Development of an esd-based interactive e-module integrating local potential and steam for junior high school ecosystem learning

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Abstract
Education for Sustainable Development (ESD) has become an important approach in education to address sustainability challenges. However, junior high school students' sustainability literacy remains limited, particularly in connecting environmental issues with local contexts and sustainable practices. This study aims to develop and examine the preliminary effectiveness of an interactive E-Module based on Education for Sustainable Development (ESD), integrated with the local potential of Bali and a STEAM approach, on Ecosystem topics to enhance students' sustainability literacy. The study employed a Research and Development (R&D) method using a modified Thiagarajan model consisting of three stages: Define, Design, and Develop, due to the focus on product feasibility and limited-scale implementation. The findings showed that the interactive e-module met the criteria of feasibility and practicality based on construct, content, and media expert validation results. Practicality testing also indicated that the e-module could be implemented effectively in classroom learning. Furthermore, a limited effectiveness test using a pre-test/post-test control group design demonstrated that students in the experimental group achieved higher post-test sustainability literacy scores than those in the control group, indicating positive improvement after implementation. In conclusion, the interactive e-module is feasible and practical for classroom use and shows potential to improve junior high school students' sustainability literacy, although wider-scale implementation is required to further confirm its effectiveness.

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1. Introduction

Indonesia is currently striving to achieve its "Golden Indonesia 2045" vision by cultivating a golden generation capable of competing in the era of the Fourth Industrial Revolution (IR 4.0) (Baiquni et al., 2024). IR 4.0, characterized by rapid technological advancements including artificial intelligence, has triggered transformations across various societal sectors, notably industry, economy, lifestyle, and education. This revolution demands an education system that equips graduates with 21st-century skills encompassing the 4Cs: critical thinking and problem-solving, creativity, communication, and collaboration (Putri et al., 2022). This shift in competency requirements is fundamentally altering educational paradigms, moving beyond traditional rote learning. Should education fail to cultivate these skills, graduates will be inadequately prepared for future challenges. Consequently, the core of educational reform must transition from what students learn to how they learn, emphasizing active, engaging, and interdisciplinary methodologies.

Indonesia has charted a pathway for IR 4.0 educational reform through the adoption of Education for Sustainable Development (ESD) (Amran et al., 2020). ESD represents a concrete step aligned with the United Nations' Sustainable Development Goals (SDGs). The objective of the SDGs is to preserve planetary health and ensure universal human well-being amidst the rapid technological advancements of IR 4.0. The SDGs encompass 17 interconnected targets, including actions to eradicate poverty, strategies to improve health and education, reduce gender inequality, and spur economic growth while simultaneously addressing climate change and working to conserve oceans and forests (Cai & Wolff, 2023). Within the SDGs framework, ESD must become a priority for educational development both in Indonesia and globally.

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According to Hsiao and Su (2021) and Nurkhin et al (2025), ESD encompasses key factors that extend beyond general education, which traditionally focuses only on cognitive, affective, and psychomotor development. ESD also emphasizes broader competencies collectively referred to as sustainability literacy. Sustainability literacy constitutes a multidisciplinary knowledge base essential for students in the IR 4.0 era, including technological literacy, data literacy, scientific literacy, environmental awareness, and problem-solving skills (Haruna et al., 2023). In this study, sustainability literacy is operationalized through students' abilities to analyze ecosystem-related environmental problems, evaluate sustainable solutions based on local Balinese potential, and apply interdisciplinary knowledge within STEAM-based learning activities. This literacy is crucial for addressing complex IR 4.0 challenges that cannot be resolved through mastery of a single discipline. Therefore, a multidisciplinary learning approach is necessary to effectively empower students' sustainability literacy.

An interdisciplinary approach that synergistically combines 21st-century skills with K-12 students' sustainability literacy is STEAM (Science, Technology, Engineering, Arts, and Mathematics). The STEAM approach emphasizes holistic integration of these dimensions to solve real-world problems (Lu et al., 2022). Furthermore, integrating ESD with STEAM can maximize the development of 21st-century skills (Solihah et al., 2024). Research by Khoiri et al (2023) indicates that developing physics learning tools based on an ESD-integrated STEAM approach possesses characteristics deemed effective for enhancing student creativity and learning outcomes. Hsiao and Su (2021) also found that combining STEAM learning with Virtual Reality (VR) can help improve student satisfaction, learning outcomes, and motivation. However, student engagement in STEAM learning still faces obstacles, as students often struggle to comprehend issues related to the SDGs, necessitating a more contextual integration of ESD (Aguilera & Ortiz-Revilla, 2021).

Contextuality can be fostered by incorporating the unique local wisdom or advantages of a region, enabling students to better recognize and visualize concepts in a tangible manner (Rejekiningsih et al., 2021; Wahyudi et al., 2025). Research by Ramdayani et al (2021) successfully addressed issues of low student motivation by designing a handout teaching material based on local potential in the Lembah Hijau Rumba area. Indonesia, particularly Bali, offers numerous examples of local potential that can be integrated with ESD issues in learning. These include the coral reefs of South Bali, the Subak irrigation system in various agricultural regions of Bali, and the pristine environment of traditional villages like Panglipuran, which remains free from air pollution. This abundance of local potential presents a viable solution for developing school-based learning that integrates ESD with local potential through a STEAM approach.

