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Integrating Education for Sustainable Development into Ecology Learning: Developing a Multimodal E-Book to Enhance Students' Scientific Literacy

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Abstract: The advancement of digital technology has driven innovation in learning resources, including the use of e-books as supportive media in science education. In the context of ecology learning at the junior secondary level, instructional materials are needed that not only present fundamental concepts but also cultivate scientific literacy and sustainability awareness. This study aimed to develop an ecology e-book grounded in the Education for Sustainable Development framework and to examine its feasibility and effectiveness in enhancing students' scientific literacy. The research employed a Research and Development approach using the ADDIE model, comprising need analysis, design, development, implementation, and evaluation. The e-book was validated by two material experts, two media experts, and twenty science teachers. Validation results showed a very high level of feasibility, with material experts awarding an average score of 96.3 percent and media experts 95.3 percent, supported by a CVI of 0.95 and a CVR of 0.93, indicating strong content validity. During implementation, the e-book's effectiveness was tested using a quasi-experimental design with 35 students in the experimental class and 27 in the control class. The analysis revealed a moderate improvement in students' scientific literacy, with an N-gain of 0.43, while the control class achieved an N-gain of 0.20. Gains were evident in knowledge and competency, particularly in understanding scientific phenomena and epistemic reasoning. The distribution of scores in the experimental class also became more homogeneous, suggesting more even conceptual understanding. Statistical tests confirmed significant differences between the two groups, strengthening the evidence of the e-book's impact. Students' responses averaged 81 percent in the very good category, covering content, language, visuals, and usefulness. These findings indicate that the ESD-based ecology e-book is feasible and effective for improving scientific literacy among junior secondary students.

Keywords: e-book, ecology, education for sustainable development, scientific literacy.

▪ INTRODUCTION

Ecology content is not merely about delivering concepts; it serves as a bridge between scientific ideas and real-world contexts. Learning in ecology requires integrating concepts, values, and actions to cultivate a deeper understanding of environmental issues (Kumar et al., 2024). At the same time, scientific literacy demands that students be able to explain phenomena scientifically, interpret data, and use evidence to make informed decisions about environmental problems. Therefore, strengthening scientific literacy in ecology instruction is essential to ensure that students not only understand ecological concepts but also can apply this knowledge to address real environmental challenges.

Data obtained from the Programme for International Student Assessment (PISA) indicate that Indonesia remains below the international average. The low level of students' scientific literacy is evidenced by the 2022 PISA results, in which Indonesia scored 383, significantly lower than Singapore's score of 561(OECD, 2023a). In the 21st century, scientific literacy plays a crucial role in developing high-quality human resources

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equipped with strong knowledge and technological competence, enabling them to compete effectively in the global era (Hartono et al., 2023; Suryanti et al., 2021). The opportunity to enhance students' understanding and skills in science requires more intensive and well-directed educational efforts. The development of scientific literacy is influenced by several factors, including the teaching materials teachers use to support concept learning. Efforts to improve scientific literacy can be integrated through the Education for Sustainable Development (ESD) approach, which aligns with the demands of 21st-century learning.

At present, Education for Sustainable Development (ESD) plays a vital role in fostering a society (Arya et al., 2024) that is aware of global challenges and capable of taking proactive actions toward a more sustainable future. ESD also enhances students' scientific literacy, enabling them to make evidence-based decisions about environmental issues. It not only focuses on academic aspects but also cultivates students' character to become responsible citizens committed to environmental stewardship and sustainable education. The primary goal of ESD is to equip students with sustainability competencies through comprehensive, interdisciplinary approaches and a range of student-centered learning methods (Rachman et al., 2024).

The advancement of digital technology has driven the emergence of various learning innovations, including the use of e-books as an alternative instructional material. Several efforts have been made to develop teaching materials aimed at improving students' scientific literacy, such as interactive multimedia (Pratama et al., 2023), STEAM-based student worksheets (Afrijal et al., 2023), E-LITE'S teaching materials (Firdaus et al., 2020), e-modules on colloid topics (Silaban et al., 2022), integrated science–physics textbooks (Fayanto et al., 2023), and marine context–based learning materials (Pursitasari et al., 2019). However, these materials have not yet adequately enabled students to develop sustainable problem-solving abilities, understand the impact of human actions on the environment, and recognize the importance of maintaining ecological balance. Previous learning materials, such as interactive multimedia, STEAM-based worksheets, or conventional modules, have a major limitation: they do not explicitly integrate ESD competencies into the ecological context. The developed e-book addresses this limitation through several concrete features that are evident throughout its content. The topic of ecology encompasses descriptive, procedural, and applied knowledge, which encourages students to inquire and take action (Larassati & Rachmadiarti, 2021).

