# Enhancing Students' Scientific Literacy Through ESD-based E-modules on Low Carbon Energy Topic

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**ABSTRACT**

Scientific literacy is a foundational competency for addressing the 21st century challenges, especially in the context of transition to low-carbon energy systems. Sadly, there is very little curriculum coverage of sustainability and energy topica; teachers are mostly unprepared; and there are almost no good-quality local instructional materials. Therefore, this study looks into the effectiveness of an ESD-based e-module on low carbon energy topic in promoting scientific literacy among ninth-grade students in Cimahi, Indonesia. Using a quasi-experimental one-group pretes-posttest design, 28 students took part in learning activities that integrated systems thinking, collaboration, and problem-solving competencies. Scientific literacy was measured using a validated 25-item test covering competencies of explaining phenomena scientifically, scientific inquiry, and scientific data interpretation. Results showed that there was a significant increase in mean scientific literacy scores from pretest (64.75) to posttest (80.57); the moderate average N-gain was 0.45. The highest improvement was found in students' ability to seek, evaluate, and use scientific information in decision-making. The statistical analysis used confirmed that the increases were significant. The results suggest that ESD-based e-modules have the potential to bridge educational gaps by making very complex sustainability concepts simpler and fostering critical scientific competencies.



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## Introduction

Scientific literacy has increasingly recognized as a fundamental competence for individuals to face the challenges of 21st century, particularly climate change and energy transition issues, has now become an important scientific competency. Scientific literacy empowers individuals to critically assess scientific information, participate in evidence-based decisions, and engage in conversations about environmental policies (OECD, 2019; Kilag et al., 2023). Critically, in developing advanced scientific literacy within and through ESD, it extends from the content knowledge that has emphasis to three core capacities: (1) developing systems thinking to analyze the interactions of energy, society, and environment, (2) epistemic skills as a means for judging different climate claims, and (3) action competence to translate knowledge into doing sustainable behavior (Wiek et al., 2011; Dieni et al., 2022; Vilmala et al., 2022). This literacy multidimensionality may be a deciding factor for sustainability efforts.

Scientific literacy, in turn, plays a particularly important role in discussions around low-carbon energy systems, where public understanding may determine the success or failure of sustainability efforts (UNESCO, 2020; Agustya & Jauhariyah, 2023). A transition towards renewable energy sources and solving climate change problems will be very difficult without an adequate scientific literacy rate in the population.

The global shift toward low-carbon energy systems constitutes one of the most far-reaching areas of sustainable development. However, technological changes alone cannot guarantee a successful energy transition; public enlightenment and engagement are equally pivotal. To engage in effective energy transitions, citizens must understand not only the basic science of renewable technologies such as solar and wind power but also the socio-economic and policy dimensions underlying these changes (DeWaters & Powers, 2013; Uzondu & Lele, 2024; Sovacool & Griffiths, 2020). However, despite this necessity, existing approaches to science education rarely prepare students to engage with such real-world energy issues (Peng et al., 2025).

Education for Sustainable Development (ESD) has been put forward as a promising framework to address these educational shortcomings (UNESCO, 2020). Unlike traditional sceince learning, ESD pursues inter- and transdisciplinary teaching that relates scientific concepts with social, economic, and policy considerations, as opposed to the more typical and clasiscal approaches of teaching science. This setting nurtures systems thinking skills specifically aimed at apprehending complex sustainability issues like energy transitions. Evidence from research shows that ESD can significantly improve scientific literacy as well as pro-environmental attitude of students (Nik Abdul Majid et al., 2025; Dianti & Sueb, 2022; Nkaizirwa et al., 2021).

Digital learning tools, including e-modules for the study of science, have displayed great promise in improving educational outcomes. Studies have shown that properly designed e-modules increase knowledge retention from 15% to 25% more than traditional methods (Astuti et al., 2022; Rhoudatul et al., 2023). If you designed according to cognitive load theory principles (Sweller, 2011), ESD e-modules can also optimize complex learning by: segmenting energy system concepts into manageable schemas, embedding worked examples of policy analysis and stripping from the sustainability problem solving tasks all the extraneous information. Most digital resources, however, are oriented towards environmental problems without much interest or effort toward solution-oriented, systems-level thinking (Ardhita & Khanafi, 2024). There is a serious shortage of e-learning materials that holistically combine the scientific, societal, and policy aspects of transitioning to low-carbon energy.

