

Strengthening Students' Ecological Problem-Solving Skills through Mangrove-Based Pro-STEM ESD E-Module Learning Management

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ABSTRACT

The strengthening of students' ecological problem-solving skills is increasingly required in response to the growing demands of sustainable education, environmental literacy, and locally contextualized learning. Mangrove ecosystems are relevant learning contexts because they contain issues of conservation, biodiversity, climate change, and sustainability that can be integrated into STEM- and ESD-based science learning. This article aims to synthesize empirical evidence on ecological learning, e-modules, STEM/STEAM, ESD, and environmental contexts as a basis for developing a mangrove-based Pro-STEM ESD e-module learning management model. A systematic literature review was conducted using the PRISMA guidelines. The search was carried out in the Scopus database using keywords related to students, education, learning, environmental, sustainability, STEM, problem solving, digital, module, and ecology. From 125 initial documents, screening based on publication year, article type, language, open access status, abstract relevance, DOI, research design, and primary data resulted in 10 included articles. The findings indicate that students' ecological problem-solving skills can be strengthened through problem-based learning, inquiry, projects, research teamwork, STEM/STEAM teaching materials, digital modules, and authentic environmental experiences. Effective e-modules do not merely serve as media for presenting content, but also function as systems for managing learning activities, observation, analysis, reflection, solution assessment, and collaboration. This review contributes as a preliminary study and conceptual foundation for developing a contextual, collaborative, and sustainability-oriented mangrove-based Pro-STEM ESD e-module learning model.

INTRODUCTION

Ecological crises and the demands of sustainable education have positioned schools as strategic spaces for developing literacy, awareness, and environmental problem-solving capacity. In cross-country case-based learning, university students' understanding of the SDGs increased when sustainability issues were connected to real dilemmas and evidence-based discussion (Vasconcelos et al., 2022). In secondary education, sustainability competency frameworks are increasingly directed toward systemic, anticipatory, normative, strategic, and collaborative thinking skills (Sposab & Rieckmann, 2024). This urgency is particularly evident in coastal ecosystems because mangrove conservation education is related to students' knowledge, attitudes, and engagement in ecosystem protection (Tagulao et al., 2022). Active learning across school and university settings has also been reported to strengthen sustainability competencies through collaborative and reflective experiences (Castaño et al., 2025). Therefore, ecological education needs to be directed toward action competence that connects knowledge, local experience, and sustainability-based decision-making in school science learning.

Recent research has shown that the integration of STEM, ESD, and active learning has become an important direction in environmental education. STEM-based teaching has been considered capable of supporting the achievement of sustainable development goals because it facilitates critical thinking, problem solving, and analysis of socio-ecological issues (AlAli et al., 2023). Findings from Pennsylvania educators also emphasize that bridges between STEM and sustainability need to be built through authentic problems, collaboration, and contextualized curriculum design (Cordaro et al., 2025). In school-based agricultural education, a systems thinking approach has been used to integrate STEM with food, natural resource, and sustainability problems (Knobloch et al., 2026). The role of mathematics in STEM-sustainability has been positioned as a means of modeling uncertainty in climate change (Li, 2025). At the early education level, sustainability-based STEM experiences have strengthened children's knowledge and skills through activities close to daily life (Abanoz & Yabaş, 2025). Accordingly, STEM-ESD research has moved from conceptual mastery toward the design of learning experiences that guide ecological analysis, modeling, and decision-making in a measurable manner.

Developments in digital research indicate that electronic modules can expand access, organize activities, and maintain the continuity of environmental learning. In the context of environmental and sustainability education, distance learning has been considered capable of closing access gaps when design, interaction, and assessment are adequately prepared (Fiedler et al., 2022). A comparison of digital and analog interventions in forestry learning showed that digital media can be used comparably to offline learning when content and learning objectives are kept consistent (Fleissner-Martin et al., 2023). The mangrove ecotourism e-module was reported to be associated with elementary students' perceptions, interest, and environmental care character (Asrial et al., 2022). The EJoy-ME model in mangrove ecosystems has also been directed toward strengthening environmental literacy through enjoyable direct

experiences (Hayati et al., 2025). Thus, locally contextualized e-modules need to be positioned as pedagogical designs that manage learning experiences, rather than merely as containers for digital content, and connect them with real actions.