The developed ecology e-book introduces several instructional innovations rarely found in standard middle-school ecology textbooks. It begins with an issue-based approach that integrates global, national, and school-level environmental problems to build a strong contextual understanding. The content embeds scientific literacy through stimulus-based questions, data analysis, inquiry activities, and multimodal resources such as videos to support independent and flipped learning. It also integrates Education for Sustainable Development by presenting practical sustainability actions and emphasizing real-world application. Combined with place-based examples from the school environment, this design produces a more contextual, inquiry-oriented, and action-focused learning experience than conventional ecology texts.

The role of e-books in ecology learning is to provide easily accessible learning resources that enable students to study ecology independently anytime, anywhere. E-

books support ecological education by providing automated, interconnected learning materials, facilitating access to diverse information, and promoting interdisciplinary learning approaches. This digital format also enhances communication and provides students with greater autonomy, making the learning experience more meaningful. Furthermore, e-books improve accessibility and information retrieval while fostering greater enthusiasm and awareness of sustainability issues among students (Sihombing et al., 2024). Therefore, the purpose of this study is to develop an ecology e-book based on the ESD framework to enhance students' scientific literacy. The research problem was further articulated into the following questions: (1) How feasible is the ecology e-book developed using the Education for Sustainable Development (ESD) framework for enhancing students' science literacy? How does students' science literacy improve after using the ecology e-book based on the Education for Sustainable Development (ESD) framework?

▪ METHOD

Participants

This study was conducted at a junior high school in Bogor, West Java, Indonesia. The sample consisted of 35 students in the experimental class and 27 in the control class. These classes were selected because their academic ability was relatively comparable. Before conducting the mean difference test, a homogeneity of variance test (Levene's test) was performed to ensure that the assumptions required for the t-test were satisfied.

Research Design and Procedures

This study employed a Research and Development (R&D) approach using the ADDIE model (Analyze, Design, Development, Implementation, and Evaluation). The analysis stage involved identifying the need to develop an ecology e-book based on the ESD framework to enhance scientific literacy, which included preliminary and literature reviews. The design stage aimed to formulate learning indicators for constructing the ESD-based ecology e-book. The development stage focused on validating the e-book prototype through expert review and subsequent revisions. The validation was conducted by two subject-matter experts, two media experts, and twenty science teachers who served as evaluators of the e-book. Science teachers assessed the e-book using a validation sheet, and the data were used to calculate the CVI and CVR values. The suggestions and feedback from the science teachers were used to revise the e-book. The implementation stage was carried out to examine the effectiveness of the ESD-based ecology e-book in improving students' scientific literacy. The implementation took place at a private school in Bogor City, involving seventh-grade students, and used a quasi-experimental design. The intervention period lasted two weeks. The teacher participated in delivering the instruction during the implementation, and the learning process was carried out in a blended format, not entirely based on the e-book. The ecology e-book served as the primary learning resource throughout the instructional activities. The evaluation stage aimed to document the development process and revise the e-book based on findings and feedback. Evaluation results were to refine the e-book and address identified weaknesses.

Instruments

The research instruments used in this study included media and content expert validation sheets, an assessment sheet for science teachers, a science literacy instrument

comprising knowledge-based test items, science literacy competency tests, and interview protocols. The blueprint of the science literacy instrument is presented in Table 1.

Table 1. The blueprint of the science literacy instrument

No	Science Literacy Aspect	Components	Number of Test Items	Total
1	Competencies	Explaining scientific phenomena	10	30
		Constructing and evaluating scientific investigations and critically interpreting data and evidence	10	
		Investigating, evaluating, and using scientific information for decision-making and action	10	
2	Knowledge	Epistemic	9	30
		Content	14	
		Procedural	7	

Reliability testing for the science literacy instrument using Cronbach's Alpha showed a coefficient of 0.850, indicating that the 30-item instrument had good internal consistency. The instrument's validity for science literacy was examined through content validity, evaluated by expert judgment, and empirical validity, determined through item-total correlation analysis, to ensure that each item accurately represented the construct being measured. Content validity was evaluated for the student response instruments.

Data Analysis

Data analysis was conducted descriptively, incorporating both quantitative and qualitative approaches (Ekantini & Wilujeng, 2018). Descriptive statistics, including the mean, standard deviation, minimum and maximum values, and percentages, were used to describe the pretest and posttest data and student responses. Assumption testing consisted of normality testing using the Shapiro-Wilk test and homogeneity testing using Levene's test. The effectiveness of the e-book was examined using Paired Sample t-tests to compare pretest and posttest scores within each group, and Independent Sample t-tests to compare posttest scores and normalized N-gain values between the experimental and control groups. Learning effectiveness was further evaluated through normalized N-gain calculations across each aspect of scientific literacy. Instrument reliability was assessed using Cronbach's Alpha, while empirical validity was examined through item-total correlations. Qualitative data from validators, teachers, and students were analyzed using thematic analysis.