Scientific literacy in Indonesia remains alarmingly fragile, as evidenced by recent PISA assessments that place Indonesian students' science performance well below the OECD average (OECD, 2023a). Indonesian students ranked 74 out of 81 participating countries on the 2022 PISA science test, with most difficulty doing something about data interpretation and evidence evaluation. Data show that only 46.6% of Indonesian textbooks deal with sustainability topics fairly, and even less deal with low-carbon energy concepts (Hudha et al., 2021; Pambudi et al., 2024). These educational shortcomings exist against a background of growing energy demands and climate vulnerabilities in Indonesia (IESR, 2022).

Several systemic factors contribute to the challenges being faced by science education in Indonesia. Whereas low-carbon energy topics are given scant coverage in the national curriculum, this constitutes a huge gap in sustainability education for students. Many teachers feel unprepared to teach these concepts, citing insufficient training in sustainability content and pedagogical approaches (Yuliyanto et al., 2024). Beyond this, a scarcity of good local materials further denies schools the opportunity to address the aforementioned gaps.

In Indonesia, the integration of Low-Carbon Energy Education (LCE) within the national curriculum remains at an early stage, despite the country's significant renewable energy potential and its commitments to reduce carbon emissions. Efforts to embed LCE are often hindered by a lack of interdisciplinary teaching materials, limited teacher training, and insufficient alignment with national policy frameworks (Nurramadhani et al., 2024). While some pilot programs and localized initiatives have introduced LCE concepts—often through extracurricular activities or project-based learning—these efforts are not yet widespread or systematically implemented. As a result, Indonesian students typically have limited exposure to the interconnected scientific, social, and policy dimensions of the energy transition. Addressing these gaps requires not only curriculum reform but also the development of contextually relevant digital resources and teacher professional development programs that explicitly target systems thinking and solution-oriented approaches to sustainable energy challenges.

In this study, an ESD-based e-module was specifically designed to teach low-carbon energy concepts to secondary school students—an approach that uniquely integrates digital learning technologies with the principles of Education for Sustainable Development (ESD). Employing a quasi-experimental pretest-posttest design, the research evaluates the effectiveness of this innovative e-module in enhancing students' scientific literacy regarding energy transitions—addressing a persistent gap where sustainability topics are often separated from core science curricula.

The ESD-based e-module utilized in this research represents an innovative approach to bridging persistent gaps in science education. Through its combination of digital learning technologies and sustainability education principles, the intervention aims to make complex energy concepts more accessible to students while fostering the scientific literacy skills needed for engaged citizenship. The study's outcomes will inform future efforts to integrate sustainability topics into mainstream science curricula, both in Indonesia and other similar contexts worldwide.

## Method

This reserach was quasi-experiment research (Campbell & Stanley, 1963). Quasi experimental method is used with the aim to assess the effectiveness of an intervention or treatment, for example introduction of a new instructional strategy or curriculum, while taking into account real-world limitations. The design in this study employed a one group pretest-posttest design, where the same dependent variable was measured in one group of participants before (pretest) and after (posttest) a treatment/intervention was administered (Cranmer, 2017), as illustrated (1).

$$O_{1\,(pretest)} \rightarrow X_{(intervention)} \rightarrow O_{2\,(posttest)} \quad (1)$$

The participants of this study were 28 ninth-grade students from a national junior highschool in Cimahi. The sampling technique was done using purposive sampling to ensure alignment with the study's objective on students exposed to low carbon energy topic.

The ESD-based E-module on low carbon energy was used as treatment, as shown in Figure 1, to improve students' scientific literacy skills. The ESD-based e-module integrated the elements of ESD key competencies, such as systems thinking, collaboration competency, self-awareness competency, and integrated problem-solving competency, in the learning activities to enhance scientific literacy competences, especially in the topic of low carbon energy.

