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Potential Application of ESD-Oriented STEAM in Ecosystem Material

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Abstract

This study aims to analyze the potential for implementing Science, Technology, Engineering, Arts, and Mathematics (STEAM) learning oriented toward Education for Sustainable Development (ESD) on ecosystem topics in elementary schools. Although this integrated approach offers a framework for contextual and sustainability-focused education, its implementation faces significant challenges regarding teacher readiness, student engagement, and the adequacy of instructional planning. To address this, a descriptive quantitative approach with a survey design supported by document analysis was employed. The participants comprised 20 elementary school teachers from the Pattimura Teacher Working Group and 20 fifth-grade students from SD Negeri 02 Api-Api, Pekalongan Regency. Data were collected via teacher and student questionnaires, alongside instructional module documentation, and analyzed using descriptive statistics. The findings revealed that teachers' understanding of STEAM and ESD was relatively adequate (73% and 72%, respectively), alongside teaching practices (74%), student engagement (79%), and reflection/evaluation (78%). However, document analysis of instructional modules revealed a critical gap: while STEAM-supporting methods were incorporated, activities for active student engagement were not optimal, and the explicit integration of ESD principles into instructional planning was largely absent. Consequently, while the potential for STEAM-oriented ESD is considerable, it requires systematic strengthening of instructional materials and the explicit integration of sustainability principles to be effectively realized.

Keywords: ecosystem, Education for Sustainable Development, ESD, science learning, STEAM

INTRODUCTION

Basic education currently faces a complex dual challenge: the demand for mastery of 21st-century skills (4Cs) and the urgency of instilling sustainability awareness amidst the global environmental crisis. Digital transformation and technological developments have shifted the learning paradigm from mere content mastery to the development of adaptive and problem-solving abilities (Mufliva & Permana, 2024; Prabandari et al., 2023). However, scientific literacy and technical skills alone are not enough; students need a value orientation to make environmentally responsible decisions. In this context, the integration of approaches*Science, Technology, Engineering, Arts, and Mathematics* (STEAM) and *Education for Sustainable Development* (ESD) offers a potential framework. STEAM provides an interdisciplinary methodology for solving problems, while ESD provides an ethical and contextual foundation for environmentally, socially, and economically sustainable solutions (Rochmah, 2023; Nursofa & Hamdu, 2021).

Ecosystems instruction in elementary schools is the most relevant platform for integrating these two approaches. The ecosystem concept not only demands a scientific understanding of biotic and abiotic

interactions but also requires a critical analysis of the impact of human activities on the balance of nature. Research by Rahma et al. (2026) and Damayanti et al. (2025) has separately demonstrated that STEAM effectively develops science process skills, and ESD effectively increases environmental awareness. However, fieldwork shows that the implementation of these two approaches is often partial or separate. Teachers often struggle to translate abstract concepts of sustainability into concrete engineering and arts activities, or conversely, become trapped in project activities that lose the essence of sustainability values.

This is where the gap lies is significant in the existing literature. Previous research tends to focus on learning outcomes or product effectiveness after interventions, such as increased creativity (Fatmawati & Mariana, 2022) or scientific literacy (Triyana, 2023). Very little research critically analyzes the potential for implementation and readiness of learning ecosystems before large-scale interventions are implemented. The existing literature does not sufficiently address how teacher understanding, the availability of tools (teaching modules), and student characteristics interact to support holistic STEAM-ESD integration in ecosystems material. Studies that position ESD-oriented STEAM as a unified whole rather than simply tackling environmental issues on science projects remain an underexplored area, particularly in mapping implementation challenges at the elementary school level.

Novelty This research lies in its efforts to not only test the effectiveness, but also to comprehensively dissect the potential and feasibility of implementing ESD-oriented STEAM. This research not only looks at the material side, but also analyzes the gap between the demands of the curriculum and the reality of classroom practice, including the extent to which existing teaching modules have accommodated the elements*engineering* and *arts*within a framework of sustainability. This is crucial because the success of a complex approach like STEAM-ESD depends heavily on the pedagogical preparedness of teachers and the relevance of learning tools to the local context of learners.