▪ RESULT AND DISSCUSSION

Media Development Result

In the Merdeka Curriculum, ecology material is taught in Grade 7 under the element of science understanding, with the learning achievement stating that students are expected to comprehend the interactions among living organisms and their environments in designing efforts to prevent and mitigate climate change. Based on this learning objective, an analysis of the learning progression was conducted in alignment with scientific literacy, resulting in a macro structure related to the ecology topic. From this macro

structure, seven main chapters were developed. By organizing the material systematically and integratively, students can build a comprehensive understanding of ecology and its complexities (Bain & Siddique, 2017). At the design stage, the conceptual framework and evaluation components were developed based on the ESD framework and scientific literacy principles, and compiled into the draft version of the ecology e-book. ESD focuses on providing knowledge, skills, values, and perspectives that foster sustainable living. It integrates the principles of sustainability encompassing social, environmental, and economic dimensions, while promoting lifelong learning (Sihombing et al., 2024). The chapters developed, and their alignment with key ESD competencies, are presented in Table 2.

Table 2. Chapters of the developed e-book and their alignment with Key ESD competencies

No	Chapter Title	Chapter Description	Key Competencies of ESD
1	Chapter 1	Introduction to Ecology	Systems Thinking Competence
2	Chapter 2	Levels of Organization in Living Systems	Critical Thinking Competence
3	Chapter 3	Ecosystems	Systems Thinking Competence
4	Chapter 4	Interactions within Ecosystems	Problem-Solving Competence
5	Chapter 5	Energy Flow and Biogeochemical Cycles	Anticipatory Competence
6	Chapter 6	Ecosystem Balance and Its Impacts	Normative Competence
7	Chapter 7	Human Roles and Sustainable Actions	Strategic Competence And Collaboration Competence

The selection of media for the e-book development was carried out during the design stage. This process included choosing texts, images or illustrations, audio, and videos or animations from various sources. This approach aligns with the literature review conducted by Abdulrahaman et al. (2020), which emphasizes that the selection of multimedia elements such as text, images, audio, video, or animation should be made during the design stage to effectively support the learning objectives of the e-book. The e-book's initial layout was created as a simple storyboard using software.

At the development stage, the e-book designed in the previous phase was expanded and refined. This process included the detailed creation of content, integration of multimedia elements, design of interactive features, and preparation of materials for validation by subject-matter experts, media experts, and assessment by a science teacher. The results of the developed ecology e-book are presented in Figure 1.

The front cover contains the book title, grade level, and author information. Each chapter in the ecology e-book includes learning objectives, instructional content, summaries, and evaluations in the form of scientific literacy questions, allowing students to become accustomed to solving literacy-based problems. Research conducted by Momani et al. (2023) indicates that the use of digital learning in science education can enhance scientific literacy and conceptual understanding when learning materials and assessments are systematically structured. The e-book also features an "Ayo Ungkap!" section with interactive activities for students. Additionally, the developed ecology e-book incorporates current ecological issues at the personal, local, national, and global

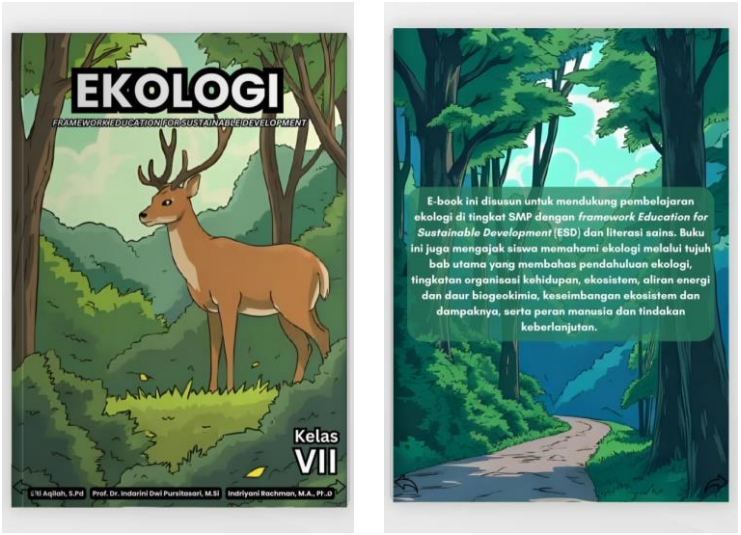


Figure 1. Front and back cover design of the ecology e-book

levels, thereby supporting the principles of Education for Sustainable Development (ESD). The ecology e-book was validated by content and media experts and evaluated by a science teacher. Overall, the developed e-book achieved an average feasibility of 96.3%, indicating it is highly feasible. This indicates that, in terms of content, language, and presentation, the e-book meets the criteria for excellent quality and is therefore suitable for use as teaching material.