The instrument used in this study was a 25-item multiple choice objective test designed to assess the three main competencies of scientific literacy, namely explaining phenomena scientifically (LS1), evaluating and designing scientific inquiry (LS2), and Interpreting data and evidence scientifically (LS3) (OECD, 2023b). The data obtained through pre-test and post-test administration of this instrument. The results were analyzed using descriptive quantitative methods, including the calculation of mean scores and standard deviation to summarize students' performance. The effectiveness of the intervention was evaluated using the N-gain Test, while paired sample T-Test was employed to determine the statistical significance ($p<0,05$) of differences between score of tests before and after the intervention using ESD-based e-module on the topic of low carbon energy. The analysis was carried out using SPSS software. The overall research flow can be seen in Figure 1 below.

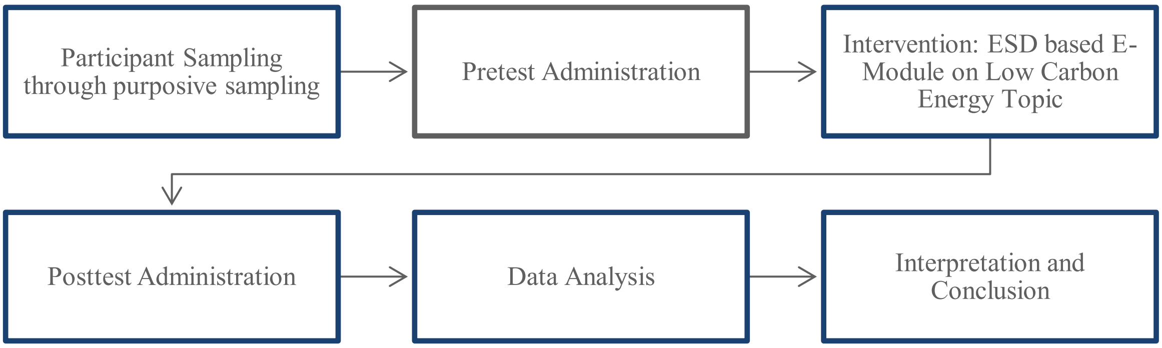


**Figure 1.** Research Flow

## Results and Discussion

The research evaluated students' scientific literacy after implementing ESD-based e-module on the topic of low carbon energy in the learning process. The e-module underwent expert validation and was deemed effective and suitable as a teaching material before the implementation. Its impact on students' scientific literacy was measured using a validated 25-item multiple-choice test, covering three main competencies: explaining scientific phenomena (LS1), constructing and evaluating scientific investigations and interpreting data critically (LS2), and seeking, evaluating, and using scientific information for decision-making and action (LS3).

### Descriptive Analysis of Pre-Tests Results

Descriptive analysis of students' scientific literacy skills prior to the intervention using ESD-based e-modules was obtained from the results of pretest using the objective test. The general description of students' scientific literacy includes the mean score, standard deviation, minimum score, and maximum score.

**Table 1.** Descriptive Analysis of Pretest and Posttest Score

| | N | Minimum | Maximum | Mean Score | Std. Deviation |
|---|---|---|---|---|---|
| Scientific Literacy Score Pretest | 28 | 40 | 88 | 64,6 | 13,45 |
| Scientific Literacy Score Posttest | 28 | 56 | 100 | 80,6 | 13,06 |

As seen in Table 1, the pre-test results revealed scientific literacy skill of 28 students has varied with the range of 40 to 88. 64.75 mean showed that students already have some existing scientific literacy skills; at the same time, the high standard deviation of 13.45 indicates that there are marked differences in the scientific literacy abilities of students. More specifically, the higher the standard deviation, the wider the variation from the individual scores to the group mean. This relatively large standard deviation proves that there is a large variance in terms of students' scientific literacy skills. Such variance shows the need for conducting a complete needs assessment to find individual students' specific learning requirements and issues.

