ruswana, A. M., & Solihah, S. (2026). Green STEAM-H pedagogy with eco-mathematical literacy: a developmental framework for sustainability-oriented education . *Interdisciplinary International Journal of Conservation and Culture*, *3*(2), 61–74. https://doi.org/10.25157/iijcc.v3i2.5942

INTRODUCTION

Global challenges related to environmental degradation, resource depletion, and socio-cultural transformation have intensified the need for sustainability-oriented development. Sustainability is inherently interdisciplinary, encompassing ecological, social, cultural, and economic dimensions that are closely interconnected in shaping human–environment relationships. Previous studies highlight that conservation efforts are not only rooted in natural and applied sciences but also involve social, cultural, and entrepreneurial perspectives, emphasizing the importance of integrated approaches to environmental and cultural preservation (Isyanto et al., 2023). In this context, education plays a crucial role in fostering awareness, values, and competencies necessary for sustainable living, particularly through approaches that integrate local wisdom and conservation-

based learning. Furthermore, sustainability is increasingly understood as a multidimensional construct that includes ecological, social, and cultural aspects, with students' perceptions shaped by their educational experiences and disciplinary backgrounds (Dadi et al., 2024). These conditions highlight the urgent need for educational approaches that can systematically integrate sustainability principles into meaningful learning experiences.

The United Nations 2030 Agenda for Sustainable Development emphasizes the central role of education in achieving the Sustainable Development Goals (SDGs), particularly in fostering the knowledge, competencies, and values required for sustainability. In this context, education is positioned as a transformative mechanism within Education for Sustainable Development (ESD) to enable learners to develop the competencies necessary to contribute to a sustainable future (Kioupi & Voulvoulis, 2019). Conceptually, it is grounded in ecological and cultural perspectives that encourage critical engagement with environmental issues and promote reflective and transformative learning experiences (Jorgenson, 2011). In practice, green pedagogy adopts eco-centric and systems-based perspectives, recognizing the interconnectedness of environmental, social, and economic systems, and is often implemented through project-based, experiential, collaborative, and problem-based learning strategies (Lozjanin et al., 2025; Maclean & Pavlova, 2017). However, despite its potential, its implementation remains challenged by limited critical engagement, difficulties in transforming students' environmental behavior, and constraints related to institutional support and assessment-oriented educational cultures (Kouam, 2025; Preston, 2011). These limitations indicate the need for more integrative and structured pedagogical frameworks that can effectively operationalize sustainability principles within interdisciplinary learning contexts. Furthermore, while green pedagogy provides a strong philosophical and value-based foundation, it often lacks a structured interdisciplinary framework for integrating multiple domains of knowledge to address complex sustainability challenges.

In addition to interdisciplinary integration, sustainability-oriented education also requires strong analytical and data-driven competencies, particularly in understanding complex environmental systems. To address the need for integrative and interdisciplinary approaches in sustainability-oriented education, the STEAM-H (Science, Technology, Engineering, Agriculture, Mathematics, and Health) framework has emerged as an extension of STEM and STEAM education. This development reflects the increasing complexity of real-world problems that require the integration of multiple disciplines, particularly in contexts such as agribusiness and sustainable development (Fatimah, Isyanto, & Toto, 2023; Fatimah, Isyanto, Toto, et al., 2023). Within this framework, agriculture plays a crucial role as both a conceptual and contextual integrator, connecting scientific, technological, engineering, mathematical, and health-related knowledge into meaningful, applied learning experiences. The STEAM-H approach emphasizes multidisciplinary, interdisciplinary, and transdisciplinary learning patterns that enable learners to engage with authentic problems and develop relevant competencies for the demands of the 21st century (Fatimah et al., 2022; Fatimah, Isyanto, et al., 2024).

Empirical studies have also demonstrated that STEAM-H-based learning can enhance students' understanding of integrated concepts while simultaneously fostering essential work skills, such as problem-solving, collaboration, and critical thinking, particularly in vocational and agribusiness contexts (Fatimah, Yuniawan Isyanto, et al., 2024). Furthermore, the implementation of STEAM-H in environmentally oriented programs, such as Adiwiyata schools, highlights its potential to integrate technological innovation with environmental awareness and sustainability practices through project-based and experiential learning (Fatimah, Adnan, et al., 2023; Fatimah, Thoyyibah, et al., 2024). Despite its potential, the conceptual integration of STEAM-H with sustainability-oriented pedagogical approaches remains underdeveloped, particularly in relation to structured frameworks that can be applied across educational levels. In practice, STEAM-H has been implemented in various educational levels through project-based and problem-based learning, particularly in vocational and Adiwiyata schools. These implementations demonstrate their flexibility

as an interdisciplinary approach; however, they often lack a systematic integration of sustainability values and analytical competencies.