Overall, the learning e-book had an average feasibility of 95.3%, indicating high feasibility. This indicates that, in terms of design and appearance, the developed ecology e-book meets high-quality standards and is suitable for use as teaching material. Feasibility assessment based on expert judgment using CVI (Content Validity Index) or CVR (Content Validity Ratio) is a methodologically valid procedure for determining the appropriateness of instructional materials (Jeldres et al., 2023). Based on the analysis, all instrument items obtained CVI values ranging from 0.90 to 1.00, with an average of 0.95, while the CVR values ranged from 0.80 to 1.00, with an average of 0.93. According to Lawshe's criteria, the minimum acceptable CVR value for 20 panelists is 0.42. Therefore, all instrument items are well above the minimum threshold and can be categorized as highly valid.

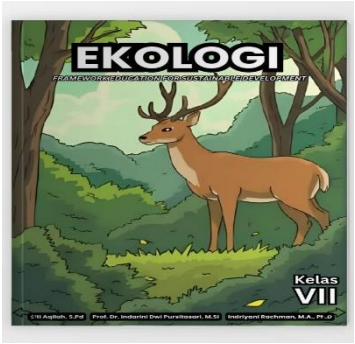
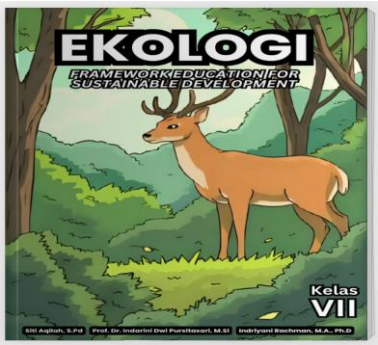
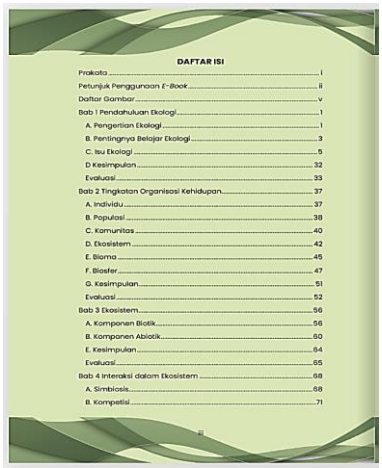
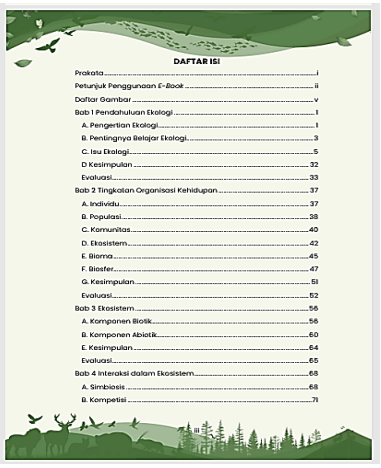
These results indicate that, overall, the e-book assessment instrument developed has met the criteria for excellent content validity. Content validity can be established through expert review of each item to assess its relevance, necessity, and usefulness, as well as the instrument's overall alignment with the construct being measured (Dinnesen et al., 2020). All instrument items were rated as relevant and representative by the evaluators, making them appropriate for assessing both the content and media aspects of the ecology learning e-book. In addition to quantitative data, qualitative feedback, including comments and suggestions for improvement, was collected.

Based on the validators' feedback, the developed teaching material still requires several improvements to improve its feasibility. First, it is necessary to incorporate contextual environmental issues in the school setting, enabling students to more easily connect ecological concepts to real-life experiences. Learning through authentic experiences and local contexts tends to improve students' environmental knowledge,

attitudes, and behavioral intentions, while supporting the need to integrate contextual environmental issues to make learning more relevant and impactful (Ardoin et al., 2020). Second, in the food web subchapter, the material should be enriched with more contextual examples to deepen students' understanding. Third, the validators emphasized the importance of adding images relevant to the material, as visual representation can help clarify abstract concepts. The use of images supports students' comprehension of abstract terms (Qadha & Mahdi, 2019; Mavropoulou et al., 2024). However, the images used must also be proportionally appropriate to avoid potential misconceptions.