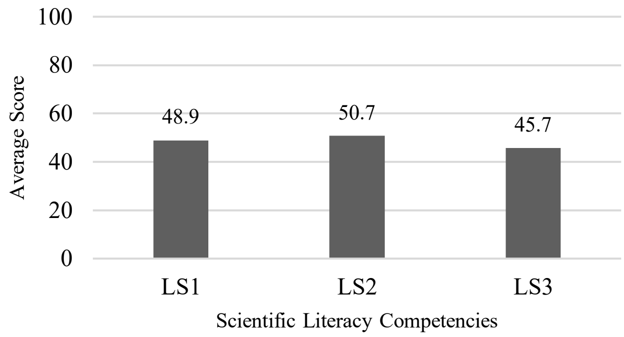


**Figure 2.** Graph of Scientific Literacy Competencies Scores in Pretest

As seen in Figure 2, the pretest results indicate that students' ability to explain phenomena scientifically (LS1) was 49%, and their ability to seek, evaluate, and use scientific information for decision-making and action (LS3) was 46%. Both competencies were below 50% and thus can be categorized as poor. These findings suggest that students may have limited ability to apply scientific knowledge to explain events and to use scientific information for making decisions and taking action in real-life contexts. Meanwhile, students' ability to construct and evaluate designs for scientific inquiry and critically interpret data and evidence (LS2) showed slightly better results, with 51% of students in the adequate category. This indicates that students possess relatively better skills in designing and critically evaluating scientific investigations.

Interpreting these findings in light of the research questions, it becomes clear that there is a pressing need for targeted interventions to enhance students' scientific literacy, particularly in the areas of scientific explanation and information evaluation. This is consistent with previous studies, which have frequently reported that students often struggle more with applying scientific knowledge in real-world contexts and making informed decisions than with procedural or inquiry-based tasks (OECD, 2019; Yore et al., 2007). The results thus support the existing literature, reinforcing the notion that scientific literacy is a multifaceted competency, with certain aspects requiring more instructional attention than others.

In summary, the pretest results reveal both strengths and weaknesses in students' scientific literacy, aligning with previous research and highlighting important directions for instructional improvement, policy development, and future study.

## Descriptive Analysis of Post-test Results

As seen in Table 1, the minimum score obtained was 56, and the maximum score reached 100. This indicates a substantial change compared to the previous pretest results. The average scientific literacy score obtained was 80.57, which represents a considerable improvement compared to the pretest results. This suggests that, on average, students have achieved a good level of scientific literacy. The standard deviation of 13.06 reflects the extent to which the data deviate from the mean. This shows there is moderate variation in students' scientific literacy scores after instruction with ESD-based E-modules. In other words, the average scientific literacy of students did improve due to the learning intervention, but some students still scored comparatively lower than others. The differences in scores could be attributed to differences in prior knowledge, learning styles, engagement, and learning speed among students. The end result is that while most students benefited from instruction, some students achieved higher mastery than others, indicating a need for differentiated approaches to cater to diverse learner needs.

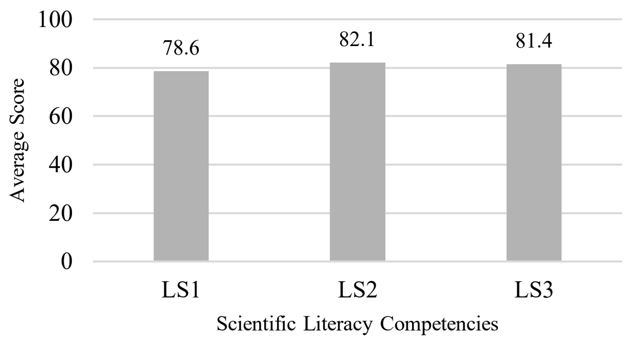


**Figure 3.** Graph of Scientific Literacy Competencies Scores in Posttest

Figure 3 shows post-test results which indicate a lower percentile of LS1 at 78.6%, which falls under the "adequate" category. This means that after the intervention, the students had an adequate ability to scientifically explain phenomena or events. Meanwhile, LS2 stood highest at 82.1%, being categorized as "good"; this indicates students' ability to design and critically evaluate scientific investigations was good. LS3 was next in line with a percentage very close to LS2 at 81.4%, also classified as "good," indicating the ability of students to use scientific information in real-life setting to be good. Taken together, the graph clearly shows improvement in students' scientific literacy competencies after the intervention, thus establishing a clear basis for the effectiveness of the ESD-based e-modules employed in instruction.

Interpreting these findings in light of the research questions, it is evident that targeted instructional interventions, such as ESD-based e-modules, can significantly improve students’ scientific literacy, especially in competencies related to scientific explanation and information evaluation. This aligns with previous studies, such as those by the OECD (OECD, 2019, 2023a), which have documented that student often find it more challenging to apply scientific knowledge in real-world contexts than to perform procedural or inquiry-based tasks. Similarly, Yore et al. (2007) emphasize that scientific literacy is a multifaceted construct, and that students frequently require additional support to develop the ability to use scientific information for decision-making and action.