Preliminary observations at a junior high school in Denpasar, Bali, revealed that science learning, while oriented towards ESD, has not been implemented optimally. Teachers introduce sustainable development by explaining ways to protect the environment within topics like environmental pollution and provide related contexts. Discussions with subject teachers indicated that the current learning approach is student-centered, predominantly utilizing methods such as discussion, varied lectures, and experiments. Field findings show that students have no prior experience with STEAM-based learning. Interview results confirmed that teachers' primary difficulty in implementing ESD with a STEAM approach is the lack of available teaching materials or modules to guide activities for both instructors and students. An analysis of the teaching materials used in the school revealed that textbooks and student worksheets (LKS) are not yet integrated with STEAM, ESD, or local wisdom. This deficiency can impede the development of students' sustainability literacy. Focused observations of student engagement in the classroom also indicated a tendency towards passivity, with approximately 40% of students appearing unfocused, lowering their heads, or conversing with peers. Therefore, a solution is needed to address the demand for an interactive e-module based on ESD, enriched with local potential, and employing a STEAM approach.

The development of such an interactive e-module for junior high school must be linked to essential subject matter appropriate for that educational level. One topic selected for the initial product development is Ecosystems. This topic was chosen due to its status as essential content in science education. The fundamental concept of mutual relationships between living organisms and their environment serves as a foundation for the goals of sustainable development, particularly in environmental sustainability. The topic of ecosystems relates directly to specific SDGs, namely Goal 13 (Climate Action), Goal 14 (Life Below Water), and Goal 15 (Life on Land). These can be woven into a unified teaching supplement that covers ecosystem and environmental concepts while empowering students' sustainability literacy. Thus, learning about ecosystems will not only develop students' conceptual mastery but also foster awareness and responsibility for environmental sustainability, positioning them as active global citizens contributing to the achievement of the SDGs.

Although previous studies have demonstrated the potential of ESD-based learning, STEAM integration, and digital teaching materials in improving students' learning outcomes, several limitations remain unresolved. Most prior studies have focused primarily on conceptual understanding or general environmental awareness, with limited emphasis on sustainability literacy as a multidimensional competency. In addition, the integration of local potential and cultural context into ESD-based digital learning resources for junior high school science learning is still rarely explored. Existing studies also tend to examine ESD, STEAM, or digital modules separately

rather than integrating these components into a single interactive learning resource. Therefore, this study seeks to address these gaps by developing an interactive ESD-based e-module integrated with Balinese local potential and a STEAM approach to enhance students' sustainability literacy. A summary of relevant prior studies and the identified gaps are presented in Table 1.

Table 1. State of the Art of thus Research

Author(S) by Year	Title	Research method	Key Findings
(Solihah et al., 2024)	Need Analysis of STEM-*ESD*-Based Development on Teaching Materials and Instrument Test	Qualitative Descriptive (needs survey, teacher and student interviews)	Identified a need for STEM-ESD-based Physics teaching materials tailored to student and teacher requirements to enhance critical thinking and problem-solving in high school students.
(Khoiri et al., 2023)	Integration of STEAM and ESD: Improving the understanding of fluid concepts and creativity	Research and Development (simplified Borg & Gall model into three steps)	Developed STEAM-integrated ESD Physics learning tools, characterized as effective for improving student creativity and learning outcomes.
(Debrah et al., 2021)	Raising Awareness on Solid Waste Management through Formal Education for Sustainability: A Developing Countries Evidence Review	Literature Review	Highlighted the effectiveness of raising sustainability awareness by integrating ESD into formal, extracurricular learning across various developing countries.
(Lu et al., 2022)	Evaluation of Disabled STEAM -Students' Education Learning Outcomes and Creativity under the UN Sustainable Development Goal: Project-Based Learning Oriented STEAM Curriculum with Micro: bit	Quasi-Experiment	Demonstrated that PBL-oriented teaching materials enable effective delivery of STEAM curricula to students with learning difficulties/special needs, achieving SDG4 targets.
(Hsiao & Su, 2021)	A Study on the Impact of STEAM Education for Sustainable Development Courses and Its Effects on Student Motivation and Learning	Quasi-Experiment	Found that combining STEAM learning with VR can improve student satisfaction, learning outcomes, and motivation. However, the proposed system requires ESD to be based on students' traditional culture to enhance self-efficacy through VR games.
(Solihah et al., 2024)	Prototype of Greenhouse Effect for Improving Problem Solving Skills in Science, Technology, Engineering, and Mathematics (STEM)-Education for Sustainable Development (*ESD*)	Quasi-experiment	STEM-ESD teaching materials successfully conveyed more information through media, stimulating student curiosity and interest in science subjects.

Based on this background and summary in Table 1, this study establishes its scholarly novelty by integrating four main components that have rarely been combined comprehensively in previous studies, namely ESD principles, Balinese local potential, a STEAM approach, and interactive digital learning features within a single e-module for junior high school ecosystem learning. It is imperative to conduct research aimed at developing an Interactive E-Module based on ESD, integrated with Local Potential, and employing a STEAM Approach for Junior High School Ecosystem topics, and testing its effectiveness on students' sustainability literacy. Unlike prior STEAM-ESD module studies that generally focus on conceptual understanding or environmental awareness, this study specifically operationalizes sustainability literacy through ecosystem problem analysis, evaluation of sustainable solutions, and interdisciplinary STEAM-based activities connected to Balinese local contexts. The aspect of interactivity, combined with digital teaching materials, will provide a more meaningful learning experience for K-12 students, who are digital natives (Putra & Pujani, 2024). Furthermore, the module is specifically designed for junior high school ecosystem topics under the theme "The Role of Science in Sustainable Development," integrating local environmental issues, cultural practices, and sustainability challenges relevant to students' daily lives. Consequently, this research is expected to contribute to improving the quality of learning by providing an empirically validated interactive learning resource that supports the development of students' sustainability literacy.