Although evidence on STEM, ESD, digital learning, and mangrove education continues to grow, a knowledge gap remains in the absence of a consolidated model that specifically connects e-module learning management, Pro-STEM ESD, mangrove ecosystems, and students' ecological problem-solving skills. Ecosystem-based fieldwork emphasizes the importance of investigation, process skills, and understanding the nature of environmental education (Molefe & Aubin, 2021). Studies on mangrove education in Indonesia also show that conservation needs to be transformed into learning strategies connected to the climate agenda (Gunawan et al., 2025). At the same time, problem-solving development in sustainable STEM still requires explicit modeling of activities, contexts, processes, and assessment (Štuikys et al., 2025). This article aims to synthesize empirical evidence on ecological learning, STEM/STEAM, ESD, e-modules, and mangroves to answer the following question: how does the pattern of evidence support the strengthening of students' ecological problem-solving skills through mangrove-based Pro-STEM ESD e-module learning management? The main contribution of this article lies in providing a preliminary study and conceptual foundation for selecting the theme, designing the model, and directing further empirical testing in the context of secondary education.

Method

A systematic literature review was used to trace, screen, and synthesize articles on strengthening ecological problem-solving skills through STEM/STEAM-based learning, ESD, digital modules, teaching materials, and environmental contexts. The search and screening procedures were conducted by referring to PRISMA principles. The initial search was conducted in the Scopus database using the following search string: students AND education AND learning AND environmental AND sustainability AND STEM AND "problem solving" AND digital AND module AND ecology. The initial search produced 125 documents. After the 2021-2026 year limit was applied, 112 documents were obtained. Screening based on journal article type produced 52 articles. The English-language filter resulted in 51 articles, while the All Open Access filter resulted in 39 articles that were then assessed based on abstracts, DOI, research design, subject, intervention, and final findings.

The inclusion criteria were journal articles written in English, published between 2021 and 2026, having an active DOI, based on primary data, and strongly related to environmental learning, ecological literacy, environmental literacy, STEM/STEAM, ESD, digital modules, teaching materials, projects, PBL, or problem solving. Articles were prioritized when they used R&D, quasi-experimental, mixed methods, quantitative, qualitative, or learning intervention evaluation designs. The exclusion criteria were applied to review articles, bibliometric studies, meta-analyses, purely conceptual articles, conference reports, non-education articles, articles without relevant interventions or primary data, articles with a focus too distant from ecological-STEM/ESD themes, duplicated titles or DOI, and articles indicated as retracted. Of the 39

assessed articles, 10 articles were retained as the final set because they were the most appropriate to the focus of strengthening students' ecological problem-solving skills through Pro-STEM ESD e-module-based learning management in environmental contexts.

The initial search results showed that 125 documents were identified through Scopus. After the 2021-2026 year filter was applied, 112 documents remained. Screening based on journal article type produced 52 documents, the English-language filter produced 51 documents, and the All Open Access filter produced 39 documents. All abstracts from these 39 articles were assessed for eligibility. A total of 29 articles were excluded because they did not meet the inclusion criteria, leaving 10 articles for the final synthesis. No duplicated titles or DOI were found in the final set. Review articles, bibliometric studies, meta-analyses, conceptual articles, conference reports, and articles with a focus too distant from the ecological-STEM/ESD-learning intervention integration were not included in the final synthesis.

The article selection flow was organized according to PRISMA guidelines, from identification in the Scopus database to the final inclusion of articles that met the eligibility criteria for further analysis. The flow describes the number of records at each stage and the reasons for systematic exclusion, as shown in Figure 1.