In summary, the results demonstrate that ESD-based e-modules effectively address gaps in students’ scientific literacy, supporting the broader literature that advocates for contextualized, inquiry-oriented, and differentiated science instruction. The findings underscore the importance of integrating such approaches into science education to foster well-rounded scientific literacy and prepare students for informed participation in society.

**Analysis of Scientific Literacy Improvement**

Using SPSS 22, pretest and posttest data were analyzed to examine the effect of ESD-based e-module instruction on students' scientific literacy skills. Reliability tests (normality and homogeneity tests) were performed to confirm that data met the assumptions required for the parametric statistical procedures, for instance, the paired sample t-test. It could be demonstrated that both the pretest and posttest scores showed normality and homogeneity, which gave validity to the later hypothesis testing. In the paired sample t-test, the obtained t values indicated a statistically significant difference in scores between pretest and posttest, thus confirming that students' scientific literacy improved significantly following the intervention. In addition, the normalized N-gain score was computed to give an indication of the magnitude of improvement, which in this case, the results demonstrated that across all competencies tested, there was a moderate average increase in scientific literacy. This was a rigorous analytical approach that showed the success of the ESD-based e-module in the enhancement of scientific literacy skills and provides quantitative justification for its further application in pedagogical practice.

**Table 2.** Analysis of Normality Test, Homogeneity Test, and Paired Sample T-Test

| Data | | Pretest | Posttest |
|---|---|---|---|
| Source of Data | | 25-item Scientific Literacy Objective Test | |
| Mean Scores | | 64,6 | 80,6 |
| Normality Test | Sig. | 0,211 | 0,195 |
| (Shapiro-Wilk) | Desc. | Data distributed normally | Data distributed normally |
| Homogeneity Test | Sig. | 0,914 | |
| | Desc. | The data are homogeneously distributed | |
| Paired Sample T-Test | Sig. | 0,000 | |
| | Desc. | There is a significance difference between pretest and posttest | |

The statistical analysis of the pre-test and post-test of students' scientific literacy scores provided validity for the paired sample t-tests through prerequisite checks (Table 2). As seen in Table 2, normality tests applying the Shapiro-Wilk method indicated that both pre-test ($p=0.211$) and post-test ($p=0.195$) data meet normal distributions and thus parametric assumptions. A further test of homogeneity ($p=0.914$) then certifies equal variances concerning groups. The paired t-tests thus significantly revealed that scientific literacy was improved, following the ESD-based e-module intervention, by $p<0.001$ and that the mean score had increased from 64.57 to 80.57. Such findings concur with methodologies from previous studies using normality tests, homogeneity checks, and paired t-tests to assess educational interventions (Gutwill & Allen, 2012; Tsui & Treagust, 2010). Strong bounds on all statistical assumptions then give simple reinforcement to the conclusion that indeed the ESD-based e-module improves scientific literacy, congruent with those investigations calling for more systematic data-driven evaluation in educational settings.

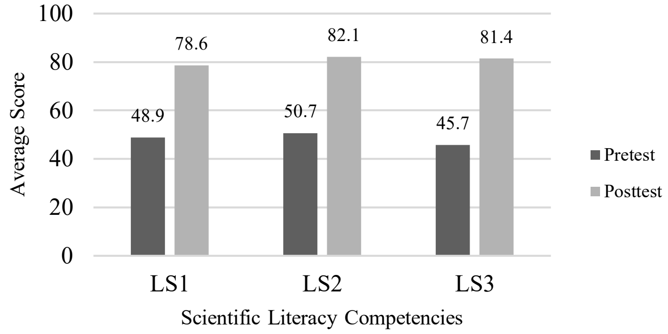


**Figure 4.** Graph of Scientific Literacy Competencies Scores

The graph in Figure 4 represents the comparison of results for each core scientific literacy competency before and after instruction. It can be seen from the three graphs that each competency experienced varying degrees of improvement. The most substantial increase occurred in the competency of seeking, evaluating, and using scientific information for decision-making and action (LS3), which rose from 45.7% to 81.4%. Similarly, the competency of explaining phenomena scientifically (LS1) increased from 48.9% to 78.6%. The competency of constructing and evaluating designs for scientific inquiry as well as critically interpreting data and evidence (LS2) also increased from 50.7% to 82.1%. These varying improvements across each competency provide a more comprehensive picture of the effectiveness of the intervention in enhancing students' scientific literacy skills.