2. Method

This study employs the Research and Development (R&D) method, utilizing the 3D model as Define, Design, and Develop, which is a modification of Thiagarajan et al (1974) 4D model (Define, Design, and Develop, Disseminate) (Hidayat & Panggabean, 2022). The Disseminate stage from the original model was not implemented because this study focused primarily on product development, validation, practicality testing, and limited-scale effectiveness testing rather than large-scale distribution or adoption. In addition, the

research was conducted within the limited timeframe of the first year of the project, making it necessary to prioritize the development and evaluation stages. The Define stage involves gathering necessary information through needs assessment. The Design stage focuses on creating the initial product draft or learning tool prototype. The Develop stage encompasses the process of refining, validating, revising, and finalizing the product through expert judgment, feasibility testing, and limited-scale effectiveness testing on student' sustainability literacy. Although the dissemination process was not conducted in this study, the development procedures remained systematic and rigorous through iterative validation and revision processes to ensure the quality and feasibility of the product. Therefore, the dissemination process is planned to be continued in the second year through broader implementation and distribution activities.

The initial stage of this research is the information-gathering phase (Define), conducted through literature review and field studies. This is followed by the creation of the initial draft of the Interactive E-Module Based on ESD Integrated with Local Potential Using a STEAM Approach for Junior High School Ecosystem Topics. Subsequently, the development stage (Develop) involves expert validation of the product's content and context. The next stage is a limited-scale testing inoved a small sample of junior high school students in one school setting to assess the preliminary effectiveness of the developed e-module in empowering students' sustainability literacy. This effectiveness testing was conducted within a restricted implementation scope and was intended to provide initial evidence regarding the feasibility and potential effectiveness of the product before broader dissemination.

Data to test the effectiveness of the e-module were collected by implementing the developed product. The effectiveness testing was conducted at State Junior High School 3 Abiansemal, located in Denpasar, Bali. This location was selected based on discussions with the relevant subject teachers, taking into account diverse student characteristics and the school's location within a tourism area rich in local potential. Then, the class sample consisted of seventh-grade junior high school students (first semester), selected using random sampling. The effectiveness test employed a One-Group Pretest-Posttest Design. Data were collected using a sustainability literacy test administered before and after the learning intervention. The collected data were analyzed by first checking the prerequisite tests of normality and homogeneity. The normality test using Kolmogorov–Smirnov showed that the data were normally distributed (Sig. = 0.200 > 0.05), while the homogeneity test using Levene's Test indicated that the data were homogeneous (Sig. = 0.317 > 0.05). Therefore, a paired t-test was conducted to determine whether there was a statistically significant difference between students' pretest and posttest scores after the intervention. In addition, normalized gain (N-gain) analysis was employed to measure the magnitude of students' improvement in sustainability literacy after the intervention. Thus, the paired t-test was used to examine statistical significance, while the N-gain score was used to evaluate the level of learning improvement achieved by students. The normalized gain score <g> and its classification were calculated using this Equation 1:

$$g = \frac{Spost - Spre}{SM1 - Spre} \quad (1)$$

Description:
(g) = normalized gain score;
Spost = post-test score;
Spre = pre-test score;
SMI = ideal maximum score.
The normalized gain score is categorized into three levels: High = (g) > 0.7; Moderate = 0.7 ≥ (g) ≥ 0.3; and Low = (g) < 0.3. (Christman, et al., 2023).

At least, this development research was conducted over 5 month from June 2025 to October 2025. The first stage is planned, and the module was developed at Ganesha University of Education. Then, the product implementation for effectiveness testing was conducted in three phases: Pre-class, In-class, and Post-class. Before the pre-class phase, teachers administered a pre-test to obtain baseline data on students' sustainability literacy using a standardized test. Pre-class: Conducted before in-class learning sessions. Students were instructed to study the e-module independently, anytime and anywhere with a two-week period allocated for completion. Teachers provided access by sharing the interactive e-module via a link and QR code, which students could open on their personal laptops or mobile phones. To minimize variability in treatment exposure, teachers provided uniform learning instructions, predetermined study duration guidelines, and a structured learning schedule for all students during the independent learning phase. Student engagement was also monitored through learning activity checklists, progress reports, and online classroom to follow-up discussions regarding the content studied independently. Teachers provided access by sharing the interactive e-module via a link and QR code, which students could open on their personal laptops or mobile phones. In-class: Conducted in the classroom with the teacher acting as a facilitator. Teachers guided students in exploring each interactive component of the e-module in greater depth and assisted with any difficulties encountered. This phase concluded with the teacher guiding students to undertake a STEAM Project outlined within the e-module, to be completed at home. Post-class: In this phase, teachers monitored the at-home projects by having students

submit evidence of their activities (e.g., photos, videos). Teachers also provided feedback and monitored the consistency of student participation throughout the project activities. Project outcomes were refined in subsequent meetings, scheduled according to the school's co-curricular timetable. Following the completion of all phases, students were given a post-test on sustainability literacy.