The development of eco-green mathematics and its integration with smart technology demonstrates that sustainable mathematical literacy no longer stands solely as a cognitive competency but as a transformative capability that connects mathematical modeling with ecological and social issues. A systematic study by Sunismi et al. ((2025) confirms that the synergy among green curriculum, artificial intelligence, and pedagogical innovation plays a crucial role in building sustainable mathematical literacy, particularly through approaches such as intelligent tutoring systems, adaptive learning, and environmental problem-based modeling. At the implementation level, technology-based learning approaches such as augmented reality have been shown to not only improve academic achievement and reduce mathematical anxiety but also strengthen the sustainability dimension through resource efficiency and inclusive learning (Meenakshi & Indu, 2025). Furthermore, game-based learning (GBL) approaches and contextual experiences provide space for the integration of sustainability concepts into learning through interactive and immersive environments, thereby encouraging active student engagement in understanding and solving real-world problems and fostering sustainable citizenship (Costin et al., 2024). This perspective is reinforced by the mathematics-in-nature approach, which positions nature as an authentic learning resource, where direct interaction with the environment can improve numeracy comprehension while fostering ecological awareness from an early age (Miguel & Pascual, 2021). Thus, eco-mathematical literacy within the framework of green pedagogy serves as an important foundation for integrating cognitive, affective, and ecological aspects into learning across all levels of education.

Despite the growing body of research on green pedagogy, STEAM/STEAM-H education, and eco-mathematical literacy, these domains have largely developed in parallel rather than as an integrated pedagogical system. Existing studies tend to emphasize either sustainability values, interdisciplinary learning, or mathematical competencies, without providing a structured framework that systematically connects these dimensions within a developmental learning progression. Furthermore, limited attention has been given to the role of eco-mathematical literacy as a central analytical component within interdisciplinary sustainability-oriented education. This gap highlights the need for a comprehensive conceptual framework that integrates green pedagogy, STEAM-H, and eco-mathematical literacy into a coherent and operationalizable model across educational levels.

Based on the synthesis of green pedagogy, eco-mathematical literacy, and the STEAM-H approach, a pedagogical framework is needed that not only integrates various disciplines but also directs the learning process towards achieving sustainability holistically across educational levels. Previous research results indicate that STEAM-H has the potential to be an integrative framework that connects science, technology, engineering, agriculture, mathematics, and health through real-world contexts, with agriculture as the primary focus. Conceptual and contextual integration learning (Fatimah, Isyanto, & Toto, 2023). Furthermore, this approach enables the implementation of multidisciplinary, interdisciplinary, and transdisciplinary patterns that are relevant to the complexity of sustainability issues in the real world. In the context of elementary to secondary education, the implementation of project-based STEAM-H, such as in hydroponics, food processing, and the use of environmentally friendly technologies, demonstrates that learning can be designed as an authentic experience that simultaneously develops literacy, work skills, and ecological awareness (Fatimah, Isyanto, & Erlin, 2023). Therefore, the development of Green STEAM-H Pedagogy as a developmental framework. It is crucial to formulate systematic learning stages, from the introduction of environmentally based concepts, through cross-disciplinary integration, to concrete sustainability-based actions. This framework is expected to bridge the gap between sustainability theory and classroom learning practices, while also providing direction for the development of curriculum and pedagogy that adapts to the challenges of the 21st century.

This study contributes to the literature by proposing a novel conceptual framework—Green STEAM-H Pedagogy with Eco-Mathematical Literacy—that integrates philosophical (green pedagogy), epistemological (STEAM-H), and analytical (eco-mathematical literacy) dimensions into a

unified system. In addition, this study introduces a developmental learning progression consisting of eco-awareness, eco-integration, and eco-transformation stages, offering a structured pathway for translating sustainability concepts into pedagogical practice. This framework provides both theoretical advancement and practical guidance for designing interdisciplinary and sustainability-oriented learning environments.