Next, N-gain was calculated to determine how effectively the ESD-based e-modules were used to enhance scientific literacy skills, drawing upon the pretests and posttests. The average N-gain obtained was 0.45, which is considered moderate. The average score being moderate means that the e-modules proved to be rather effective, though there is still much improvement that can be done. This concurs with what previous research has found; namely, moderate to high N-gain values were also reported when e-modules were implemented in the processes of science learning. For instance, Putri et al. (2025) showed that ESD-based e-modules had a very positive impact on student learning outcomes, which saw an N-gain value of 0.83 (high category), indicating a decisive improvement in students' understanding and engagement with the material.

Nurhayati et al. (2025) presented similar findings, demonstrating that their locally based wisdom e-modules gained an N value of 0.57, placing it also under the moderate category, and were effective in enhancing students' scientific literacy essentially by the indicators of explaining scientific phenomena, evaluating and designing scientific research, and interpreting scientific data and evidence. Meanwhile, research done by Prasetyo (2021) through the use of e-modules based on STEM entities determined that the N-gain values for scientific literacy were in the medium category, while a paired t-test statement proved significant differences to exist in pretest and posttest scores. All of these studies point to the convincing conclusion that e-modules, especially those having ESD principles or contextualized content as their main focus, lead to some significant improvements in scientific literacy.

The observed moderate N-gain in this study was quite congruent with the other literature stating the practicality and effectiveness of e-modules among different education settings as well as different student populations. E-modules have been shown to be feasible and valid as tools for teaching; go ahead to promote active learning, critical thinking, and the use of scientific ideas for actual sustainability problems (Najwa & Suhartini, 2023; Widodo et al., 2024). While implying moderate N-gain is still quite encouraging, it should remind educators and instructional designers about the dynamic nature of teaching strategies, and e-module content needs to be continuously improved and adapted for maximum learning gains. On the whole, the evidence supports that the continued development and implementation of ESD-based e-modules remain a good avenue through which one can empower students with scientific literacy skills.

**Table 3.** N-Gain Scores of Each Scientific Literacy Competencies

| Main Competencies | Pretest Score | Posttest Score | N-Gain Score | Description |
|---|---|---|---|---|
| LS1 | 48,9 | 78,6 | 0,58 | Moderate |
| LS2 | 50,7 | 82,1 | 0,64 | Moderate |
| LS3 | 45,7 | 81,4 | 0,66 | Moderate |

According to Table 3, the N-gain values for the LS1, LS2, and LS3 competencies were all categorized as moderate. This means that students, in general, produced different N-gain results for each of the scientific literacy competencies. LS3 received the highest N-gain, with an average of 0.66, thereby assuring that ESD-based e-modules centered on low-carbon energy allow for deeper experience for students in searching, evaluating, and using scientific information for decision-making and action. LS1 received the lowest N-gain of 0.58, indicating further evaluation of e-modules that could provide more in-depth experience in the scientific facets of low-carbon energy phenomena. LS2, with a moderate N-gain of 0.64, signifies that student availed themselves of adequate experience in composing and examining designs for scientific inquiry and critically interpreting data and evidence with the help of ESD-based e-modules on low-carbon energy.

The moderate levels of N-gain in LS1 (0.58), LS2 (0.64), and LS3 (0.66) reflect the findings of research that have assessed technology-enhanced interventions in scientific literacy. The largest N-gain in LS3 for competencies in seeking, evaluating, and applying scientific information (0.66 N-gain) was similar to findings of (Ruswanto & Atmojo, 2023), who found a comparable gain (N-gain = 0.74) resulting from SETS-based guided inquiry models. This study pointed out that structured, problem-based tasks encourage students to analyze real-world data and make evidence-based decisions in much deeper engagements with scientific information-a principle that is built into the framework of ESD-based e-modules. Pratiwi et al. (2023) also found that including a sustainability context in learning materials encouraged students to apply scientific information in decision-making, as was evidenced in the performance of LS3. In this way, the outcomes would also have been aided by the interactive design of the e-modules that allowed students to iteratively explore low carbon energy scenarios, thus connecting theoretical knowledge with practical application.