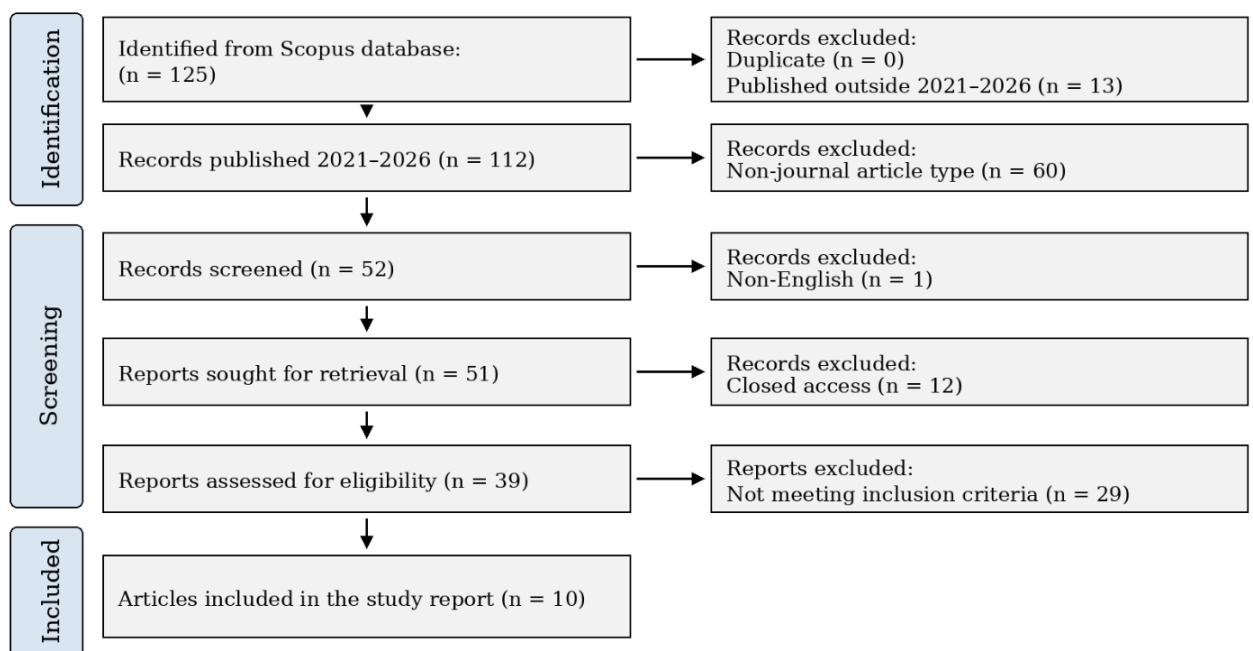


Figure 1. PRISMA Flowchart

RESULTS

The screening results showed that the 10 included articles had the strongest thematic proximity to the development of ecological literacy, STEM/STEAM-based learning, ESD, teaching materials or digital modules, conservation, biodiversity, climate change, and problem solving. Most articles used quasi-experimental, mixed methods, R&D, or learning intervention evaluation designs. The retained articles did not all focus specifically on mangroves, yet all provided

empirical foundations that could be mapped into the design of mangrove-based Pro-STEM ESD e-module learning management within a local ecological context.

Table 1. Results of article review

No.	Name	Findings
1	Perez Jr. et al. (2025)	The IB-STEAM packet significantly improved conceptual understanding and ecoliteracy and was positively received by pre-service teachers and lecturers.
2	Daryanes et al. (2025)	RTBL was more effective than RBL and TBL in strengthening students' research skills for analyzing environmental problems.
3	Sari et al. (2025)	STEAM integration significantly improved critical thinking skills, including the habit of questioning assumptions and evaluating solutions.
4	Mahardika et al. (2026)	The web-based conservation model improved positive responses, environmental observation, analysis, solution development, and students' scientific-environmental literacy.
5	Patonah et al. (2025)	The STEAM-SDGs IPAS model was practical to use and supported collaborative planning, creativity, environmental literacy, and green economy readiness.
6	Jekel Könnel et al. (2025)	The outdoor program improved ecological knowledge and highlighted the importance of adjusting modules to school level and characteristics.
7	Hakim et al. (2023)	STEM-based physics teaching materials improved high school students' climate literacy, with an average N-Gain in the moderate category.
8	Mukhitdinova et al. (2026)	Biodiversity integration in STEM improved ecological literacy, biodiversity understanding, STEM application skills, and conservation orientation.
9	Ayerbe-López & Perales-Palacios (2023)	The PBL-based urban ecology project increased motivation, participation, and learning socialization, but was constrained by time, group work, and ICT.
10	Simbolon et al. (2025)	The AI- and sociocultural-based interactive digital module improved scientific literacy, especially in complex concepts related to climate and earth systems.

DISCUSSION

The synthesis of the included articles shows that ecological problem-solving skills cannot be separated from learning experiences that connect environmental

phenomena, inquiry activities, and reflection on alternative solutions. A PBL-based urban ecology project showed that motivation, participation, and learning socialization increased when students were positioned as problem solvers in relation to real environmental issues (Ayerbe-López & Perales-Palacios, 2023). This finding is reinforced by research team-based environmental science learning, which was proven to be more effective than regular research-based learning and team-based learning in improving students' research skills (Daryanes et al., 2025). In addition, biodiversity integration in STEM confirms that ecological literacy and STEM application skills can develop when tasks are organized in a problem-focused and evidence-based manner (Mukhitdinova et al., 2026). Outdoor environmental education programs also show that ecological knowledge needs to be managed according to school level and characteristics (Jekel Könnel et al., 2025). Therefore, ecological problem solving becomes stronger when learning is managed as a contextual inquiry process rather than merely as the delivery of environmental concepts.