CONCEPTUAL FOUNDATION OF GREEN STEAM-H PEDAGOGY WITH ECO-MATHEMATICAL LITERACY

Green STEAM-H pedagogy with eco-mathematical literacy is conceptualized as an integrative educational framework that synthesizes sustainability-oriented pedagogy, interdisciplinary STEAM-H learning, and eco-mathematical literacy into a coherent system of knowledge and practice. This framework reconceptualizes these components as interconnected dimensions that collectively address the complexity of sustainability-oriented education.

At the philosophical level, this framework is grounded in green pedagogy, which emphasizes ecological awareness, critical reflection, and the development of sustainability-oriented values. Green pedagogy positions education as a transformative process that fosters ecological consciousness and learner agency in responding to environmental challenges (Lozjanin et al., 2025). It also highlights the importance of critical engagement, where learners are encouraged not only to understand environmental issues but also to question, reflect, and construct their own responses (Preston, 2011). Furthermore, green pedagogy adopts a systems-based perspective that recognizes the interconnectedness of ecological, social, and cultural dimensions, thereby supporting a holistic approach to sustainability education (Maclean & Pavlova, 2017).

At the epistemological level, the framework integrates the STEAM-H approach as an interdisciplinary and transdisciplinary model of learning. STEAM-H extends the conventional STEM/STEAM paradigm by incorporating agriculture and health as contextual domains, enabling a more comprehensive engagement with sustainability issues such as food systems, environmental health, and resource management. Within this framework, agriculture functions as both a conceptual and contextual integrator that connects scientific, technological, engineering, mathematical, and health-related knowledge into meaningful learning experiences (Fatimah, Isyanto, & Toto, 2023). Recent studies also demonstrate that STEAM-based approaches can effectively support sustainability education, including in teacher preparation programs and transformative learning contexts, where learners develop competencies aligned with sustainable development goals (Alsina & Silva-Hormazábal, 2023; Djam'an, 2025; Taylor, 2023). This integrative structure supports multidisciplinary, interdisciplinary, and transdisciplinary learning patterns that are essential for addressing complex real-world problems.

At the analytical level, eco-mathematical literacy serves as a key competency that enables learners to interpret, model, and analyze environmental phenomena using mathematical reasoning. Mathematical literacy is understood as a socially situated competence that involves the ability to critically evaluate real-world situations shaped by mathematical structures (Jablonka, 2015). Extending this perspective, critical mathematics education highlights the role of mathematics in engaging with complex and uncertain "post-normal" situations such as climate change, where mathematical reasoning influences how problems are framed and understood (Barwell, 2018). A dialogical and relational perspective further emphasizes that mathematics education carries ethical responsibility in shaping learners' engagement with real-world sustainability issues (Barwell et al., 2022).

The contextualization of mathematical literacy within sustainability domains is further supported by emerging frameworks that integrate mathematics, technology, and sustainability in learning design. For example, the IMETS framework demonstrates how mathematical education can be aligned with sustainability goals through the integration of technology, although it does not yet incorporate broader interdisciplinary structures such as STEAM-H (Meylani, 2025). Empirical studies also indicate that environmental literacy and digital literacy significantly contribute to students'

mathematical thinking, highlighting the interconnected nature of these competencies (Farida et al., 2023). In addition, the development of environmental numeracy materials shows how mathematical concepts can be embedded in real-world sustainability contexts such as waste management, thereby strengthening students' applied understanding (Delamontano et al., 2025).

Despite these advancements, challenges remain in translating conceptual integration into classroom practice. Evidence suggests that although educators demonstrate awareness of sustainability-oriented mathematics, the integration of eco-green mathematics, environmental data, and digital technologies is still limited in practice (Sunismi et al., 2025, 2026). This gap indicates the need for a structured pedagogical framework that not only conceptualizes integration but also guides its implementation across educational contexts.

By integrating these philosophical (green pedagogy), epistemological (STEAM-H), and analytical (eco-mathematical literacy) dimensions, this framework establishes a holistic pedagogical paradigm that connects values, knowledge, and action. It provides a conceptual foundation for designing interdisciplinary, contextually relevant, and transformative learning experiences that help learners understand complex systems and contribute to sustainable solutions.