Lower N-gain values obtained for LS1 connoted that there have been some persistent difficulties in explaining abstract phenomena scientifically, a concern stated in many literatures on science education. Tsui & Treagust (2010) reported that without specific interventions aimed at supporting conceptual understanding with multimodal representations (e.g., drawings, simulations), students do not perform well on tasks evaluating explanatory power. On the other hand, the ESD-based e-modules provide students with a moderate performance increase for their LS1; thus, the low gain presents an opportunity for guided scaffolding such as dynamic visualizations of low-carbon energy systems that consolidate causal reasoning of explanations. Gormally et al. (2012) also found that inquiry-based modules do not explicitly target instruction in explanatory skills; hence, additional improvements to e-module content concerning LS1 are necessary.

In LS2 (designing and evaluating scientific inquiries), the moderate N-gain showed that inquiry-driven pedagogies are effective when embedded in the ESD framework (0.64). Guided inquiry models using multimedia showed to be effective in improving students' skills in designing experiments and interpreting data (N-gain = 0.70), a finding consistent with LS2 results (Suprianti et al., 2021). The e-modules relevant to low-carbon energy scenarios likely provided real contexts for students practicing hypothesis testing and data analysis, as

Gutwill & Allen (2012) defined, in which contextualized inquiry tasks feature significantly in procedural skill learning. The variability in LS2 scores (SD = 13.06) would denote individual differences in terms of student engagement with inquiry processes and reflects the idea put very clearly by Mahat & Idrus. (2016): self-paced e-modules may require different mechanisms to ensure effective feedback for addressing dissimilar learning paces.

Despite these positive outcomes, several limitations should be acknowledged. The moderate N-gain values, especially in LS1, indicate that the e-modules may not have fully addressed all aspects of scientific literacy, particularly the development of explanatory skills. Additionally, the study's reliance on self-paced e-modules may have introduced variability in student engagement and learning outcomes, as noted by Mahat & Idrus. (2016). The sample size and context-specific nature of the intervention may also limit the generalizability of the findings.

Future research should explore the integration of dynamic visualizations and multimodal scaffolding within e-modules to better support the development of explanatory skills (Tsui & Treagust, 2010). Longitudinal studies with larger and more diverse samples could provide deeper insights into the long-term impact of ESD-based e-modules on scientific literacy. Additionally, investigating adaptive feedback mechanisms and differentiated instructional strategies within e-learning environments may help address individual differences in learning pace and engagement (Mahat & Idrus., 2016).

## Conclusion

The study found that ESD-based e-modules focusing on low-carbon energy significantly enhanced students' science literacy across various competencies, including explaining scientific phenomena, constructing and evaluating scientific investigations, and using scientific information in decision-making. Using a rigorous pretest-posttest design, the results showed statistically significant improvements, with an average N-gain of 0.45, indicating moderate and meaningful learning gains. This demonstrates the effectiveness of ESD-based e-modules in addressing science literacy gaps, particularly in sustainability and energy transition education, where traditional methods may fall short. Given these positive outcomes, educators, curriculum developers, and policymakers should consider wider adoption and further refinement of such e-modules. Future designs should emphasize increased scaffolding for scientific explanations, adaptive feedback to meet diverse learner needs, and contextual relevance through local content. Further research is necessary to evaluate the long-term sustainability of these digital interventions on scientific literacy and pro-environmental behaviors, as well as their scalability across different educational contexts. ESD-based e-modules have the potential to better equip students with the knowledge, skills, and dispositions needed to address climate change and sustainable development challenges. However, some limitations must be acknowledged, including the relatively small sample size of 28 students, which may affect the generalizability of the findings. The reliance on objective tests, while providing standardization, may not fully capture the complexity of students' scientific literacy in real-world situations. Test anxiety or unfamiliarity with the assessment format could also have influenced student performance. Despite these limitations, the study offers valuable insights into the promise and challenges of integrating ESD-based digital tools in science education. The findings highlight the need for ongoing development and evaluation to maximize the impact of such interventions. Overall, ESD-based e-modules represent a promising approach for advancing science literacy and promoting sustainability in education.

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