Based on this analysis, this study aims to analyze the potential for implementing ESD-oriented STEAM on ecosystem material in elementary schools. The analysis focuses on three main dimensions: (1) teachers' understanding and readiness for the integration of scientific disciplines and sustainability issues, (2) the suitability of learning tools (teaching modules) with STEAM-ESD principles, and (3) students' responses and engagement in the learning scenarios offered. The results of this study are expected to provide a strong empirical foundation for the development of learning models that are not only intellectually intelligent but also ecologically concerned.

METHODS

This study employed a quantitative descriptive approach to obtain a comprehensive overview of the conditions, readiness, and potential for implementing Science, Technology, Engineering, Arts, and Mathematics (STEAM) learning oriented toward Education for Sustainable Development (ESD) on ecosystem topics. A quantitative approach was selected because the data were collected in the form of numerical scores and percentages, allowing for statistical analysis aligned with the research objectives (Creswell & Creswell, 2023).

Specifically, the study utilized a survey design supported by document analysis. The survey was employed to capture teachers' understanding, perceptions, and student engagement in the context of ESD-oriented STEAM learning. Concurrently, document analysis was conducted to identify the extent to which

STEAM and ESD elements were reflected in the instructional planning documented in the teaching modules. The combination of these data sources provided a more holistic picture of the implementation potential.

Participants and Setting

The research was conducted in Wonokerto District, Pekalongan Regency. The participants comprised 20 elementary school teachers who are members of the Pattimura Teacher Working Group (KKG) in Wonokerto District, and 20 fifth-grade students from SD Negeri 02 Api-Api. Teachers were selected as respondents due to their central role in planning, implementing, and evaluating the learning process. Meanwhile, students were involved to provide supporting data regarding their active involvement, responses, and experiences during learning activities.

Data Collection Instruments

Data were collected using questionnaires and document analysis. The teacher questionnaire measured five main indicators: (1) understanding of STEAM learning, (2) understanding of ESD, (3) learning methods and habits, (4) student involvement in learning, and (5) reflection and evaluation practices. The student questionnaire served as a supplementary instrument to assess student responses, motivation, and engagement.

Additionally, document analysis was conducted on the teaching modules used by the teachers. This analysis evaluated the extent to which the planned learning accommodated STEAM characteristics and ESD sustainability principles. Specifically, it focused on the inclusion of project-based or problem-solving methods, active student engagement activities, reflection sessions, feedback mechanisms, and the integration of environmental issues. The results of this document analysis were used to triangulate and compare the data obtained from the teacher questionnaires.

Research Procedure

The research procedure was executed in several systematic stages. The first stage involved the development of research instruments based on STEAM and ESD indicators. The second stage was data collection through the distribution of questionnaires to teachers and students. The third stage consisted of collecting and analyzing teaching module documents used in the learning process. The fourth stage was data processing, which involved calculating scores and achievement percentages for each indicator. The final stage was interpreting the analysis results to determine the potential for applying ESD-oriented STEAM to ecosystem material.

Data Analysis

The quantitative data from the questionnaires were analyzed using descriptive statistics, specifically percentages, to describe the obtained data without generalizing it to a broader population (Sugiyono, 2020). The percentage achievement for each indicator was calculated using the following formula:

$$\boldsymbol{P = (\Sigma X / \Sigma Xm) \times 100\%}$$

Where:

P = percentage of achievement

ΣX = total score obtained

ΣXm = maximum possible score

The resulting percentages were interpreted based on predefined achievement level categories. A higher percentage across the indicators of teacher understanding, learning practices, student engagement, and module readiness indicates a greater potential for implementing ESD-oriented STEAM. To strengthen the interpretation, data from the teacher questionnaires, student questionnaires, and document analysis were compared and synthesized descriptively. This triangulation identified both supporting factors and aspects requiring further strengthening in the implementation of ESD-oriented STEAM learning.