3. Results and Discussion

3.1. Validity and Feasibility of the ESD-Based Interactive E-Module

The validity of the research product was assessed using a questionnaire distributed alongside the completed initial draft of the module. The validity test involved three expert validators selected purposively based on their academic qualifications, expertise, and professional experience relevant to the evaluated aspects of the product. The validation covered three key aspects: content/material validity, construct validity, and media design validity. The material/content validator was a professor in the field of environmental science and sustainability education, selected to assess the accuracy, relevance, and appropriateness of the ecosystem and ESD content. The construct validator was a lecturer in the Science Education Study Program with expertise in curriculum and science learning design, responsible for evaluating the suitability of the learning structure, learning objectives, and STEAM integration. Meanwhile, the media validator was a lecturer who teaches instructional media and educational technology courses, selected to evaluate the interactivity, visual design, usability, and technical quality of the e-module. Although the number of validators was limited, each validator represented a distinct area of expertise closely aligned with the specific validation aspect, theregby strengthening the rigor and credibility of the validation process. The complete results of the validity test are presented in Table 2.

Table 2. Expert Validity Test Summary

Aspect	Score	Description
Content	92.14	Highly Valid
Construct	97.05	Highly Valid
Media	73.35	Valid

The conclusion is guided by a modified version of Arikunto's Criterion-Referenced Assessment. Based on the results of the expert validity test for the Interactive E-Module based on Education for Sustainable Development (ESD), integrated with local potential using a STEAM approach on Ecosystem material, scores were obtained across three assessment aspects: content, construct, and media.

The content aspect received a score of 92.14, categorized as highly valid. This indicates that the material presented in the e-module aligns with the basic competencies and learning indicators and is relevant to the context of Education for Sustainable Development and the integration of Bali's local potential. Furthermore, the content was assessed as accurate, up-to-date, and capable of supporting the achievement of learning objectives. The construct aspect received a score of 97.05, also categorized as highly valid. This result confirms that the structure of the e-modul adheres to pedagogical principles, is systematic, and follows the guidelines for developing STEAM-based teaching materials. The flow of material presentation, the completeness of learning components, and the interconnections between module sections were rated as excellent. The media aspect received a score of 73.35, categorized as valid. This means that the e-module's layout and design are sufficiently feasible for use, although there are still some technical aspects that could be improved, such as interactivity, media variety, or visual aesthetics, to make it more engaging for students. Overall, this interactive e-module is deemed feasible and highly valid for use in ecosystem learning based on a STEAM approach, integrating Bali's local potential within the Education for Sustainable Development framework. Table 3 shown a feasibility test summary.

Table 3. Feasibility Test Summary

Aspect	Average Score	Description
Content Clarity	95.36	Highly Practical
Layout and Design	88.89	Highly Practical
Language Clarity	90.00	Highly Practical
Ease of Use	92.14	Highly Practical
Overall	91.59	Highly Practical

Based on the data in Table 3, the results of the practicality test for the interactive e-modul product show excellent scores from practitioners. The overall average score reached 91.59, with the predicate "Highly Practical". In detail, each tested aspect also received high ratings. The Content Clarity aspect obtained the highest score of 95.36, indicating that the presented material is easily understandable. Meanwhile, the Ease of Use and Language Clarity aspects were also rated highly, with scores of 92.14 and 90.00, respectively. The Layout and

Design aspect received a score of 88.89, which also falls into the "Highly Practical" category. In addition, observations during the classroom implementation indicated that students were able to access, navigate, and use the interactive features of the e-module with minimal technical difficulties. Students also demonstrated active participation during independent and classroom-based learning activities, suggesting positive usability experiences.

The findings also demonstrate differences compared to several previous studies on e-module implementation. Earlier studies frequently reported that students tended to show low engagement when using e-modules due to various limitations, such as text-dominated content, minimal interactive features, and fragmented access to supporting materials where videos or quizzes could only be accessed through external links. These conditions often made the learning process less practical and reduced students' motivation and enthusiasm during independent learning activities (Sintawati & Margunayasa, 2024; Rochsun & Agustin, 2020). In contrast, student responses and observations during this study indicated that the developed interactive e-module possessed characteristics that better supported student engagement and usability. The product was designed with attractive visual layouts, interactive games, integrated quizzes, STEAM project, clear language, contextual illustrations with local potencial integrated, and embedded multimedia features that could be accessed directly within the module without requiring external links. In addition, students were able to monitor their own learning progress through a progress-tracking feature provided on the final pages of the e-module, enabling them to reflect on and evaluate their learning outcomes independently.

Overall, these findings indicate that the e-module is feasible and user-friendly in terms of content, language, layout, and usability. These findings suggest that the effectiveness and practicality of e-modules are strongly influenced not only by content quality but also by the design characteristics that support user interaction, accessibility, and student engagement. So, the discussion regarding the characteristics of this ESD-Based Interactive E-Module is important to better understand how digital teaching materials can effectively support sustainability literacy learning in junior high school contexts.

3.2. Characteristics of the ESD-Based Interactive E-Module

3.2.1. Introductory Pages

The introductory section of the ESD-based interactive e-module consists of several key pages: Cover Page: The cover design incorporates elements of Balinese local potential, featuring illustrations of a subak (traditional irrigation system) and a temple (pura). This aligns with the module's primary objective of integrating ESD with Balinese local context., Orientation Page: This page contains an illustration and a reflective question, such as "What might happen to Bali in the future if development continues without considering sustainability?" This prompt is designed to spark students' curiosity and motivate them to explore the core concepts of sustainability. Learning Objectives Page: This section outlines the various competencies students are expected to achieve. The objectives extend beyond conceptual mastery to explicitly include the development of sustainability literacy. Prior Knowledge Page: Here, students engage with interactive content in the form of a mini-game titled "Subak Ecosystem." This activity helps activate students' prior knowledge, preparing them for more in-depth learning. E-Module Features Page: This part explains all navigation buttons within the e-module, facilitating ease of use and helping students operate each feature and activity. Finally, a table of contents located on the side panel allows students to navigate easily between different pages. Design and Pedagogical Rationale: In these introductory pages, considerations for media feasibility are well accommodated. This is evidenced by the use of engaging and content-appropriate imagery, readable typography, and the inclusion of interactive game-based activities designed to foster student engagement and active participation. This approach aligns with prior research on Game-Based Learning implementation, which emphasizes that engaging students at the onset of learning is crucial for the success of the overall process (Izat et al., 2025). A visual example of the introductory pages from the ESD-Based Interactive E-Module is provided in Figure 1.