DEVELOPMENTAL FRAMEWORK OF GREEN STEAM-H PEDAGOGY

The developmental framework of green STEAM-H pedagogy is proposed as a structured learning progression that integrates sustainability values, interdisciplinary knowledge, and eco-mathematical literacy into a coherent learning trajectory. This framework is designed to address the gap between conceptual understandings of sustainability-oriented education and its practical implementation in classroom contexts. By organizing learning into progressive stages, the framework enables learners to develop not only awareness and knowledge but also analytical competence and transformative action.

The framework is grounded in three interrelated principles: (1) sustainability as a value-oriented foundation emphasized in green pedagogy, (2) interdisciplinarity through STEAM-H integration, and (3) eco-mathematical literacy as a tool for analysis and decision-making. These principles are operationalized through a developmental progression consisting of three stages: eco-awareness, eco-integration, and eco-transformation. The progression reflects increasing levels of cognitive complexity, interdisciplinary engagement, and sustainability-oriented action. These principles are operationalized through a developmental progression consisting of three stages: eco-awareness, eco-integration, and eco-transformation. The progression reflects increasing levels of cognitive complexity, interdisciplinary engagement, and sustainability-oriented action. To illustrate the integrative structure and developmental progression of the proposed framework, Figure 1 presents the Green STEAM-H Pedagogy Framework with Eco-Mathematical Literacy.

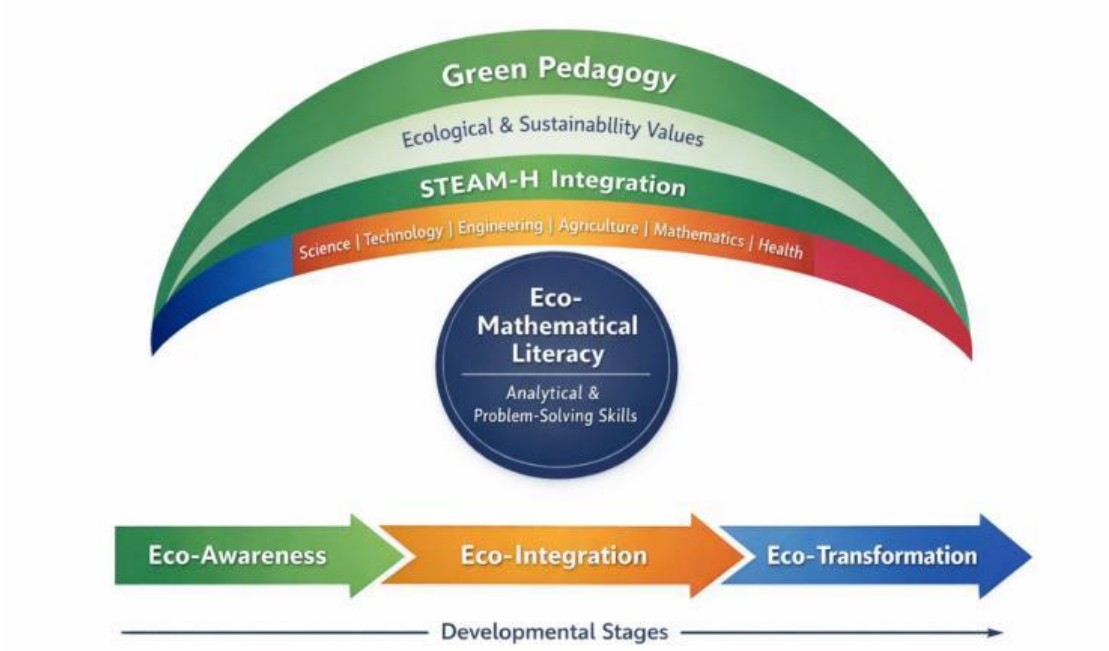

Figure 1 Green STEAM-H Pedagogy Framework

Existing studies on sustainability-integrated STEAM and STEM learning environments provide relevant support for the development of such frameworks. For instance, a scoping review of Green-STEAM practices in primary education highlights the use of diverse and constructive pedagogical approaches, including real-world problem-solving, integrated learning techniques, and reflective processes that support students' abstraction and conceptual understanding (Rantanen et al., 2024). Similarly, broader pedagogical frameworks for STEM learning environments emphasize the importance of design principles that integrate teaching methods, socio-emotional development, and cross-curricular competencies in supporting meaningful learning experiences (Mäkelä et al., 2020). In addition, integrative STEAM approaches have been adapted across educational contexts through thematic and interdisciplinary learning designs, demonstrating the flexibility of STEAM in accommodating broader educational goals and local contexts (Hapidin et al., 2020). However, these frameworks have not explicitly incorporated eco-mathematical literacy as a central analytical component, nor have they extended integration toward the STEAM-H perspective. This gap reinforces the need for a more comprehensive developmental framework.