Table 1. Data Sources, Instruments, and Aspects Analyzed

Data Source	Instrument	Aspects Analyzed
Teacher	Questionnaire	STEAM Understanding
Teacher	Questionnaire	ESD Understanding
Teacher	Questionnaire	Learning Methods
Teacher	Questionnaire	Student Involvement
Teacher	Questionnaire	Reflection and Evaluation
Student	Questionnaire	Response and Engagement in Learning
Teaching Module	Document Analysis Sheet	Project activities, experiments, problem-solving, student activities, reflection, and ESD integration

RESULTS AND DISCUSSION

Teacher Understanding of STEAM Learning

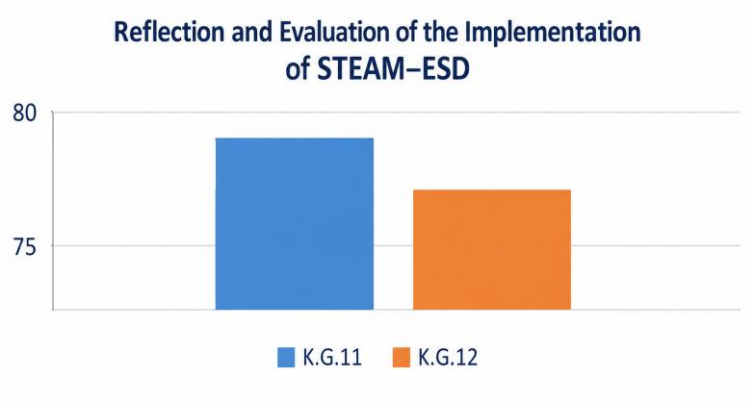

Figure 1. Percentage of Teacher Questionnaire Responses for 5 Indicators (Teacher Understanding of STEAM Learning)

Information:

K.G.1: Teachers can explain the concept of sustainability in the context of STEAM (Science, Technology, Engineering, Arts, and Mathematics) in IPAS learning.

K.G.2: Teachers understand the relationship between STEAM and social or environmental issues in IPAS learning.

K.G.3: Teachers can apply the concepts learned in everyday life.

The first indicator, namely teachers' understanding of Science, Technology, Engineering, Arts, and Mathematics (STEAM), obtained an average percentage of 73% and was categorized as good. This result indicates that teachers have an adequate understanding of the basic concepts of STEAM and its potential application in IPAS learning. This condition provides an important starting point because STEAM implementation requires teachers to connect different fields of knowledge through contextual and problem-solving-oriented learning activities.

The highest sub-indicator was teachers' ability to apply the concepts learned in everyday life, with a percentage of 74%. Meanwhile, the lowest percentage was found in teachers' ability to explain the concept of sustainability in the context of STEAM in IPAS learning, at 72%. This difference indicates that teachers are relatively more prepared to connect learning materials with everyday life than to explain conceptually the relationship between STEAM and sustainability.

These findings indicate that teachers' understanding of STEAM is already at a relatively good level, but the integration of sustainability aspects still needs to be strengthened. This is important because STEAM is not only concerned with combining several fields of knowledge but can also be used to develop students' abilities to understand real-world problems and produce contextual solutions. Studies on STEAM implementation in elementary education indicate that STEAM learning can be developed through experiments, projects, creative assignments, and learning activities that connect subject matter with students' lives (Rakhmawati et al., 2024).

Teacher readiness is increasingly important because the success of STEAM implementation is strongly influenced by teachers' ability to understand the characteristics of the approach and translate them into learning activities. Research by Afifatin et al. (2025) shows that elementary school teachers generally have motivation to implement STEAM but still face challenges in mastering integrative concepts and using supporting technology. Therefore, the 73% achievement in this study indicates good potential while also showing the continued need to strengthen teachers' conceptual understanding, particularly regarding the relationship between STEAM and sustainability.

In the context of ecosystem learning, this strengthening can be achieved by connecting scientific concepts concerning relationships among ecosystem components with technology, solution-design processes, creativity, and mathematical measurement. In this way, STEAM becomes not merely a variation of teaching methods but an approach that helps students understand environmental problems more comprehensively.