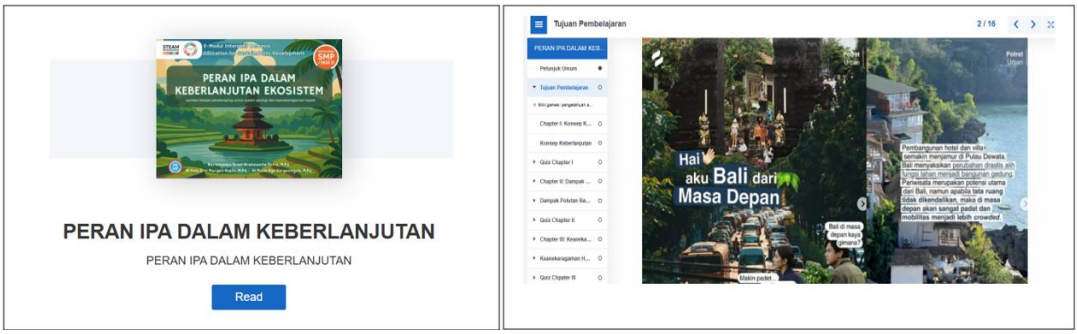

Figure 1. Introductory pages

Figure 1 presents the introductory pages of the ESD-Based Interactive E-Module developed in this study. These introductory pages were designed to provide students with an initial overview of the learning theme, contextualize sustainability issues, and stimulate students' curiosity before entering the main learning activities. The left side of the figure displays the opening cover page of the e-module entitled "Peran IPA dalam Keberlanjutan Ekosistem" (The Role of Science in Ecosystem Sustainability). This page functions as the entry point of the learning process and was designed using attractive visual elements and contextual ecosystem illustrations to increase students' motivation and readiness for learning. The design also reflects the integration of environmental and sustainability themes relevant to the ecosystem topic. Meanwhile, the right side of the figure shows one of the introductory learning pages containing contextual visual narratives related to Bali's environmental and socio-cultural conditions. This section introduces students to real-world sustainability issues connected to local potential and environmental challenges, thereby supporting the contextual implementation of Education for Sustainable Development (ESD). The use of authentic local imagery and storytelling was intended to help students connect scientific concepts with their surrounding environment and daily experiences.

3.2.2. Orientation Page (Get Ready!)

The innovative feature of the ESD-based e-module on this material orientation page distinguishes it from conventional teaching supplements. The purpose of the material orientation page is to prepare students to construct their knowledge through a pop-up button system. This system provides content such as articles, videos, and mini-games that students can interact with. This feature serves as an effective advance organizer for integrating Balinese local potential into the presented material. Students can click on the interactive buttons to access various information, including news, photos, and videos highlighting Balinese local potential. Examples of local potential content available via the pop-up buttons include: The Subak system as a model of a sustainable ecosystem; The Tumpek Wariga cultural philosophy emphasizing flora conservation; Coverage of waste management innovations on the island of Bali. Thus, this ESD-based interactive e-module can directly integrate ESD principles into the students' life context. This statement is supported by research from Chang et al (2024), which found that contextualizing material through such local wisdom not only increases learning relevance but also builds student engagement with the subject matter, as they directly observe the application of abstract sustainability concepts within their own culture.

The material orientation page, titled "Get Ready!" in this ESD-based e-module, also fulfills the multimedia interactivity principle. The presence of pop-up buttons displaying various information formats grants students learner control, allowing them to explore the material based on their interests. This creates a personalized and active learning experience. Research by Clanton (2024) confirms that interactive elements in e-modules significantly increase student engagement and intrinsic motivation. Therefore, it can be concluded that the e-module design, which prioritizes interactivity and contextual media presentation in this orientation phase, has successfully created high engagement from the outset. The impact is that students enter the core material with a strong foundation of contextual knowledge and sustained motivation, which ultimately contributes substantially to optimizing the overall module implementation and fosters an increase in sustainability literacy. A visual example of the Material Orientation Page from the ESD-Based Interactive E-Module is provided in Figure 2.