Eco-awareness stage

The eco-awareness stage represents the initial phase of learning, where the primary focus is on developing learners' awareness of environmental issues and sustainability values. At this stage, green pedagogy plays a central role in fostering ecological consciousness, critical reflection, and value formation (Lozjanin et al., 2025; Preston, 2011). Learning experiences are designed to connect students with real-world environmental contexts through observation, exploration, and guided inquiry.

In terms of eco-mathematical literacy, learners begin to engage with simple environmental data and recognize basic relationships between mathematical concepts and ecological phenomena. Contextual learning approaches, such as interaction with natural environments, support students' understanding by linking abstract concepts with concrete experiences (Miguel & Pascual, 2021). However, awareness alone is often insufficient to drive behavioral change, highlighting the need for further stages that promote deeper engagement and action (Maclean & Pavlova, 2017).

Eco-integration stage

The eco-integration stage emphasizes integrating interdisciplinary knowledge through the STEAM-H framework. At this level, learners engage in problem- and project-based learning that connects science, technology, engineering, agriculture, mathematics, and health to address sustainability-related issues. Agriculture serves as a conceptual and contextual integrator, linking disciplinary knowledge with real-world applications (Fatimah, Isyanto, & Toto, 2023).

Eco-mathematical literacy becomes more central in this stage, as learners analyze environmental data, construct mathematical models, and evaluate relationships among variables. This aligns with the view that mathematical literacy involves the ability to critically engage with real-world situations and support informed decision-making (Barwell, 2018; Jablonka, 2015). The integration of sustainability, mathematics, and technology further strengthens analytical competence, as highlighted in emerging frameworks that connect these domains within learning design (Meylani, 2025). Empirical evidence also suggests that environmental and digital literacy contribute to the development of mathematical thinking, reinforcing the interconnected nature of these competencies (Farida et al., 2023). Thus, this stage represents a transition from awareness to analytical integration across disciplines.

Eco-transformation stage

The eco-transformation stage represents the highest level of the framework, where learning is oriented toward real-world application and sustainability action. At this stage, learners apply their interdisciplinary knowledge and eco-mathematical competencies to design, implement, and evaluate solutions to environmental problems.

This stage reflects the transformative goals of sustainability education, where learners are positioned as active agents of change. STEAM-based approaches have been shown to support such transformative learning by enabling learners to engage with sustainability challenges through authentic and project-based experiences (Alsina & Silva-Hormazábal, 2023; Taylor, 2023). In addition, dialogical perspectives in mathematics education emphasize the ethical responsibility of applying knowledge to real-world contexts (Barwell et al., 2022).

Eco-mathematical literacy functions here as a decision-making and evaluation tool, supporting learners in assessing the effectiveness and sustainability of their solutions. Nevertheless, challenges remain in implementation, particularly in bridging the gap between conceptual understanding and practical application, as identified in studies on eco-green mathematics and digital integration (Sunismi et al., 2025, 2026). This reinforces the importance of structured pedagogical guidance in achieving sustainability-oriented learning outcomes.

PEDAGOGICAL MODEL OF GREEN STEAM-H PEDAGOGY WITH ECO-MATHEMATICAL LITERACY

The pedagogical model of green STEAM-H pedagogy is developed to operationalize the proposed developmental framework into structured learning practices. This model integrates green pedagogy, STEAM-H interdisciplinary learning, and eco-mathematical literacy into a coherent instructional design that guides teaching and learning processes toward sustainability-oriented outcomes. It emphasizes not only knowledge acquisition but also the development of analytical competencies and transformative actions.