Teachers' Understanding of ESD in Ecosystem Learning

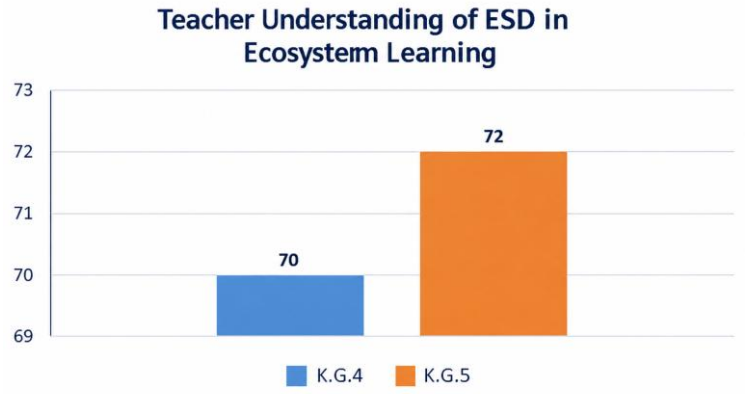

Figure 2. Percentage of Teacher Questionnaire Responses for 5 Indicators (Teacher Understanding of ESD)

Information:

K.G.4: Teachers can integrate ESD principles into the ESD curriculum.

K.G.5: Teachers design learning activities that support sustainability.

The second indicator was used to determine teachers' level of understanding of Education for Sustainable Development (ESD). The analysis showed that teachers' understanding of ESD obtained an average percentage of 72% and was categorized as good. This result indicates that teachers have an initial understanding of the importance of sustainability in learning, including the possibility of connecting environmental issues with ecosystem content.

The highest sub-indicator was teachers' acceptance of integrating ESD concepts into IPAS learning on ecosystems, at 72%. Meanwhile, teachers' ability to integrate ESD concepts into learning obtained 70%. This difference indicates a gap between acceptance of the ESD concept and the ability to apply it concretely in learning.

This condition is an important finding in the study. Teachers may accept the importance of sustainable development education, but such acceptance does not automatically result in learning plans that explicitly contain sustainability-based objectives, activities, projects, and assessments. Research on elementary school teachers' perceptions of ESD emphasizes the importance of teachers' understanding of sustainability goals so that ESD principles can be translated into learning processes more concretely (Suhartini et al., 2025). Understanding ESD also needs to be directed toward developing student competencies rather than merely inserting environmental issues into subject matter. ESD should provide opportunities for students to understand problems, analyze their causes and impacts, consider alternative solutions, and take responsible action. In elementary education, literacy and numeracy competencies can also be developed alongside ESD principles so that sustainability learning does not stand alone but is integrated with other learning competencies (Umroh et al., 2023).

Ecosystem content has strong potential for ESD integration because its concepts are directly related to environmental balance, biodiversity, pollution, resource use, and human-environment relationships. Therefore, the 70% achievement in the ability to integrate ESD can be viewed as an area for development, particularly through the preparation of learning tools that provide concrete examples of how sustainability principles can be applied in IPAS learning. Teachers' Learning Practices and Pedagogical Readiness

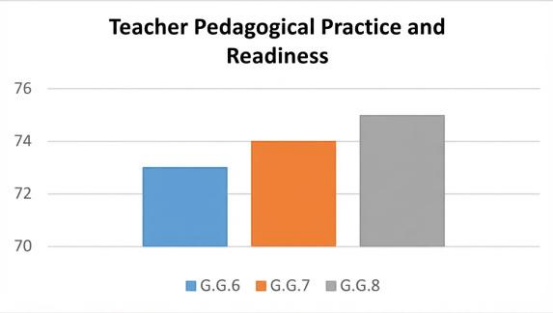

Figure 3. Percentage of Teacher Questionnaire Responses for 5 Indicators (Teachers' Teaching Method Practices)

Information:

K.G.6: Teachers use learning methods that encourage student collaboration.

K.G.7: Teachers apply a project-based approach in STEAM learning.

K.G.8: Teachers use a variety of approaches in IPAS learning.

The analysis of the third indicator showed an average percentage of 74% and was categorized as good. This result indicates that teachers have developed a habit of using various learning methods that have the potential to support STEAM implementation in IPAS learning. The lowest sub-indicator was the direct application of the STEAM approach in learning activities, at 73%. Meanwhile, the use of varied learning

approaches obtained the highest percentage, at 75%. These findings indicate that teachers already have experience using various learning approaches, but STEAM as an integrated approach has not yet become a fully consistent learning practice.

This condition demonstrates a relatively strong pedagogical foundation. Varied learning methods can provide a basis for teachers to develop project-based learning, experimentation, problem solving, and collaboration. Research by Fadhilah et al. (2024) shows that the STEAM approach in elementary science learning can integrate different learning areas through activities that encourage students to think and solve problems.

