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# Development of Education for Sustainable Development (ESD)-Based E-Module on the Topic of Biochar to Train Students' Scientific Literacy

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**Abstract: Development of an Education for Sustainable Development (ESD)-Based E-Module on Biochar to Train Students' Scientific Literacy.** This study aims to develop an ESD-based e-module on biochar to train students' scientific literacy. The research method used was Type 1 Design and Development Research (DDR), which focuses on specific project phases: analysis, design, development, and evaluation. This study was limited to a pilot test during the evaluation phase. This study involved nine 11th-grade students at a high school in Bandung. Data collection instruments included validation sheets for the base text, practice questions, and analysis of student responses. The results showed that the ESD-based e-module on biochar was valid and suitable for learning. Furthermore, the results of the pilot test of students' scientific literacy profiles indicated good achievement levels across all aspects of scientific literacy. The developed ESD-based e-module on biochar was found to be valid and has the potential to train students' scientific literacy in chemistry education.

**Keywords:** Biochar, E-Module, Education for Sustainable Development, Scientific Literacy.

***Abstrak: Pengembangan E-Modul Berbasis Education for Sustainable Development (ESD) pada Topik Biochar untuk Melatih Literasi Sains Peserta Didik.*** *Penelitian ini bertujuan untuk mengembangkan produk berupa e-modul berbasis Education for Sustainable Development (ESD) pada topik biochar untuk melatih literasi sains peserta didik. Metode penelitan yang digunakan adalah Design and Development Research (DDR) tipe 1, yang berfokus pada tahap specific project phases: analisis, perancangan, pengembangan, dan evaluasi. Penelitian ini dibatasi sampai uji coba terbatas pada tahap evaluasi. Penelitian ini melibatkan sembilan peserta didik kelas XI di salah satu SMA di Kota Bandung. Instrumen pengumpulan data dilakukan menggunakan lembar validasi untuk teks dasar, latihan soal, dan analisis jawaban peserta didik. Hasil penelitian menunjukkan bahwa produk e-modul berbasis ESD pada topik biochar dinyatakan valid dan layak digunakan dalam pembelajaran. Selain itu, hasil uji coba terbatas pada profil literasi sains peserta didik menunjukkan tingkat capaian yang baik pada semua aspek literasi sains. E-Modul berbasis ESD pada topik biochar yang dikembangkan dinyatakan valid dan memiliki potensi untuk melatih literasi sains peserta didik dalam pendidikan kimia.*

***Kata Kunci**: Biochar, E-Modul, Literasi Sains, Pendidikan untuk Pembangunan Berkelanjutan.*

## ▪ INTRODUCTION

21st-century education is characterized by rapid advancements in science and technology, requiring students to possess essential competencies such as critical thinking, problem-solving, and scientific literacy to address global challenges (Anggraeni et al., 2022).

Scientific literacy is defined as an individual's ability to understand scientific concepts, evaluate evidence, and apply knowledge to make informed decisions in everyday life (Sutrisna, 2021). Within the Programme for International Student Assessment (PISA) 2025 framework, the Organization for Economic Cooperation and Development (OECD) (2023), it emphasizes that scientific literacy involves engaging with science-related issues and participating in discussions about technology.

Despite its importance, scientific literacy among Indonesian students remains a significant challenge. The 2022 PISA results show Indonesia ranked 65th out of 81 countries, with a score of 383, which is considerably below the international average of 485 (OECD, 2023a). Factors contributing to this low performance include poor reading skills, a lack of contextual teaching, and a heavy reliance on traditional textbooks that fail to engage students in real-world applications (Fuadi et al., 2020).

Scientific literacy consists of four main aspects: scientific competence, knowledge, context, and scientific identity. Scientific competence within the PISA 2025 framework has three main dimensions: 1) explaining phenomena scientifically, 2) designing and evaluating scientific investigations, and critically interpreting data and evidence, and 3) researching, evaluating, and using scientific information for decision-making and action. To achieve these scientific competencies, knowledge is required that goes beyond mere content knowledge, procedural and epistemic knowledge, as well as a sense of scientific identity, are also necessary (OECD, 2023b). Research by Enawaty & Erlina (2021) shows that the highest level of literacy is found in the content domain, while the process and context domains remain low; therefore, to improve chemistry literacy skills, it is recommended to use problem-solving strategies in instruction.