Although no single study explicitly formulates a unified framework of green STEAM-H pedagogy, existing literature provides converging evidence on integrated STEAM pedagogical models that combine mathematical literacy with environmental and sustainability-oriented learning. Previous studies demonstrate that STEAM-based learning can enhance mathematical literacy through interconnected and contextual problem-solving processes (Pratikno et al., 2025). In addition, eco-green mathematics integrated with digital and AI-based learning highlights the role of mathematical modeling in addressing sustainability challenges (Sunismi et al., 2026). Empirical

implementations also show that combining mathematical modeling with STEAM contexts, such as agricultural or environmental projects, can simultaneously promote conceptual understanding and environmental awareness among students (Roberto et al., 2021).

To strengthen the practical relevance of the proposed framework, existing implementations of STEAM-H-based learning provide important empirical illustrations. In Indonesian educational contexts, STEAM-H has been applied across multiple levels through project-based and problem-based learning approaches. For example, at the secondary level, STEAM-H has been implemented in vocational schools such as SMK Negeri 1 Cipaku through Problem-Based Learning (PBL) and Project-Based Learning (PjBL) (https://sites.google.com/unigal.ac.id/steam-hplusliterasi/steam-h-di-smk/steam-h-untuk-smk), where students engage in real-world agribusiness and environmental projects. At the primary level, STEAM-H has been integrated in Adiwiyata schools such as MIS Handapherang using project-based approaches to connect environmental education with interdisciplinary learning (https://sites.google.com/unigal.ac.id/steam-hplusliterasi/steam-h-di-sdmi/steam-h-organik-organik). These examples demonstrate that STEAM-H is not only a conceptual framework but also an adaptable pedagogical approach that can be implemented across educational levels. However, such implementations often focus on interdisciplinary integration without systematically incorporating sustainability values and eco-mathematical literacy as core components, which further highlights the contribution of the proposed framework.

Pedagogically, these approaches are commonly implemented through project-based and experiential learning models that emphasize real-world problem solving and interdisciplinary integration (Bertrand & Namukasa, 2023; Iaskyana et al., 2022). Some frameworks further highlight the importance of explicitly integrating mathematical concepts within interdisciplinary activities to ensure conceptual depth and coherence (Roberto et al., 2021). In the context of STEAM-H, interdisciplinary integration extends further by positioning agriculture as both a conceptual and contextual integrator that connects science, technology, engineering, mathematics, and health within authentic learning environments (Fatimah, Isyanto, Toto, et al., 2023).

However, despite these advances, existing models remain fragmented and have not yet articulated a comprehensive pedagogical structure that integrates sustainability values, interdisciplinary STEAM-H learning, and eco-mathematical literacy within a developmental progression. This limitation underscores the need for a more structured pedagogical model, as proposed in this study. To operationalize the proposed framework into classroom practice, Figure 2 illustrates the pedagogical model of Green STEAM-H Pedagogy with Eco-Mathematical Literacy.