The use of project-based learning is also strongly aligned with the characteristics of STEAM. Projects allow students to encounter problems, design solutions, develop products, test results, and make improvements. In the context of this study, ecosystem content can be developed into simple projects related to environmental problems around the school, such as waste management, water utilization, reforestation, or biodiversity conservation.

Thus, the 74% achievement in learning practices indicates that teachers at SD Negeri 02 Api-Api have pedagogical potential to implement STEAM. However, this development needs to be directed so that the variety of methods already used by teachers does not merely represent activity variation, but instead forms a learning experience that integrates Science, Technology, Engineering, Arts, and Mathematics while simultaneously addressing sustainability goals. Student Engagement in Learning

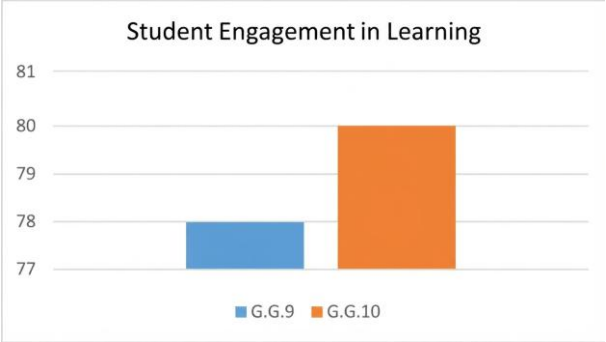

Figure 4. Percentage of Teacher Questionnaire Responses for 5 Indicators (Student Engagement)

Information:

K.G.9: Students show high motivation toward STEAM activities.

K.G.10: Students actively participate in discussions and projects.

The research results showed that student engagement obtained an average percentage of 79% and was categorized as good. This was one of the highest results among all research indicators. It indicates that students responded positively to learning activities involving activities, discussions, and projects.

The student motivation sub-indicator obtained 78%, while participation in discussions and projects reached 80%. The high level of participation in discussions and projects indicates that students have the potential to engage in active, collaborative, and contextual learning.

These findings are relevant to the characteristics of STEAM, which positions students as active subjects in the learning process. A systematic review of STEAM in elementary education indicates that STEAM implementation can provide students with opportunities for exploration, problem solving, collaboration, and the creation of products or solutions through the integration of various disciplines (Yim et al., 2024).

The research results of Küçük et al. (2023) also show that the implementation of a sustainability-oriented STEAM program among elementary school students had a positive effect on critical-thinking dispositions and academic achievement. These findings strengthen the view that STEAM can be developed not only as an

approach for increasing learning activity but also as a means of developing students' thinking and problem-solving abilities.

In ecosystem learning, high student engagement can be utilized through activities that originate from real-world problems. Students can be encouraged to observe environmental conditions around the school, identify ecosystem problems, collect simple data, discuss their causes and impacts, and then design solutions. Such activities allow STEAM and ESD elements to be implemented simultaneously.

Reflection and Evaluation as Support for STEAM ESD Implementation

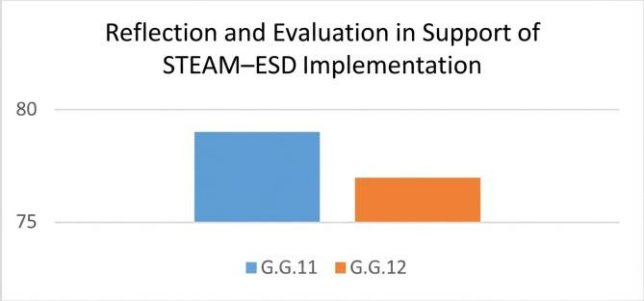

Figure 5. Percentage of Teacher Questionnaire Responses for 5 Indicators (Reflection and Evaluation)

Information:

K.G.11: Teachers reflect on the learning process that has been conducted.

K.G.12: Teachers evaluate students' learning motivation related to ESD (Education for Sustainable Development).

The fifth indicator showed that teacher reflection and evaluation obtained an average percentage of 78% and was categorized as good. This result demonstrates that teachers have developed a habit of reflecting on the learning process and paying attention to student motivation in sustainability-related learning.