Current teaching practices often struggle to bridge the gap between abstract scientific theories and contextual reality. To address this, scientific literacy can be integrated through the Education for Sustainable Development (ESD) approach. ESD empowers students with the values and skills necessary for a sustainable future by integrating global issues such as climate change and resource management into the curriculum (UNESCO, 2017). However, the implementation of ESD in Indonesia is hindered by a shortage of innovative teaching materials that combine sustainability with core scientific concepts.

One promising solution is the development of e-modules. Unlike printed books, e-modules offer the advantages of greater flexibility and easier accessibility, allowing students to quickly find information and make use of various learning features available on a single device in a more interactive way (Yuniastuti et al., 2021). E-modules offer interactive multimedia features, such as animations and navigation tools, that provide immediate feedback and support independent learning (Lastri, 2023). According to the Kemendikbud (2017), effective e-modules must be self-instructional, adaptive, and user-friendly.

In the context of chemistry education, the topic of biochar can serve as an opportunity for the integration of ESD. Biochar is a carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions (Hidayat & Prmuga, 2024). Biochar functions as a soil conditioner because it is rich in base minerals (Ca, Mg, K) that can raise pH, reduce toxic aluminum solubility ($Al^{3+}$), and sequester carbon long-term (Liu et al., 2025). A common practice farmers often use to neutralize soil acidity is adding lime/calcite ($CaCO_2$). However, in the long term, this practice has the potential to cause nutrient imbalances in the soil (Krisnawati et al., 2019).

This context aligns with the 2025 Phase F Chemistry Curriculum Guidelines, which state that the Acid-Base Equilibrium topic has contextual applications in agriculture, such as the addition of lime to farmers' cultivated land to neutralize acidic soil (Kemendikdasmen, 2025). The use of the biochar context in chemistry instruction not only helps students understand the concept of Acid-Base Equilibrium but also raises awareness of environmental and sustainability issues.

A number of studies have developed e-modules based on Education for Sustainable Development (ESD) for chemistry education. Research by Hanifah et al. (2025) indicates that ESD-based e-modules are valid and reliable and can improve students' scientific literacy. Research by Puteri & Sulistina (2025) indicates that the development of ESD-oriented e-modules on reaction rate material is considered valid and capable of raising students' awareness of sustainability to achieve the Sustainable Development Goals (SDGs). Furthermore, research by Sari et al. (2024) indicates that ESD-based e-modules on the topic of bioplastics received an excellent response from students and were effective in enhancing scientific literacy through the presentation of contextualized content.

Research on e-modules covering chemical equilibrium has also advanced extensively. Research by Gurusinga et al., (2024), indicates that developing project-based STEM e-modules on chemical equilibrium is valid. Additionally, research by Anggraeni & Rahmawan (2024), indicates that the development of science literacy-based e-modules on chemical equilibrium is deemed suitable for use.

However, no research has yet specifically developed ESD-based e-modules on the topic of biochar in relation to the concept of acid-base equilibrium to train scientific literacy. Therefore, this study aims to produce an ESD-based e-module on the topic of biochar to train students' scientific literacy. Through this study, it is hoped that teaching materials can be developed that not only train students' scientific literacy but also cultivate awareness in achieving sustainable development goals across environmental, economic, and social dimensions. This study is also expected to contribute to the field of education, particularly in the development of innovative, contextual teaching materials aligned with ESD principles.

## ▪ METHOD

This study employs a research and development (R&D) approach to produce an ESD-based e-module on the topic of biochar, designed to train students' scientific literacy. The development model used is Type 1 Design and Development Research (DDR) proposed by Richey & Klein (2007), which comprises four stages: analysis, design, development, and evaluation.

This study was limited to the evaluation phase, which consists of a pilot study involving nine students. This pilot test aimed to determine the feasibility of using the e-module as well as the students' scientific literacy achievement in the pilot test. The results of this study are exploratory and cannot be generalized widely. The DDR model was implemented through the following systematic steps:

1. Analysis Phase
   This phase involves analyzing the needs for e-module development using a qualitative approach. In this phase, the following activities are carried out: 1) a literature review on scientific literacy and ESD, 2) an analysis of the learning outcomes (LO) for

chemistry in the 2025 Merdeka Curriculum, 3) an analysis of the content and context of the biochar topic, and 4) a preliminary survey via Google Forms regarding the needs for the e-module to be developed.