Based on evaluations by science teachers, the e-book is considered well-designed, engaging, and supportive of students' scientific literacy development; however, it still needs improvements in visual design, language consistency, and overall readability. The teachers recommend adopting a more dynamic, high-contrast layout, incorporating additional illustrations or interactive activities, and simplifying certain sections to better align with the comprehension level of junior high school students. Several technical revisions are also necessary, including correcting typographical errors, clarifying the function of embedded videos, and ensuring that each learning objective is clearly reflected in the accompanying student activities. Overall, these suggestions highlight the need to strengthen contextual relevance, real-world connections, and visual quality in the teaching material. Based on expert validation and teacher evaluation results, revisions were made to the developed ecology e-book. The outcomes of these revisions are presented in Table 3.

Table 3. revisions of the ecology e-book based on experts' suggestions

No	Before Revision	After Revision	Description
1			Adjustment of text size on the cover, along with brightness and contrast enhancements.
2			Improvement of the e-book background design.

No	Before Revision	After Revision	Description
3	-		Inclusion of school-based ecological issues.

Overall, Table 6 illustrates how the e-book was refined to become more engaging, informative, and contextually relevant based on the validators' feedback, encompassing aspects from the cover and background to the illustrative content. Within the framework of ESD, it is essential to ensure that learning materials are relevant to students' local contexts, as this relevance enhances their engagement and understanding of sustainability issues encountered in their daily lives (Gokool-Ramdoo & Rumjaun, 2017). The inclusion of interactive design elements in the e-book can further increase students' engagement with the learning material, ensuring that they take an active role in the learning process and develop a deeper understanding of the content.

Pilot Study

The pilot study was conducted to test the e-book and the instruments developed prior to their use in the implementation phase, involving 31 students. The pilot study results indicated that the ecology e-book could be accessed on various devices, including smartphones, laptops, and tablets. A trial of the scientific literacy test instrument was also carried out with students who had previously studied ecology material. This trial aimed to assess the validity and reliability of the developed scientific literacy test items. All test items were found to be valid, and the results of the scientific literacy test instrument trial are presented in Table 4.

Table 4. Results of the scientific literacy test item validity

No	Number of Items	Percentage (%)	Description
1	30	100	Valid

The trial results indicated that the ecology e-book functioned effectively. The images, text, and videos were displayed clearly and operated well. However, since the e-book requires an internet connection, some students with limited connectivity had difficulty playing the videos. Therefore, adequate internet access is essential for optimal use of the ecology e-book and to ensure that all its features can be fully utilized.

Effectiveness Test Results

The analysis of the pretest and posttest results showed an improvement in students' scientific literacy skills after participating in learning activities using the ecology e-book. The results of this analysis are presented in Figure 2.

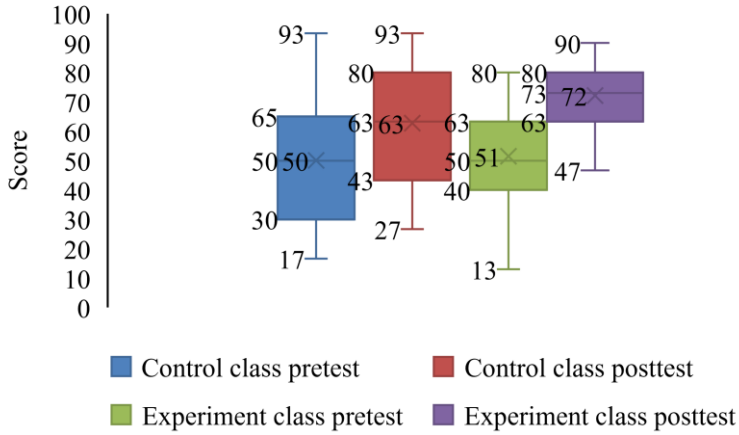


Figure 2. Descriptive analysis of students' scientific literacy

Both classes showed improvement. However, the experimental class showed a larger increase. The score distribution in the experimental class became more consistent and stable after the intervention, reflecting a more uniform enhancement in students' scientific literacy. The N-gain calculation yielded 0.43 for the experiment class, which falls into the moderate category, and 0.20 for the control class, which falls into the low category, suggesting that the implemented learning more significantly enhanced students' scientific literacy in the experiment class.