The teacher reflection sub-indicator obtained 79%, while evaluation of students' learning motivation related to sustainable development obtained 77%. This difference indicates that general reflection on the learning process is relatively stronger than evaluation that specifically connects student motivation with ESD.

Reflection is important in STEAM ESD implementation because this approach requires a learning process that remains open to improvement. Teachers need to determine whether the activities provided truly enable students to integrate knowledge, solve problems, collaborate, and understand sustainability issues. Therefore, reflection is not only related to the success of delivering subject matter but also to the quality of students' learning experiences.

In this context, the findings indicate that teachers have a good foundation for continuously improving learning. However, reflection needs to be directed toward more specific indicators, such as student engagement, quality of collaboration, ability to generate solutions, understanding of environmental problems, and the ability to connect learning with real-world action.

Readiness of Teaching Modules for Integrating STEAM and ESD

In addition to teacher and student questionnaire data, this study used document analysis as supporting data to determine the extent to which STEAM and ESD characteristics were reflected in learning planning. The analysis was conducted on teaching-module documents used by teachers in ecosystem learning at SD Negeri 02 Api-Api, Wonokerto District, Pekalongan Regency.

No.	Observation Aspect	Total	Percentage
1	Teacher reflection notes on learning effectiveness are included in the teaching-module document.	1	33%

2	The teaching module includes various learning methods, such as projects, experiments, and problem-based learning.	2	67%
3	The teaching module includes activities that actively involve students, such as group projects or experiments.	1	33%
4	Teacher reflection notes concerning learning effectiveness are included in the teaching module.	2	67%
5	Teachers use feedback to improve the curriculum in the future, as stated in the teaching module.	2	67%

The document analysis results indicate that several characteristics supporting active learning are present in the teaching modules. Sixty-seven percent of the documents include various learning methods, such as projects, experiments, and problem-based learning. In addition, 67% of the documents show the presence of reflective notes and the use of feedback to improve learning.

However, activities explicitly demonstrating active student engagement were found in only 33% of the documents. This finding indicates a difference between teachers' perceptions or practices as captured through the questionnaire and their written reflection in the learning materials. This condition is important because teaching modules function as guidelines for translating learning objectives into concrete activities. STEAM learning requires planning that enables students to explore, design, experiment, evaluate, and improve solutions. Therefore, merely using terms such as "project" or "experiment" in a module is insufficient if the steps of student activities, resulting products, testing processes, and assessment formats are not systematically explained.

The most important finding was that explicit ESD integration in the teaching modules reached 0%. This means that although ecosystem content is strongly connected with environmental and sustainability issues, ESD principles have not been explicitly incorporated into the learning materials. This indicates a gap between the potential of the subject matter, teachers' understanding, and learning planning. This gap can become a major focus in developing ESD-oriented STEAM learning. Teaching modules should include sustainability-related objectives, environmental problem-solving activities, projects that produce solutions, and assessments that measure not only knowledge but also critical thinking, collaboration, creativity, and decision-making skills.

The development of ESD-based learning tools also needs to consider students' local context. Ecosystem learning at SD Negeri 02 Api-Api can be connected with environmental conditions surrounding the school so that students not only learn theoretical concepts but also understand the relationship between the material and real-world issues in their environment.

Based on the overall analysis, the implementation of ESD-oriented STEAM in ecosystem learning at SD Negeri 02 Api-Api has strong potential for development. This potential is demonstrated by several key findings: teacher understanding of STEAM was 73%, understanding of ESD was 72%, learning practices were 74%, student engagement was 79%, and reflection and evaluation were 78%. These results indicate that supporting factors for STEAM ESD implementation are already present, particularly in teacher understanding, the variety of learning methods, student engagement, and the habit of reflection. Student engagement reaching 79% is also an important asset because STEAM learning requires active participation through exploration, discussion, collaboration, and projects. However, the teaching-module analysis revealed a gap between teacher readiness and the learning reflected in the documents. Some characteristics of active learning have emerged, but explicit ESD integration remains at 0%. Therefore, the main issue is not solely the low potential of teachers or students, but rather the suboptimal translation of STEAM and ESD concepts into learning planning.