2. Design Phase
   In this phase, several design activities are carried out based on the results of the analysis phase, including 1) the formulation of learning objectives based on an analysis of the Learning Outcomes (CP) for chemistry in the 2025 Merdeka Curriculum, the graduate profile dimensions, and ESD aspects, 2) the formulation of content and context for chemistry materials on the topic of biochar, 3) the development of an e-module outline in accordance with the criteria outlined in the e-module development guidelines published by the (Kemendikbud, 2017).

3. Development Phase
   The e-module is created based on the blueprint developed during the design phase. During this phase, the following tasks are carried out: 1) integrating and refining the original text content and contextual material on the topic of biochar, 2) drafting the core text with visual analysis (images, illustrations, sketches), 3) the formulation of practice and assessment questions, 4) the development of the e-module in digital format, and 5) the validation of the e-module as a whole. The validation results serve as a reference for refining the e-module in accordance with the suggestions and feedback from the validators.

4. Evaluation Phase
   After revisions were made based on the expert validation results, a limited pilot test was conducted to assess students' comprehension in answering the questions in the e-module. This limited pilot test involved nine students divided into high, medium, and low ability groups, each consisting of three students, to determine the overall achievement of students' scientific literacy across all aspects. The students' answers were then analyzed based on the alignment of their response keywords with a scoring range of 0–2 to determine their scientific literacy profile. Students' achievement in scientific literacy aspects was categorized into three groups: 1) fully achieving scientific literacy aspects (score of 2), partially achieving scientific literacy aspects (score of 1), and not yet achieving scientific literacy aspects (score of 0).

**Research Participants and Subjects**

This study involved several groups of participants to ensure data validity. During the needs analysis phase, ten chemistry teachers served as informants. During the development and validation phase, two expert lecturers and one chemistry teacher acted as validators. The evaluation phase involved a pilot test with nine 11th-grade students at a high school in Bandung. Students were selected purposively and categorized into high, medium, and low academic ability groups to gather a comprehensive scientific literacy profile.

The instruments used were the validation instruments for the core text and practice questions in the e-module, as well as the student scientific literacy profile instrument based on an analysis of student responses. The validation form is completed by expert validators to assess the validity of the content and practice questions included in the developed e-module. The assessment indicators for validating the core text and questions in the e-module are presented in Table 1 below:

**Table 1.** Assessment indicators for the validation of source texts and questions

| Validation Sheet Assessment | Indicators Score | Score |
|---|---|---|
| Source Text | Alignment of content with learning objectives | 0-1 |
| | Accuracy of content and context | |
| | Accuracy of illustrations, images, symbols, and sketches in relation to the text | |
| | Appropriateness of language for students' developmental level | |
| Practice Questions | Alignment of questions with scientific literacy aspects | |
| | Alignment of questions with learning objectives | |
| | Accuracy of answer keys | |

**Data Analysis Techniques**

The data analysis techniques used in this study include analysis of product validation result and analysis of students' scientific literacy achievement.

1. Product Validation Analysis

   The assessment of the source text and questions was conducted using a validation sheet based on the Guttman scale, with a score of 1 assigned to the "yes" category and a score of 0 to the "no" category. The validation results were expressed as percentages using the formula proposed by Akbar (2017) as follows:

$$NP_{r1,r2,r3} = \frac{TS_{-e}}{TS_{-max}} \times 100\% \qquad (1)$$

   After obtaining the validation results from each validator, the overall validation result from the three validators is then calculated using the following formula:

$$V = \frac{NP_{r1} + NP_{r2} + NP_{r3}}{3} \qquad (2)$$

   Notes:

   | | | |
   |---|---|---|
   | V | = | Overall validation percentage |
   | $NP_{r1}$ | = | Score from the first validator |
   | $NP_{r2}$ | = | Score from the second validator |
   | $NP_{r3}$ | = | Score from the third validation |
   | $TS_{-e}$ | = | Total score obtained from the validators |
   | $TS_{-max}$ | = | Maximum total score |

   To assess the validity of the developed e-module, the validity level was determined by applying the validity criteria adapted from Akbar (2017), as presented in Table 2.