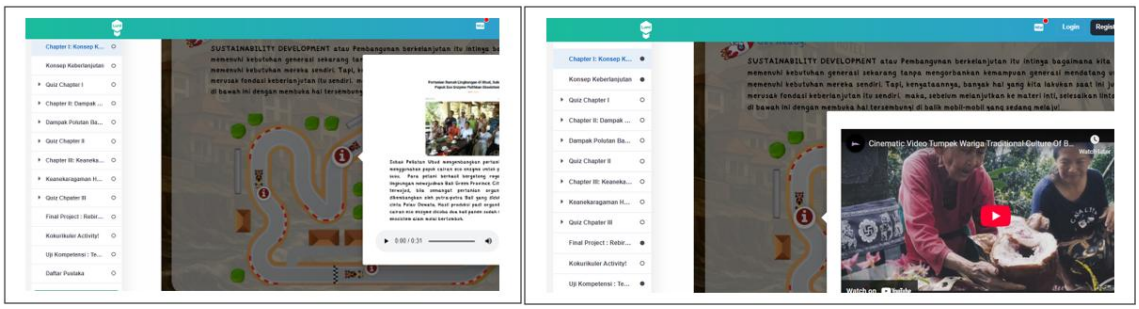

Figure 2. Orientation Page

Figure 2 presents the Orientation Page of the ESD-Based Interactive E-Module, which serves as the introductory section for students before entering the main learning activities. This page was designed to provide contextual stimulation and increase students' initial engagement with sustainability-related issues. As shown in the figure, the page integrates multimedia elements such as visual illustrations, structured navigation menus, and embedded videos that can be accessed directly within the e-module interface without requiring external links. The left display illustrates the main orientation interface, where students are introduced to ecosystem and sustainability concepts through contextual narratives and interactive visual layouts. Meanwhile, the right display shows the integration of embedded video content used to support students' conceptual understanding through audiovisual explanations related to environmental issues and local sustainability practices. The direct

integration of videos within the module was intentionally designed to reduce technical barriers commonly encountered in conventional e-modules, where students must open external platforms separately.

In addition, the structured side navigation menu allows students to access learning sections systematically and monitor their learning progression more easily. The combination of multimedia features, contextual content, and interactive navigation on this page reflects the implementation of multimedia and interactivity principles aimed at increasing student engagement and supporting sustainability literacy learning in a more meaningful and accessible manner.

3.2.3. Interactive Content Page

The ESD-Based Interactive E-Module presents ecosystem learning materials in a style distinct from conventional teaching supplements. The content is delivered in a more interactive manner and incorporates environmental conservation themes as an implementation of Education for Sustainable Development. The interactive presentation of the material can be seen in Figure 3.

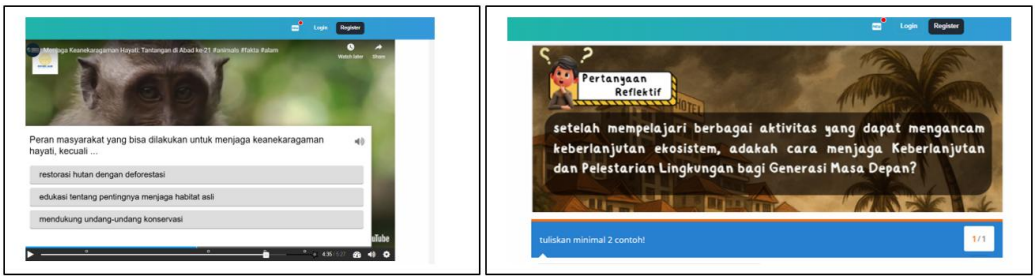

Figure 3. Interactive Content features

Figure 3. Interactive Content features illustrates how content on biodiversity and the importance of its conservation is presented via an interactive video. As students watch the video, multiple-choice quiz pop-ups appear at key moments, which students can answer directly. This feature fosters greater student activity and focus while engaging with the instructional video. Furthermore, at the end of the content section, reflective questions are provided to help students monitor their understanding of the material. These questions also aid in empowering students' sustainability literacy, as they are trained to answer applied, problem-solving questions. Consequently, their comprehension of each topic extends beyond mere concepts, enabling them to master various dimensions of sustainability literacy, such as methods for environmental conservation, policy evaluation, and other practical applications.

3.2.4. The STEAM Activity page (STEAM Activity!)

The "STEAM Activity!" page in the ESD-based module represents the implementation of the STEAM approach through structured activities within the e-module. The integration of STEAM dimensions in each activity was designed to support the development of students' sustainability literacy, as reflected in the improvement of post-test scores and positive student engagement observed during implementation. Problem Orientation Activities encourage students to identify sustainability issues in their immediate environment, such as imbalances in food chains or pollution, thereby building contextual awareness as a foundation for sustainability literacy (Baena-Morales et al., 2023).

During classroom implementation, students actively discussed local environmental problems and proposed contextual solutions, indicating increased participation in sustainability-related inquiry activities. Virtual Lab Simulations train students to manipulate variables to detect characteristics of polluted water. The simulations in this e-module serve as a tool for understanding pollution concepts, providing an engaging, technology-enhanced basis for advancing sustainability literacy. Observational findings showed that students were able to interact independently with the simulations and demonstrated greater interest in exploring ecosystem pollution concepts compared to conventional learning activities.

Arts and Mathematics Dimensions are expressed through activities like creating infographics and calculating energy transfer in food chains. The infographic feature aims to raise awareness about biodiversity conservation, fulfilling the arts dimension while simultaneously strengthening science communication skills, a key component of sustainability literacy (Shivni et al., 2021). Students' infographic products demonstrated their ability to communicate ecosystem and biodiversity conservation issues visually and contextually, which aligns with sustainability literacy competencies related to scientific communication. The energy transfer calculations integrate mathematics, prompting students to analyze energy efficiency within food chains and fostering quantitative thinking about the impacts of ecosystem imbalances. The STEAM activity page on this e-module presented at Figure 4.