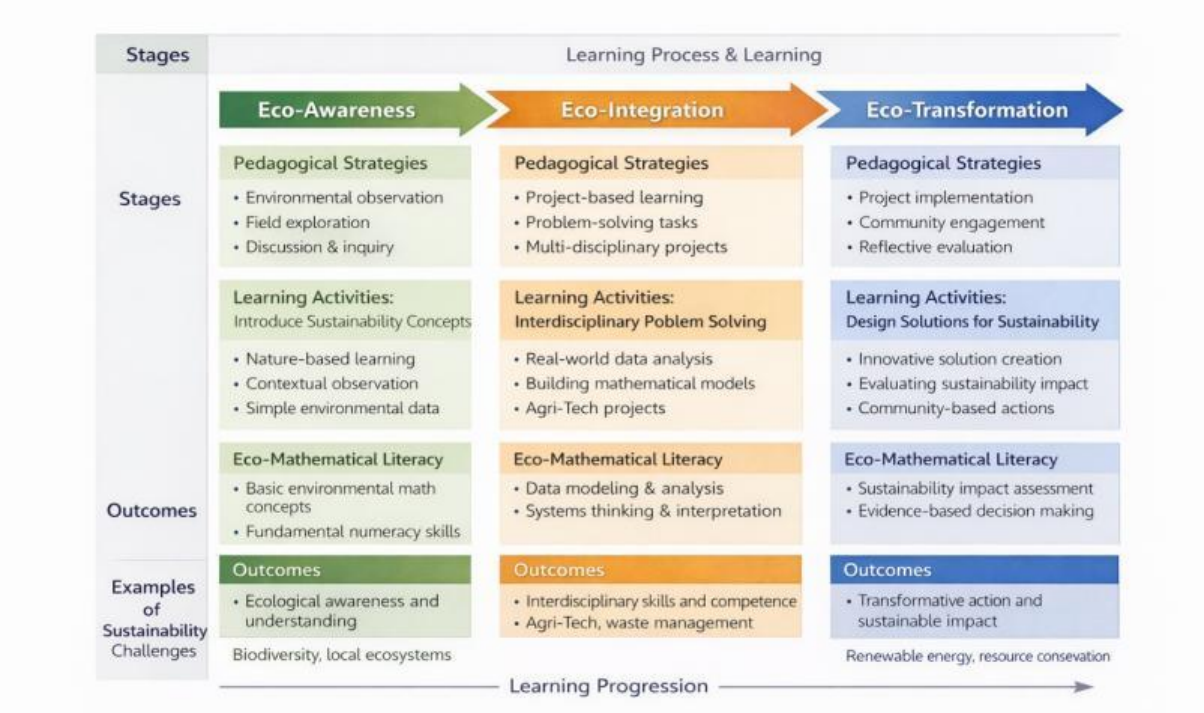

Figure 2 Pedagogical Model of Green STEAM-H Pedagogy with Eco-Mathematical Literacy

IMPLICATIONS FOR CURRICULUM AND PEDAGOGY

The proposed green STEAM-H pedagogy with eco-mathematical literacy offers significant implications for curriculum development and pedagogical practices in sustainability-oriented education. At the curriculum level, it calls for a shift from subject-based structures toward integrative and interdisciplinary designs. The STEAM-H framework enables the alignment of science, technology, engineering, agriculture, mathematics, and health within meaningful contexts, where agriculture can function as both a conceptual and contextual integrator connecting disciplinary knowledge with real-world sustainability issues (Fatimah, Isyanto, & Toto, 2023). In this context, curriculum development must move beyond content transmission toward transformative learning experiences that integrate knowledge, skills, values, and action. This direction is consistent with broader sustainability education frameworks that emphasize holistic and systemic curriculum design to support meaningful learning outcomes (Lozano, 2017).

Furthermore, the framework highlights the importance of embedding eco-mathematical literacy as a core competency within the curriculum. Mathematical literacy should not be viewed merely as a cognitive skill, but as a critical tool for analyzing, modeling, and making decisions related to ecological and social challenges. Integrating environmental data, mathematical modeling, and sustainability analysis into learning activities can strengthen students' ability to engage critically with real-world problems (Barwell, 2018; Jablonka, 2015). This perspective is further supported by emerging studies on eco-green mathematics and digital innovation, which emphasize the role of technology and interdisciplinary integration in advancing sustainability-oriented mathematical literacy (Sunismi et al., 2025). Thus, eco-mathematical literacy becomes a central bridge linking mathematical thinking with sustainability competencies.

At the pedagogical level, the model implies a shift toward student-centered, inquiry-based, and project-based learning approaches that emphasize active and experiential engagement. A systematic review identified key pedagogical cornerstones—scientific action-integrated, community-based, and value-oriented approaches—supported by strategies such as art-based, outdoor-based, and project- and problem-based learning (Bascopé et al., 2019). Empirical studies further demonstrate that problem-based learning, project-oriented learning, and cross-disciplinary workshops effectively foster sustainability competencies and environmentally responsible practices

(Albareda-Tiana et al., 2019). These findings align with STEAM-based pedagogical perspectives that emphasize interdisciplinary problem-solving and real-world engagement (Lozjanin et al., 2025; Schneider et al., 2020). In addition, contextual and nature-based learning environments can strengthen ecological awareness while supporting meaningful understanding of mathematical concepts (Miguel & Pascual, 2021).

However, implementing this pedagogical model requires strengthening teacher competence and providing institutional support. Despite positive attitudes toward sustainability-oriented learning, teachers' practical competencies—particularly in integrating interdisciplinary approaches, eco-mathematical literacy, and digital technologies—remain limited (Sunismi et al., 2026). Moreover, broader structural challenges such as disciplinary silos, limited resources, and insufficient professional preparation continue to hinder effective implementation (Rafiq-uz-Zaman et al., 2025).