This gap is increasingly important because STEAM learning in elementary education should be designed as a learning experience that connects different disciplines with real-world problems. Systematic reviews indicate that STEAM implementation in elementary education has substantial potential to develop integrative, contextual, and 21st-century-skills-oriented learning (Yim et al., 2024). Ecosystem content is particularly suitable for development within this framework. Teachers can use environmental problems surrounding students as learning contexts and then integrate science, technology, engineering, arts, and mathematics to develop solutions. For example, students could identify waste problems, design simple waste bins, calculate the amount of waste generated, create environmental campaign designs or posters, and present the solutions they develop.

Thus, the application of ESD-oriented STEAM to ecosystem learning can be directed toward three main aspects. First, strengthening teacher competence, particularly in integrating STEAM and ESD into learning objectives and activities. Second, developing teaching modules by explicitly incorporating sustainability issues, projects, collaborative activities, and authentic assessment. Third, developing student activities that enable them to observe environmental problems, process information, design solutions, produce products, and reflect. Overall, this study shows that ESD-oriented STEAM has potential to be applied to ecosystem learning at SD Negeri 02 Api-Api, but its implementation still requires strengthening in the area of learning planning. The potential reflected in teacher understanding and student engagement needs to be translated into teaching modules and learning activities that explicitly integrate sustainability principles. Thus, ecosystem learning can move beyond conceptual mastery and also develop students' abilities to understand environmental problems, think critically, collaborate, design solutions, and take responsible action toward sustainability.

DISCUSSION

The findings demonstrate that the implementation of ESD-oriented STEAM in ecosystem learning has a strong foundation at SD Negeri 02 Api-Api. Teacher understanding of STEAM (73%), teacher understanding of ESD (72%), learning practices (74%), student engagement (79%), and reflection and evaluation (78%) were all categorized as good. These results suggest that the basic conditions required for implementation are present, particularly in teacher pedagogical readiness and student participation. The relatively high level of student engagement is particularly relevant. Participation in discussions and projects reached 80%, while student motivation reached 78%. This indicates that students have the potential to participate actively in learning activities involving collaboration, discussion, investigation, and project work. Such characteristics are consistent with the student-centered orientation of STEAM.

Nevertheless, the study identifies an important implementation gap. Teachers' acceptance and understanding of ESD do not yet correspond to explicit ESD integration in the teaching modules. Teachers' ability to integrate ESD was 70%, while explicit ESD integration in the analyzed modules was 0%. This difference suggests that conceptual understanding and positive attitudes toward sustainability have not yet been fully translated into written instructional planning. The discrepancy between questionnaire findings and document analysis is important for interpreting the overall results. Questionnaire data suggest relatively strong teacher readiness, whereas the teaching modules show limited explicit evidence of active student engagement and no explicit ESD integration. Therefore, strengthening implementation should focus not only on teacher awareness but also on practical capacity to translate STEAM ESD principles into objectives, learning steps, projects, assessments, and reflection.

Ecosystem learning provides a meaningful context for addressing this gap. Issues such as waste management, water use, biodiversity, environmental balance, and pollution can become authentic problems

through which students apply scientific knowledge and integrate technology, engineering, arts, and mathematics. Students can investigate a problem, collect data, design a solution, create a product, test it, present the results, and reflect on its sustainability implications. The findings therefore indicate that STEAM ESD implementation should be understood as an integrated learning process rather than simply the use of several teaching methods. The presence of projects or experiments in a teaching module does not by itself demonstrate full STEAM ESD implementation. The learning design should explicitly show how disciplines are integrated, how students participate in solving authentic problems, and how sustainability objectives are connected to assessment and reflection.

IMPLICATIONS

The findings have several implications for elementary education practice and the development of ESD-oriented STEAM learning. First, teacher professional development should emphasize practical integration rather than only conceptual introduction. Teachers need opportunities to develop sustainability-oriented learning objectives, design STEAM projects, formulate authentic problems, integrate multiple disciplines, and develop assessments that capture students' knowledge and sustainability-related competencies. Second, teaching-module development should become a major priority. Because explicit ESD integration in the analyzed modules was 0%, future modules should clearly include sustainability objectives, environmental problems, student-centered project activities, solution-design stages, assessment criteria, and reflection activities. Third, student engagement can be used as an important foundation for implementation. The 79% level of student engagement and 80% participation in discussions and projects suggest that students can be involved in more active and contextual learning experiences. Teachers can build on this potential through investigations, collaborative projects, experiments, environmental campaigns, and solution-design activities. Fourth, school-level environmental contexts can be incorporated into learning. Local environmental conditions can serve as authentic learning resources for ecosystem topics. This approach can help students connect classroom knowledge with problems in their surroundings and understand sustainability through direct experience. Fifth, reflection and assessment should be strengthened. Teachers should evaluate not only whether students understand ecosystem concepts but also their ability to collaborate, think critically, generate solutions, make decisions, and connect learning with responsible environmental action.