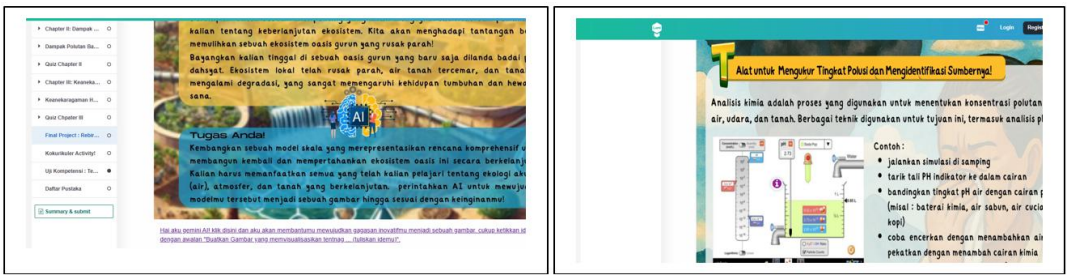

Figure 4. STEAM Activity Page

Figure 4 also shown that the Culminating Feature of this e-module is an AI menu that allows students to materialize their solution ideas such as designing eco-friendly technology or visualizing an ideal ecosystem into visual representations. This use of AI as a creative tool demonstrates the application of cutting-edge technology to build students' agency and confidence in creating solutions for a sustainable future (Melnyk & Pypenko, 2025). Student responses during implementation indicated that this feature increased their enthusiasm and creativity in expressing sustainability-related ideas. However, the present study only provides preliminary evidence based on classroom observations and learning outcomes, and does not specifically measure each competency dimension separately. Therefore, further studies are needed to examine the contribution of each interactive feature toward specific sustainability literacy competencies in greater depth.

3.2.5. Evaluation Page

The Evaluation Page in the e-module functions as a metacognitive instrument that fosters the development of students' self-regulation. On this page, students can independently monitor and reflect on their learning process, the challenges encountered, and the simulated impact of their actions on ecosystem balance. This structured documentation and reflection activity requires students to plan, monitor, and evaluate their own understanding and learning strategies, which is a key characteristic of self-regulated learning (Jdaitawi, 2019). The self-regulated learning process inherent in this page represents the internalization of students' awareness to evaluate situations, including their environmental sustainability context. Figure 5 shown a evaluation page.

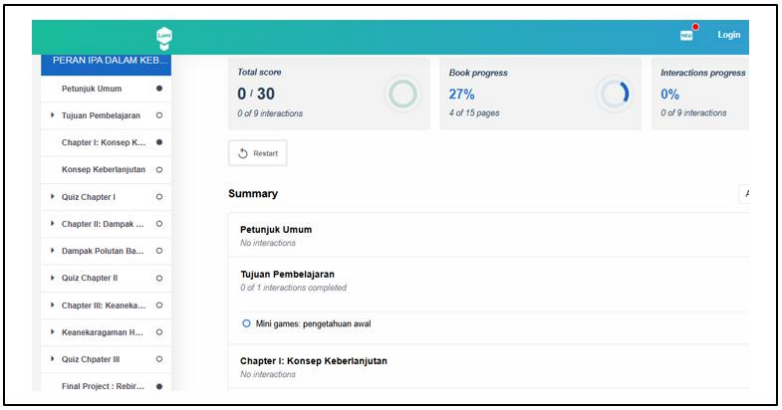

Figure 5. Evaluation Page

Figure 5 presents the Evaluation Page of the ESD-Based Interactive E-Module. This page was specifically designed to help students monitor and reflect on their learning progress after completing the learning activities within the module. The evaluation page displays several indicators, including learning duration, quiz scores, assignment completion status, and overall learning progress percentage. The presence of this feature supports students' self-regulated learning by enabling them to independently evaluate their achievement and identify learning components that still need improvement. In addition, the structured summary section provides students with clear feedback regarding their participation and performance throughout the learning process. This characteristic differentiates the developed e-module from many conventional e-modules that generally function only as reading materials without providing integrated progress-monitoring features.

3.3. Effectiveness of the ESD-Based Interactive E-Module on Students' Sustainability Literacy

The final stage of this research was a limited trial of the module, focusing on its effectiveness in improving students' sustainability literacy. Data on sustainability literacy scores were obtained using a sustainability literacy test administered to students before and after the intervention. The collected data were analyzed using IBM SPSS Statistics version 26. The analysis began with prerequisite assumption testing, including the

Kolmogorov–Smirnov normality test and Levene's homogeneity test, to ensure the suitability of parametric analysis. The results indicated that the data were normally distributed and homogeneous (Sig. > 0.05). Subsequently, descriptive statistical analysis and a paired t-test were conducted to determine the significance of differences between pretest and posttest scores. In addition, standardized N-Gain analysis was employed to measure the magnitude of improvement in students' sustainability literacy after the intervention. These analyses served as the basis for drawing conclusions regarding the preliminary effectiveness of the developed ESD-based interactive e-module,

The results of the data analysis by paired t-test were conducted to determine the significance of differences between pre-post sustainability literacy scores are presented in Table 4.

Table 4. Paired Samples Test Results of Sustainability Literacy Scores

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	pre - post	-22.32812	5.51205	.68901	-23.70499	-20.95126	-32.406	63	.000

Based on the paired samples t-test results, the significance value obtained was 0.000 ($p < 0.05$), indicating a statistically significant difference between students' pre-test and post-test sustainability literacy scores after the implementation of the ESD-based interactive e-module. These findings suggest that the learning intervention using the developed e-module contributed to an improvement in students' sustainability literacy. Therefore, further analysis using the normalized gain (N-Gain) score was conducted to measure the level of improvement in students' sustainability literacy after the intervention. The N-Gain analysis result are presented in Table 5.