**Table 2.** Categorization of E-Module Validity

| Validity Criteria | Validity Level |
|---|---|
| 80,01% - 100% | Highly valid, can be used with minor revisions based on feedback |
| 60,01% - 80,00% | Valid, can be used but requires revision |

| | |
|---|---|
| 40,01% - 60,00% | Less valid; not recommended for use as major revisions are needed |
| 20,01% - 40,00% | Invalid; must not be used |
| 00,00% - 20,00% | Highly invalid; must not be used |

2. Analysis of Students' Scientific Literacy Achievement

   Overall scientific literacy achievement is determined by calculating the percentage of correct answers. This calculation follows the formula proposed by Purwanto (2019) as shown in Equation 3.

$$NP = \frac{R}{SM} \times 100 \quad (3)$$

   Notes:
   NP = Calculated percentage
   R = Student's score
   SM = Maximum total score

   The resulting percentage values were then interpreted using the classification index adapted from Sudijono (2013) as presented in Table 3.

**Table 3.** Classification of the Scientific Literacy Index

| **Score** | **Category** |
|---|---|
| 85 – 100 | Very Good |
| 70 – 84 | Good |
| 55 – 69 | Fair |
| 50 – 54 | Poor |
| 0 – 49 | Very Poor |

## ▪ RESULT AND DISCUSSION

The development of the ESD-based e-module on the topic of biochar was carried out using the DDR model, focusing on training students' scientific literacy through four systematic stages: analysis, design, development, and evaluation.

### Analysis Stage

A needs analysis was conducted by identifying the chemistry learning outcomes (CP) in the 2025 Merdeka Curriculum that align with the biochar topic and by identifying the content and context to be developed in the e-module. Subsequently, a preliminary survey regarding the needs for the e-module to be developed was conducted via a Google Form distributed to ten 11th-grade chemistry teachers at several high schools in the City/Regency of Bandung. The results of the preliminary survey showed that all teachers agreed and opined that the development of an ESD-based e-module on the biochar topic has the potential to train students' scientific literacy in terms of scientific competencies, knowledge, and scientific identity, as the e-module being developed is linked to contextual phenomena and has an environmental perspective. Teachers also hope that the development of ESD-based e-modules on the topic of biochar will not only train students' scientific literacy but also cultivate their environmental awareness and enable them to apply the chemical concepts they have learned to address scientific issues occurring in their surrounding environment.

**Design Phase**

In this phase, learning objectives are formulated based on the PISA 2025 scientific literacy framework; the content and context of the chemistry material on the topic of biochar are defined; and an outline for the e-module is developed in accordance with the Kemendikbud (2017) guidelines for e-module development. The framework for developing e-modules is presented in Table 4.

**Table 4.** E-Module Outline Structure

| Component | E-Module Content |
|---|---|
| E-Module Components | Front Cover<br>Foreword<br>Table of Contents<br>List of Figures<br>List of Videos<br>List of Tables |
| Introduction | E-Module Information<br>E-Module Description<br>User Guide E-Module<br>Concept Map |
| Learning Activity 1 and Learning Activity 2 | Learning Objectives<br>Content<br>“Let’s Read” Feature<br>“Let’s Practice” Feature<br>Summary<br>Assessment<br>Self-Reflection |
| Conclusion | Glossary<br>Bibliography<br>Author Profile |

**Development Phase**

During the development phase, the original text of the content and the context of the chemistry material on the topic of biochar were consolidated and refined; a basic text was drafted using visual analysis (images, illustrations, sketches); practice and assessment questions were formulated; and an e-module was created in digital format using the Canva application, which is then shared as a website. Additionally, the e-module is equipped with integrated features for practice questions, assessments, and self-reflection via Google Forms, allowing students to complete these directly within the e-module using electronic devices connected to the internet.

At this stage, validation instruments were also developed to assess the core text and questions contained within the e-module. The validation process involved investigator triangulation, engaging three validators: two expert professors specializing in chemistry and scientific literacy, and one chemistry teacher. This investigator triangulation aims to enhance the validity of the analysis results (Donkoh, 2023). The validation results serve as a reference for developing the e-module in accordance with the suggestions and feedback from the validators. The validation results for the base text developed in the e-module are presented in Table 5.

**Table 5.** Validation Results for the Base Text in the E-Module

| Validator | Empirical Score | Maximum Score | Average Validity Percentage for Each Validator | Validity Criteria |
|---|---|---|---|---|
| Validator 1 | 48 | 48 | 100% | Highly Valid |
| Validator 2 | 48 | 48 | 100% | Highly Valid |
| Validator 3 | 48 | 48 | 100% | Highly Valid |
| **Combined Average Percentage** | | | 100% | Highly Valid |

Based on Table 5, it is evident that the validation results of the base text in the e-module using the Guttman scale yielded a combined average percentage of 100% across the three validators, meeting the criteria for "highly valid" and deemed suitable for use with minor revisions based on validator feedback. This indicates that the developed e-module has met the suitability criteria regarding content, presentation, language, and alignment with ESD principles. The results of the validation of the practice questions developed in the e-module are presented in Table 6.