Overall, these findings confirm that the learning intervention using the ecology e-book had a positive impact on improving students' scientific literacy. However, there remains room for improvement to achieve a high-level category. The e-book relies on static images and text-based activities without interactive simulations, self-check quizzes, or embedded formative assessments. As a result, students receive limited feedback and opportunities for active exploration, which slows the correction of misconceptions and reduces potential learning gains. These results are consistent with previous studies indicating that interactive e-books can enhance engagement and retention in science learning. However, their effectiveness largely depends on instructional design and technical aspects. Therefore, while the developed ecology e-book has positively influenced scientific literacy, further refinement is required to reach higher achievement levels (Franco & Bidarra, 2022; Weng, 2022; Tang, 2021). To examine the improvement statistically, a Paired-Samples T-Test was conducted, as shown in Table 5.

Table 5. Results of paired samples correlations

		N	Correlation	Significance	
				One-Sided p	Two-Sided p
Experiment Class	Pretest & Posttest	35	0.519	<0.001	0.001

Control Class	Pretest & Posttest	27	0.426	0.013	0.027

Correlations of 0.519 in the experimental class and 0.426 in the control class indicate a moderate, positive relationship between the pretest and posttest scores. This implies that students who scored high on the pretest also tended to achieve high scores on the posttest, although improvements were observed following the intervention. The significance level ($p = 0.001 < 0.05$) indicates that the relationship between the pretest and posttest scores is statistically significant. The students' scientific literacy results based on the knowledge aspect are presented in Figure 3.

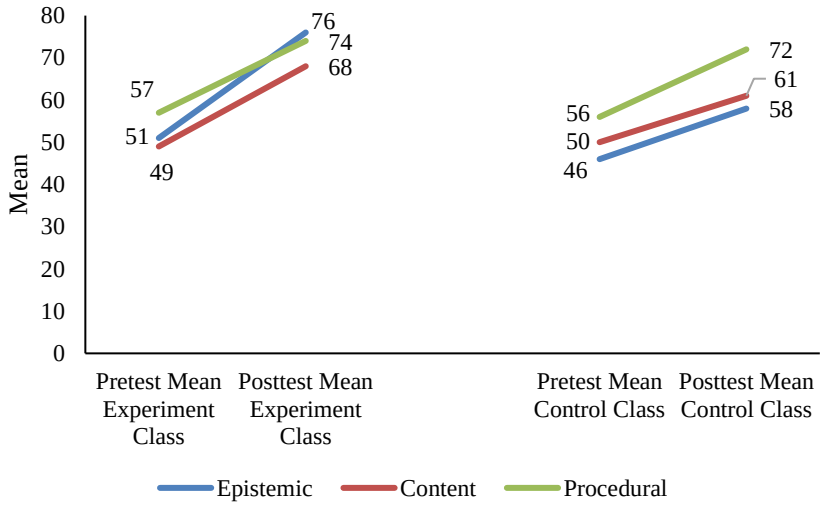


Figure 3. Comparison of mean pretest and posttest scores on the knowledge aspect of scientific literacy for experiment and control class

The comparison of mean pretest and posttest scores on the knowledge aspects of scientific literacy shows improvement across all dimensions. In the epistemic aspect, the mean score increased, indicating that students developed a better understanding of how scientific knowledge is constructed and validated. The content aspect also increased, suggesting that students' mastery of fundamental ecological science concepts improved after the learning intervention. Meanwhile, the procedural aspect increased, reflecting students' development of skills in applying scientific procedures and methods. Overall, these results indicate that e-book–based ecology learning effectively enhanced students' scientific literacy across epistemic, content, and procedural dimensions, with the highest achievement observed in the epistemic domain. Bibliometric reviews and empirical studies have shown that interactive e-books (incorporating animations, videos, quizzes, and hyperlinks) improve scientific literacy, particularly in conceptual understanding (content) and cognitive engagement (Kurniadin, 2025).

The ecology e-book includes case studies and reflective questions that help students evaluate cause-and-effect relationships and apply scientific evidence to understand ecological issues. These features cultivate evidence-based reasoning and critical thinking skills, thereby enhancing both procedural and epistemic knowledge. The concept-value-action framework embedded in the e-book encourages students to connect scientific

concepts with sustainability values and concrete actions. Furthermore, hypothetical scenarios provide opportunities for students to predict, evaluate, and make evidence-based decisions, thereby reinforcing scientific literacy in accordance with ESD principles. The students' scientific literacy results based on competency aspects are presented in Figure 4.