LIMITATIONS

This study has several limitations. First, the research was conducted in a specific school context, namely SD Negeri 02 Api-Api, Wonokerto District, Pekalongan Regency. Therefore, the findings describe the conditions identified in the research context and should not automatically be generalized to all elementary schools. Second, the study used teacher questionnaire data as an important source for examining teacher understanding, learning practices, and readiness. Questionnaire responses represent reported perceptions and may not fully capture actual classroom implementation. Third, document analysis was used as supporting evidence, but the available teaching-module data provide a limited representation of instructional practice. The finding that explicit ESD integration reached 0% describes the written learning plans that were analyzed; it does not by itself establish that no ESD-related ideas were ever discussed or practiced orally in the classroom. Fourth, this study primarily identifies the potential and readiness for ESD-oriented STEAM implementation. It does not provide a controlled measurement of the long-term effects of a fully implemented STEAM ESD intervention on student learning outcomes, critical thinking, environmental literacy, or sustainability behavior. Finally, the study focuses on ecosystem learning in one elementary-school context. The applicability of the findings to other science topics, schools, grade levels, or geographical contexts requires further investigation.

FUTURE RESEARCH

Future research should develop and test an ESD-oriented STEAM teaching module or learning model for ecosystem learning that directly addresses the implementation gap identified in this study. The development should translate the existing teacher readiness into explicit learning objectives, student activities, sustainability projects, assessment procedures, and reflection stages.

Future studies should also include classroom observations to compare teachers' reported practices with actual classroom implementation. Observation data can provide more direct evidence regarding how STEAM and ESD principles are enacted during learning. In addition, development research and quasi-experimental studies can be conducted to examine the effectiveness of ESD-oriented STEAM learning. Potential outcomes include students' critical thinking, problem-solving skills, creativity, collaboration, environmental literacy, sustainability awareness, and academic achievement. Further research should involve multiple elementary schools and larger participant groups with different school and environmental contexts. Such research can provide broader evidence regarding the applicability of the approach.

Future research can also examine the role of locally relevant environmental problems in strengthening students' sustainability competencies. Projects concerning waste, water, biodiversity, environmental conservation, or school gardens could be designed and evaluated as STEAM ESD learning contexts. Finally, longitudinal research is recommended to examine whether repeated implementation of ESD-oriented STEAM learning contributes to sustained changes in students' environmental awareness, attitudes, responsible behavior, problem-solving abilities, and capacity to apply sustainability principles in everyday life.

CONCLUSION

This study concludes that implementing Science, Technology, Engineering, Arts, and Mathematics (STEAM) learning oriented toward Education for Sustainable Development (ESD) on ecosystem topics holds considerable potential, supported by the strong initial readiness of teachers and students. Specifically, teachers demonstrated adequate understanding of STEAM (73%) and ESD (72%), alongside positive teaching practices (74%), high student engagement (79%), and effective reflection and evaluation (78%). However, the implication of these findings reveals a critical gap in instructional planning; while foundational readiness exists, current teaching modules lack optimal active STEAM activities and entirely miss explicit ESD integration. Therefore, systematically developing instructional modules that explicitly embed both STEAM characteristics and sustainability principles is essential to actualize this potential in the classroom. Despite these insights, the study has limitations, notably its small sample size, restricted geographical scope, and reliance on descriptive data, which prevent broader generalizations. Consequently, it is suggested that future research expand the participant pool and research locations, and advance beyond descriptive analysis by developing, implementing, and empirically testing STEAM-ESD instructional modules directly in classroom settings to measure their actual impact on student learning outcomes and sustainability awareness.

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