**Table 6.** Validation Results for Practice Questions in the E-Module

| Validator | Empirical Score | Maximum Score | Average Validity Percentage for Each Validator | Validity Criteria |
|---|---|---|---|---|
| Validator 1 | 36 | 36 | 100% | Highly Valid |
| Validator 2 | 36 | 36 | 100% | Highly Valid |
| Validator 3 | 36 | 36 | 100% | Highly Valid |
| **Combined Average Percentage** | | | 100% | Highly Valid |

In Table 6 above, the results of the validation of practice questions in the e-module using the Guttman scale yielded a combined average percentage of 100% across the three validators, meeting the criteria for "highly valid" and suitable for use. This indicates that the developed questions have met the criteria for validity and can be used to measure students' scientific literacy skills.

After making revisions based on the expert validation results, the researcher then compiled the e-module that had previously been designed during the design phase. The e-module was designed using the Canva application and then shared via a website to make it interactive. The e-module cover design consists of the title, target audience, curriculum used, author's name, and illustrations. The images or illustrations used must be appropriate to facilitate or even capture students' interest in the presented material (Suprayekti et al., 2018).

The e-module developed integrates aspects of ESD and scientific literacy; thus, it is designed to present phenomena related to topics connected to issues in the surrounding environment. The learning activities in this e-module consist of two components: 1) The Problem of Acidic Soil and Its Impact on Corn Growth, and 2) The Utilization of Corn Cobs as Biochar. According to Kosasih (2021), one criterion for a good module is the use of materials related to real-life facts and the surrounding environment. By presenting phenomena or facts occurring in daily life, students can enhance their critical thinking skills and take action regarding issues in society, thereby developing their scientific literacy skills (Warningsih et al., 2019).

The "Let's Read" feature presents a reading text discussing issues related to acidic soil in agriculture; these issues are linked to the context of biochar and acid-base equilibrium chemistry as an application of concepts to address acidic soil. Additionally, there is a "Let's Practice" feature that presents questions based on the reading text, integrating indicators from the scientific literacy domain to develop students' scientific literacy skills.

A study by Wati & Fatisa (2017), indicates that questions requiring students to find answers by analyzing evidence and evaluating and processing data can encourage students to develop critical thinking skills and scientific literacy.

**Evaluation Phase**

After making revisions based on the results of expert validation, a limited pilot test was conducted to assess students' comprehension in answering the questions contained in the e-module. This limited pilot test involved nine students divided into high, medium, and low ability groups, each consisting of three students, with the aim of assessing the students' scientific literacy profiles after using the ESD-based e-module on the topic of biochar. The scientific literacy measured encompassed three main aspects: scientific competencies, scientific knowledge, and scientific identity.

The analysis of student responses was conducted using a previously designed and validated rubric with a scoring range of 0–2. During the analysis of student responses, a process of triangulation among researchers (investigator triangulation) was carried out. This process aims to ensure the accuracy of the interpretation of the analysis results of student responses, to enhance the validity of the research findings, and arrive at accurate conclusions (Donkoh, 2023). The results of the analysis of students' scientific literacy profiles for each item are presented in Table 7.