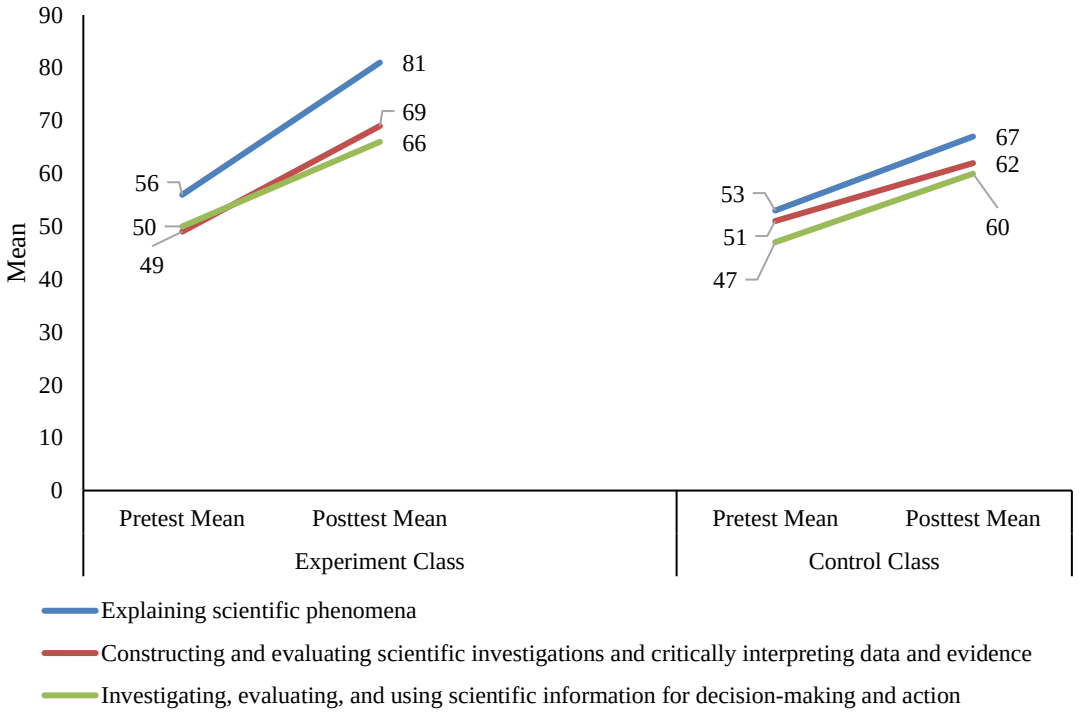


Figure 4. Comparison of mean pretest and posttest scores on the competency aspect of scientific literacy for experiment and control class

Overall, learning using the ecology e-book within the ESD framework successfully enhanced students' scientific literacy competencies across the three measured aspects. The greatest improvement was observed in the conceptual understanding aspect (explaining phenomena), whereas gains in the application and evaluation aspects (designing investigations and using scientific information) still require reinforcement. This highlights that ecological learning is not only effective in strengthening conceptual mastery but also requires more authentic experiences, projects, and problem-based learning (PBL) to develop students' critical thinking and evidence-based decision-making skills. Previous studies have shown that PBL is effective in enhancing critical thinking and problem-solving abilities, suggesting that its implementation in ecology learning is recommended to strengthen students' procedural skills (Yew & Goh, 2016). Studies implementing PBL in ecology have reported increased student motivation and engagement, indicating that enriching learning with field projects and authentic experiences can further enhance students' ability to make evidence-based scientific decisions (Burrow, 2018).

The aspect of explaining scientific phenomena shows the greatest improvement, indicating that students tend to progress more readily in their understanding of scientific

concepts and phenomena, even when learning occurs without the use of the ecology e-book. In the ecology e-book, many features and activities focus on helping students understand concepts, the relationships between ecosystem components, and various environmental phenomena. For example, the "Ayo Amati" observation tasks, the follow-up questions, and the clear, systematic presentation of conceptual material all require students to explain why certain events or processes occur. These features directly support the development of explaining scientific phenomena, which is why this aspect shows greater improvement compared to the other competency areas.

The improvement in students' scientific literacy, reflected in the moderate N-gain of 0.43 and the increases across epistemic, content, and procedural knowledge, can be attributed to the coherent alignment between the e-book chapters and the key ESD competencies presented in Table 3. Chapters emphasizing systems thinking (Chapters 1 and 3) strengthened students' ability to explain ecological phenomena, which was the most improved competency. Critical thinking embedded in Chapter 2 supported gains in epistemic reasoning, while the problem-solving focus of Chapter 4 contributed to better use of scientific information in decision-making. Anticipatory competence in Chapter 5 enhanced students' predictive and analytical skills, and the normative emphasis in Chapter 6 fostered evaluative reasoning related to ecological balance. Finally, the strategic and collaboration competencies embedded in Chapter 7 reinforced students' motivation and engagement. Collectively, integrating these ESD competencies into the chapter structure provides a clear mechanism for explaining the observed enhancements in students' scientific literacy. Students' responses to the ecology e-book within the ESD framework are presented in Table 6.