The integration of STEM/STEAM in the included articles demonstrates the important function of teaching materials as connectors among scientific concepts, solution design, and sustainability literacy. Inquiry-based STEAM teaching packets have been shown to improve conceptual understanding and ecoliteracy because learners are guided to interpret ecological issues through structured inquiry activities (Perez Jr. et al., 2025). In science learning, STEAM integration significantly improved critical thinking skills because students were encouraged to question assumptions, connect concepts, and evaluate solutions from multiple perspectives (Sari et al., 2025). STEM-based physics teaching materials on climate change issues also improved high school students' climate literacy with a moderate N-Gain category, mainly because the material was linked to ecosystem consequences and student actions (Hakim et al., 2023). The STEAM-SDGs IPAS model further shows that modules, worksheets, and assessment instruments need to be designed practically so that sustainable projects can be managed collaboratively (Patonah et al., 2025). Thus, the Pro-STEM ESD e-module needs to integrate concepts, local problems, design tasks, and solution assessment in a coherent manner.

The digital aspect in the article set shows that e-modules do not merely function as media for presenting materials, but also as systems for managing learning activities. The web-based conservation learning model supported observation, analysis, problem solving, communication, and environmental activities that increased from the initial to the final meetings (Mahardika et al., 2026). The AI-based interactive digital module with a Papuan sociocultural context also showed a 49.19% increase in science concept understanding, especially in earth systems, climate change, energy, and CO₂ radiation absorption (Simbolon et al., 2025). These findings align with the STEAM-SDGs IPAS model, which emphasizes the importance of teaching materials, worksheets, and assessments for managing project work systematically (Patonah et al., 2025). The IB-STEAM packet also shows that learning products developed through R&D require expert evaluation, limited implementation, and user feedback (Perez Jr. et al., 2025). Therefore, effective e-modules must organize the

learning flow, guide investigation, accommodate reflection, and measure the quality of ecological solutions.

Although the empirical findings tend to be positive, several limitations show that ecological learning management still requires control of time, readiness for collaboration, and technological support. In the urban ecology project, constraints were found in time management, group work, methodological experience, and ICT use (Ayerbe-López & Perales-Palacios, 2023). The GewässerCampus program also emphasizes that the effectiveness of environmental education modules is influenced by differences in school level and school type, so learning design cannot be treated uniformly (Jekel Könnel et al., 2025). In STEAM integration, the success of critical thinking improvement depends on cognitive experiences that challenge students to evaluate solutions, rather than merely produce products (Sari et al., 2025). In RTBL, the strength of the model lies in the explicit organization of research roles and teamwork so that environmental problem analysis can be developed systematically (Daryanes et al., 2025). Therefore, e-module management needs to include project scheduling, role distribution, digital scaffolding, solution rubrics, and continuous reflection.

The mangrove context has not been explicitly tested in the 10 included articles, but the conceptual and empirical foundations for building the model are available. Biodiversity integration in STEM shows that biodiversity issues can be used to improve ecological literacy and STEM application skills (Mukhitdinova et al., 2026). The web-based conservation model shows that real environmental issues can be combined with observation, analysis, communication, and solution development in a digital platform (Mahardika et al., 2026). STEM teaching materials on climate change provide evidence that ecosystem problems can be studied through structured science materials (Hakim et al., 2023). The sociocultural digital module indicates that local contexts strengthen the relevance of science learning and SDGs for students (Simbolon et al., 2025). The PBL-based urban ecology project provides an operational model for positioning students as researchers of local environmental problems (Ayerbe-López & Perales-Palacios, 2023). This integrated evidence addresses the research gap by showing that the theme of strengthening ecological problem-solving skills through mangrove-based Pro-STEM ESD e-module learning management is appropriate as a basis for preliminary study and for selecting the research focus. Thus, mangroves can be positioned as local ecological laboratories that integrate conservation, biodiversity, climate change, technology, and sustainable solutions.

CONCLUSION

This review shows that ecological problem-solving skills are most likely to be strengthened through learning that integrates real environmental contexts, STEM/STEAM, ESD, structured teaching materials, digital modules, inquiry, projects, and solution reflection. The 10 included articles show that ecological literacy, environmental literacy, climate literacy, conservation, biodiversity, and problem-based learning are strongly connected in developing students' competence to understand ecosystem problems and design relevant solutions.

The synthesis of findings confirms that mangrove-based Pro-STEM ESD e-modules need to be developed as learning management systems, rather than

merely as digital media. The main components that need to be integrated include the mapping of mangrove ecological problems, environmental observation, integration of science and technology concepts, solution design, collaborative work, rubric-based assessment, sustainability reflection, and formative feedback. The success of the model is also influenced by the clarity of student roles, teacher readiness, time management, adequate scaffolding, and suitability to the local context. Therefore, the mangrove-based Pro-STEM ESD e-module learning model has the potential to serve as a relevant pedagogical strategy for strengthening students' ecological literacy and problem-solving skills in a contextual, collaborative, and sustainability-oriented manner.

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