Table 5. N-Gain Effectiveness Test Result

Sustainability literacy	N	Mean	Std.Dev	<g>	Category.
Pretest	64	62.09	0.11	0.58	Moderate
Postest	64	84.42	11.78		

Based on the data analysis in Table 5, the ESD-based interactive e-module integrated with local potential using a STEAM approach demonstrated potential in improving students' sustainability literacy within the limited implementation context of this study. This is evidenced by a medium increase in the mean score from 62.09 (pre-test) to 84.42 (post-test) in the sample class of 64 students. Further analysis using the standardized N-Gain score yielded a value of 0.58. Therefore, the improvement in students' sustainability literacy after using the developed ESD-based e-module can be categorized as moderate. These findings suggest that the combination of the STEAM approach, which emphasizes applied and creative learning experiences, together with the contextualization of material through local potential, may support students in sustainability literacy more meaningfully. However, given that the N-Gain result falls within the moderate category and the study was conducted on a limited scale, broader implementation and further investigation are still required to confirm the consistency of these outcomes.

The finding that the implementation effectiveness remains in the moderate category (<g> = 0.58) is attributed to two main factors: (1) the relatively short duration of the module implementation, and (2) the limited scope of the subject matter. Building comprehensive sustainability literacy requires a continuous process of internalizing values, which cannot be achieved instantly through a single essential unit of material (Olsson et al., 2022). Time constraints limited students' opportunities to reflect, discuss, and deeply apply ecosystem stability concepts to broader contexts. Consequently, the internalization of sustainability values has not yet reached an optimal level.

The improvement in students' sustainability literacy can be attributed to the key features and components integrated into this interactive e-module:

a. Fundamental ESD Integration: The integration of ESD fundamentally directs learning content toward interconnected social, environmental, and economic issues. The e-module is designed not only to convey conceptual knowledge but also to instill awareness and proactive attitudes in students to address global challenges.

b. Contextualization through Local Potential: The utilization of local potential, such as the Subak irrigation system, the Tumpek Wariga cultural philosophy, and various examples of waste management initiatives in Bali, made the learning context more contextual and concrete for students. By using examples from their

immediate environment, students could easily relate global concepts to their lived reality, leading to a deeper and more meaningful understanding of the role of science in ecosystem sustainability.

c. Integrated STEAM Approach: The STEAM approach, integrated as STEAM Activities within the e-module, was a supporting factor in improving sustainability literacy. For example, the "*Agent Palawan Sampah*" (Waste Warrior Agent) STEAM project was conducted enthusiastically by students, resulting in highly diverse recycled products with artistic and economic value. This reinforces prior research by Hsiao and Su (2021), stating that the STEAM approach encourages students to think holistically and apply knowledge from various disciplines. Through activities involving problem-solving (Engineering), data analysis (Science), and creative expression (Arts), the e-module effectively trains students' critical thinking and innovation skills, which are central to sustainability literacy.

d. Interactive Features: The fulfillment of interactivity in the characteristics of this ESD-based e-module optimally enhanced student engagement. Features such as simulations, quizzes, and audiovisual media made the learning process more engaging and facilitated self-directed learning, ultimately strengthening information retention and content mastery.

Therefore, the development of this ESD-based interactive e-module is expected to be expanded by integrating ESD principles into various other essential topics within the curriculum. For instance, material on the circulatory system could be linked to SDG 3 (Good Health and Well-being) by discussing the impact of environmental pollution on human health. Similarly, genetics topics could be connected to principles of biodiversity and conservation as main pillars of biosphere sustainability. Research by Ferguson et al (2022) shows that a cross-curricular and sustained approach to integrating ESD is effective in instilling long-term environmental awareness. Thus, replicating and adapting the design of this interactive ESD-based e-module integrating local potential with a STEAM approach across various other topics can create repeated and consistent exposure, which in turn can strengthen the development of a sustainability mindset in learners.

The successful integration of Local Potential in this Interactive E-Module is demonstrated by the increased student engagement and contextual understanding of sustainability concepts. Integrating sustainability concepts with tangible examples from students' immediate environment, such as the Subak system as a model of sustainable water resource management and the values of Tumpek Wariga in conservation, created meaningful contextualization for students. The link between this active engagement and the improvement in sustainability literacy is supported by research from Debrah et al (2021), which confirms that contextualizing material through local wisdom significantly enhances learning motivation and knowledge retention in this case, understanding environmental sustainability. Consequently, the integration of local potential not only serves as a learning context but also successfully acts as an effective bridge to transform conceptual knowledge into applicable awareness and concern for sustainability issues.

4. Conclusion

The ESD-based Interactive E-Module, integrated with local potential and employing a STEAM approach for ecosystem topics, has been assessed as highly valid in terms of content and construct, and valid in terms of media design based on expert validation results. However, the validation process involved a limited number of expert validators, so the findings should be interpreted within the scope of expert-based evaluation. The feasibility test, which was primarily based on practitioner perceptions and supported by limited classroom observations as showed that indicates that the product is highly practical for classroom use within the context of this study. Students were generally able to access and operate the e-module independently using their personal devices with minimal technical assistance from the teacher, actively engaged with interactive features. The e-module's characteristics include features that fulfill principles of multimedia and interactivity, while incorporating local potential and STEAM-based activities. Furthermore, the implementation results indicate that the interactive e-module has the potential to improve students' sustainability literacy, with the level of improvement categorized as moderate based on the N-Gain analysis.

This study supports the theoretical perspective that integrating the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach with Education for Sustainable Development (ESD) and local potential may contribute positively to sustainability literacy development. The developed ESD-Based Interactive E-Module Integrating Local Potential and STEAM may provide as an innovative teaching material to assist teachers in delivering sustainability literacy interactively and contextually. Nevertheless, broader-scale implementation and further studies involving more diverse participants and classroom settings are needed to strengthen the generalizability of the findings.

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The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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