Table 6. Students' responses to the ecology e-book

No	Aspect	Percentage (%)	Category
1	Content or Material	83	Very High
2	Language	82	Very High
3	Presentation	78	High
4	Appearance	81	Very High
5	Usefulness	84	Very High
	Mean	**81**	**Very High**

The analysis of students' responses to the ecology e-book shows that, overall, it received a very high rating, with an average of 81%. Examining each aspect, the content aspect achieved 83% very high), indicating that the material presented was considered relevant, easy to understand, and supportive of the learning objectives. The language aspect received 82% (very high), indicating that the e-book's language was clear, communicative, and appropriate for junior high school students. The presentation aspect scored 78% (high), indicating that while the e-book presentation was adequate, it could be further enhanced to be more interactive and engaging.

The visual aspect received 81% (very high), demonstrating that the visual design, colors, images, and supporting media were appropriate and facilitated students' understanding of the material. Meanwhile, the utility aspect achieved the highest score of 84% (very high), indicating that the e-book was highly beneficial in increasing learning motivation, supporting independent learning, and raising students' awareness of

ecological issues. Therefore, it can be concluded that the developed ecology e-book is suitable as a teaching resource, although improvements to its presentation are recommended to further optimize its quality.

The results of the independent-samples t-test indicate that there is no significant difference in N-gain between students who rated the e-book's Presentation aspect as "High" and those who rated it as "Low" or "Medium," $p = 0.099$. The p-value exceeding 0.05 suggests that students' perceived quality of the e-book's presentation does not have a statistically significant effect on their improvement in scientific literacy.

Implications for Practice

This study makes an important theoretical contribution to the development of cognitive learning theory, instructional design, and the ESD framework. The findings demonstrate that the use of an e-book integrating multiple forms of representation, including text, images, videos, and data-driven activities, can enhance students' information-processing capabilities. This provides empirical support for information-processing theory, dual coding theory, and cognitive load theory, all of which emphasize the effectiveness of structured multimodal presentation in facilitating deeper learning. From an instructional design perspective, the study clarifies how ESD principles can be operationalized in digital learning media by incorporating real environmental issues, inquiry activities, and scientific literacy tasks that collectively foster higher cognitive engagement. These results align with constructivist theory, which highlights the importance of authentic contexts in shaping meaningful learning experiences. Furthermore, the study advances theoretical understanding of ESD by showing that integrating ESD competencies, such as systems thinking, critical thinking, and sustainability-oriented decision-making, into e-book design can enhance students' ability to connect ecological concepts to relevant environmental issues while simultaneously strengthening their scientific literacy.

Limitations of the Study

This study has several limitations that should be considered. First, the effectiveness trial was conducted on a limited sample, namely two classes in a single school, so the results cannot yet be generalized widely. Second, the implementation period was relatively short, preventing the assessment of long-term impacts on knowledge retention and students' behavioral changes related to environmental sustainability. Future research is recommended to involve the science identity aspect, a larger sample, extend the intervention period, and conduct an in-depth exploration of students' learning experiences and the effectiveness of the e-book in real-world learning contexts.

▪ CONCLUSION

This study provides new insights into how the design of an ESD-based digital e-book can meaningfully influence students' scientific literacy in the context of ecology learning. The findings show that embedding ESD principles such as systems thinking, anticipatory reasoning, and action-oriented learning within the structure of a digital e-book creates a learning environment that strengthens not only conceptual understanding but also students' ability to interpret evidence, connect scientific ideas to real environmental issues, and engage critically with socio-ecological problems. The

integration of multimodal features, contextual case studies, and literacy-focused tasks appears to support the development of epistemic and procedural knowledge more effectively than conventional text-based materials. The positive shifts in scientific literacy outcomes, particularly in explaining scientific phenomena and interpreting scientific information, demonstrate that intentionally aligned digital learning resources can foster deeper cognitive engagement and enhance students' capacity to participate in sustainability-related decision-making.

This study also highlights several important implications for science education. It suggests that digital learning materials grounded in ESD can help bridge the gap between scientific concepts and students' everyday environmental experiences, thereby increasing relevance and motivation in learning. At the same time, the study reveals several limitations that require further exploration. The short duration of implementation limits understanding of long term retention of concepts and of changes in students' sustainability-related behaviors. The absence of more advanced interactive features also leaves open questions about how richer digital interactivity might further strengthen students' inquiry processes and critical reasoning. In addition, the limited research setting restricts broader generalization of the patterns observed. Future research is therefore encouraged to examine how different design features, such as adaptive feedback, interactive simulations, or opportunities for student-generated content, interact with ESD elements to shape scientific literacy outcomes across diverse learning contexts.

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