**Table 7.** Results of the Analysis of Students' Scientific Literacy Profiles

| Question | Scientific Literacy Aspect | | Student Ability Group | | | | | | | | | Achievement Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | High | | | Moderate | | | Low | | | |
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 | |
| 1 | CK | SC1 | ● | ● | ● | ● | ● | ● | ● | ◐ | ● | |
| 2 | CK | SC1 | ● | ● | ● | ● | ◐ | ● | ● | ● | ◐ | |
| 3 | SI2 | SC3 | ● | ● | ● | ● | ● | ● | ● | ● | ◐ | |
| 4 | CK | SC1 | ● | ● | ● | ● | ● | ◐ | ◐ | ◐ | ◐ | |
| 5 | CK | SC1 | ● | ● | ● | ● | ● | ● | ● | ● | ● | |
| 6 | SI1 | SC1 | ● | ● | ● | ● | ● | ● | ◐ | ● | ● | |
| 7 | EK | SC1 | ● | ● | ● | ● | ● | ● | ● | ● | ● | |
| 8 | EK | SC1 | ● | ● | ● | ● | ● | ● | ● | ◐ | ● | |
| 9 | CK | SC2 | ● | ● | ● | ● | ● | ● | ● | ● | ● | |
| 10 | CK | SC1 | ◐ | ● | ● | ◐ | ● | ● | ◐ | ● | ◐ | |
| 11 | PK | SC1 | ● | ● | ● | ● | ● | ● | ● | ◐ | ● | |
| 12 | SI3 | SC1 | ● | ● | ● | ● | ● | ● | ● | ● | ● | |
| | ● | | 11 | 12 | 12 | 11 | 11 | 11 | 9 | 8 | 8 | **86,11%** |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ◐ | 1 | 0 | 0 | 1 | 1 | 1 | 3 | 4 | 4 | **13,89%** |
| ○ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0%** |

Notes:

SI1 : Scientific Identity Dimension 1: Valuing Scientific Perspectives and the
Scientific Approach in Research
SI2 : Scientific Identity Dimension 2: The Affective Elements of Scientific Identity
SI3 : Scientific Identity Dimension 3: Environmental Awareness, Concern, and
EK : Agency
CK : Epistemic Knowledge
PK : Content Knowledge
SC1 : Procedural Knowledge
SC2 : Scientific Competency Dimension 1: Explaining Phenomena Scientifically
Scientific Competency Dimension 2: Designing and Evaluating Designs for
SC3 : Scientific Inquiry and Critically Interpreting Data and Evidence
Scientific Competency Dimension 3: Investigating, Evaluating, and Using
● : Scientific Information for Decision-Making and Action
◐ : Achieves all aspects of scientific literacy as measured
○ : Achieves some aspects of scientific literacy as measured
Has not yet achieved all aspects of scientific literacy as measured

Based on the results in Table 7, the scientific literacy profiles of students in the three group categories show that 86.11% of students were able to meet the measured aspects of scientific literacy. This indicates that, in general, students already possess good scientific literacy skills. However, there are still 13.89% of students who can only meet some aspects of scientific literacy. This may be due to differences in students' academic ability levels, particularly among those in the moderate and low ability groups. This finding aligns with the research by Rohmania & Suryanti (2024), which shows that students with low academic ability tend to have low levels of scientific literacy because they experience difficulties in applying their scientific knowledge. The achievement of scientific literacy in each aspect is presented in Figure 1.

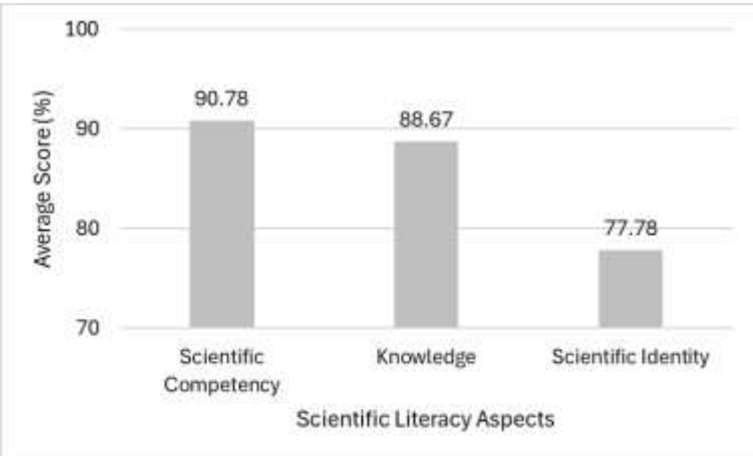


**Figure 1.** Graph of Average Scores for Overall Scientific Literacy

Based on the diagram in Figure 1, it can be seen that the scientific competency aspect has the highest average score compared to the other two aspects. The average score obtained for the scientific competency aspect was 90.78%, which falls into the "very good" category. This indicates that the biochar e-module developed is effective in training students to explain scientific phenomena. In the e-module, the presentation of the biochar context is linked to real-world problems such as the utilization of corn cob waste and soil quality improvement, thereby encouraging students to connect chemical concepts with phenomena occurring in the surrounding environment. Additionally, through the "Let's Read" and "Let's Practice" features, students are guided to analyze information, identify cause-and-effect relationships, and explain phenomena based on the biochar context in acidic soil. This aligns with research by Santoso et al. (2023), which states that contextual phenomenon-based learning demonstrates effective results in improving students' scientific literacy, particularly in explaining phenomena scientifically, as students are directly engaged in problem-solving processes based on real-life issues. Research by Milanto et al. (2023) also shows that contextual learning is effective in improving students' ability to explain phenomena scientifically.