Addressing these challenges requires sustained investment in professional development that emphasizes continuous training, collaborative learning, and experiential pedagogical practices (Susanti et al., 2024). In addition, assessment practices must be reoriented to capture not only cognitive achievement but also interdisciplinary understanding, sustainability awareness, and the ability to apply knowledge in real-world contexts. This can be achieved through authentic assessment strategies such as project-based and performance-based assessment, which are aligned with active and experiential learning approaches in sustainability-oriented education (Bascopé et al., 2019; Lozjanin et al., 2025).

Overall, these implications suggest that integrating green pedagogy, STEAM-H, and eco-mathematical literacy requires systemic transformation across curriculum, pedagogy, teacher development, and assessment practices to support sustainability-oriented education effectively.

CONCLUSION

This study proposes a novel conceptual framework, Green STEAM-H Pedagogy with Eco-Mathematical Literacy, as an integrative approach to sustainability-oriented education. The framework synthesizes three key dimensions—green pedagogy as a value-oriented foundation, STEAM-H as an interdisciplinary structure, and eco-mathematical literacy as an analytical component—into a coherent and comprehensive pedagogical system. By positioning eco-mathematical literacy as a central analytical bridge, the framework extends existing sustainability and STEAM-based models that have typically treated these domains separately.

A key contribution of this study is the introduction of a developmental learning progression consisting of three stages: eco-awareness, eco-integration, and eco-transformation. This progression provides a structured pathway that connects sustainability values, interdisciplinary knowledge, and analytical competencies, enabling learners to move from understanding environmental issues to engaging in integrative problem-solving and ultimately to taking transformative action. In addition, the proposed pedagogical model translates this framework into practical instructional design by aligning pedagogical strategies, learning activities, and expected outcomes across stages.

The framework offers important implications for curriculum and pedagogy. It supports a shift toward interdisciplinary, context-based, and sustainability-oriented learning environments, while emphasizing the role of eco-mathematical literacy in strengthening students' capacity to analyze, model, and make informed decisions related to complex environmental challenges. Furthermore, it highlights the need for systemic transformation in curriculum design, teaching practices, and assessment to ensure the effective implementation of sustainability-oriented education.

Despite its contributions, this study is conceptual in nature and has not yet been empirically validated. Future research is needed to examine the effectiveness of the proposed framework across different educational levels and contexts. Empirical studies may explore how the integration of green pedagogy, STEAM-H, and eco-mathematical literacy influences students' sustainability competencies, interdisciplinary understanding, and transformative learning outcomes. In addition, further research is required to investigate teacher readiness, instructional design strategies, and assessment models that support the practical implementation of this framework.

Overall, the Green STEAM-H Pedagogy with Eco-Mathematical Literacy provides a comprehensive and forward-looking framework that bridges the gap between sustainability theory and classroom practice. By integrating values, knowledge, and action within a developmental and interdisciplinary structure, the framework contributes to advancing sustainability-oriented education and preparing learners to address complex challenges in the 21st century.

Limitations and future direction

This study is limited by its conceptual nature, as the proposed Green STEAM-H Pedagogy with Eco-Mathematical Literacy has not yet been empirically validated in classroom settings, and its development is based on a literature synthesis that may not fully represent diverse educational contexts. In addition, practical challenges related to teacher readiness, resource availability, and assessment implementation are not examined empirically. These limitations suggest important directions for future research, including empirical testing of the framework across educational levels, investigation of its impact on students' cognitive, affective, and sustainability-related competencies, and the development of instructional designs, assessment models, and teacher professional development strategies that support its implementation. Further studies may also explore the integration of emerging technologies, such as artificial intelligence and data-driven learning, as well as conduct longitudinal and cross-contextual research to examine the adaptability and long-term impact of the framework in sustainability-oriented education.

Acknowledgements

The authors would like to express sincere appreciation to all parties who have supported the development of this research, particularly Adiwiyata schools and agribusiness schools whose continuous contributions to STEAM-H-related educational practices have significantly informed and shaped the conceptual framework proposed in this study.

Declarations

The authors declare that all contributions to this study were made collaboratively. The authors declare no conflict of interest related to this publication.

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