In terms of knowledge, the average score achieved was 88.67%, which also falls into the "very good" category. This indicates that through the biochar e-module, students' cognitive abilities are developed not only through content knowledge but also through procedural and epistemic knowledge. In the ESD-based e-module, contextual problems are presented that require in-depth understanding through reading activities, analyzing information, and answering reasoning-based questions. Students not only understand concepts but also how those concepts are used to explain phenomena and solve problems. This aligns with research by Pradipta et al. (2021) which shows that ESD-based learning can enhance problem-solving skills and encourage students to think more deeply about contextual problems. Furthermore, the PISA 2025 framework also emphasizes that knowledge in scientific literacy encompasses content, procedural, and epistemic knowledge that are mutually integrated in building students' scientific understanding (OECD, 2023b).

There is a correlation between scientific competencies and knowledge, such that high achievement in knowledge is accompanied by high achievement in scientific competencies. This indicates that students with a strong conceptual understanding are more capable of using that knowledge to explain phenomena scientifically. This aligns with the OECD, (2023b) which states that scientific competency is closely linked to knowledge, where scientific knowledge serves as the foundation for students to develop the ability to explain scientific phenomena, use scientific evidence, and solve science-based problems. In the e-module, this connection is evident in how students use information from the reading text to answer questions that require scientific reasoning. This aligns with the research by Saraswati et al. (2021), which states that students with strong conceptual mastery are better able to apply their knowledge in various situations.

Meanwhile, regarding scientific competencies, the average score obtained was lower than that for scientific knowledge, at 77.78%, which falls into the "good" category. The low achievement in the aspect of scientific identity is influenced by various factors, one of which is that students are not yet accustomed to linking their learning to values and attitudes toward the environment. This aligns with research stating that attitudes and values are internal factors that play a role in shaping students' behavior and environmental awareness; thus, if these aspects have not developed adequately, students' scientific identity has also not been optimally formed (Pratama et al., 2024). Nevertheless, the implementation of the ESD approach in the e-module has begun to show signs of developing students' environmental awareness. Students are beginning to understand that the chemistry concepts they learn are not merely theoretical but can also be applied in real life, for example, in the use of biochar to neutralize acidic soil in agriculture. This aligns with the PISA 2025 framework, which emphasizes that scientific literacy does not focus solely on cognitive aspects but also encompasses a scientific identity related to values, attitudes, and actions (OECD, 2023b).

Overall, the findings of this study indicate that the ESD-based e-module on biochar developed in this study has the potential to train students' scientific literacy, particularly in terms of scientific competencies and knowledge. However, these results are still limited to a small-scale pilot study and therefore cannot be widely generalized. Consequently, further research with a larger scope is needed to assess the effectiveness of the e-module in training students' scientific literacy across various learning conditions.

## ▪ CONCLUSION

This research produced an e-module based on Education for Sustainable Development (ESD) on the topic of biochar, which has been deemed suitable for use in chemistry education based on expert validation results. Limited pilot test results indicate that the use of the e-module has the potential to develop students' scientific literacy across various academic ability levels (high, moderate, and low). Achievements in the aspects of scientific competence and knowledge fell into the "very good" category with respective percentages of 90.78% and 88.67%, while the aspect of scientific identity fell into the "good" category at 77.78%. This indicates that the biochar context linked to acid-base equilibrium concepts, specifically neutralization reactions and $Al^{3+}$ hydrolysis, along with the ESD approach in the e-module, provides a contextual and meaningful learning experience. Consequently, the developed e-module has the potential to serve as an alternative instructional resource in supporting the implementation of contextual and sustainable chemistry education.

However, this study has several limitations, including the fact that the product trial was conducted only on a limited scale with a relatively small number of students, so the research results cannot yet be widely generalized. Furthermore, it did not involve learning implementation over a longer period, so the impact of the e-module on changes in students' attitudes and sustainability awareness could not yet be optimally observed.

Further research is recommended to conduct trials on a larger scale, using a wider variety of instruments, and to implement e-modules in long-term learning to obtain a more comprehensive picture of students' scientific literacy development.

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