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Modules STEM-Based Science Learning Integrated with Education for Sustainable Development Materials on Environmental Pollution to Improve Science Literacy and Independent Learning

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Abstract: This study aimed to develop and evaluate a science learning module based on a STEM approach integrated with Education for Sustainable Development (ESD) on environmental pollution material for seventh-grade students. The research examined the module's validity, practicality, and effectiveness in improving scientific literacy and learning independence. The development process employed the ADDIE model, while effectiveness testing used a quasi-experimental design with three groups: a STEM–ESD integrated module (experimental group), a STEM-only module, and an ESD-only module (comparison groups). The participants were seventh-grade students of SMPN 3 Sanggau Ledo. Data were collected using expert validation sheets, teacher and student response questionnaires, scientific literacy tests, and learning independence questionnaires. The results indicated that the module was categorized as very valid in terms of content, construction, and language, and very practical based on teacher and student responses. Effectiveness testing showed that the STEM–ESD integrated module resulted in higher improvements in scientific literacy compared to the STEM-only and ESD-only modules, with mean differences of 15.9 and 21.7, respectively. Statistical analysis using t-test and MANOVA revealed significant differences among the three groups ($p < 0.05$). In addition, students in the STEM–ESD group achieved the highest learning independence score (88.4%). In conclusion, the STEM–ESD integrated module is valid, practical, and statistically effective in enhancing scientific literacy and learning independence.

Keywords: ADDIE; Environmental pollution; ESD; Learning independence; Science learning module; Scientific literacy; STEM

Introduction

The 21st century is characterized by rapid and complex changes that significantly influence various aspects of life, including education (Malik, 2018). These changes demand learning approaches that are not only knowledge-oriented but also capable of equipping students with essential competencies to face future challenges. According to Patel et al. (2024), 21st-century skills encompass learning skills (critical thinking, problem solving, creativity, collaboration, and communication), literacy skills (information, media, and technology), and life skills (flexibility, leadership, initiative, productivity, and social skills). Therefore, learning innovation that integrates these competencies into classroom practice is an urgent necessity.

One approach that is widely recognized for supporting these competencies is STEM (Science,

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Technology, Engineering, and Mathematics) education. STEM integrates multiple scientific disciplines to engage students in solving real-world problems through inquiry, experimentation, and evidence-based reasoning, thereby strengthening conceptual understanding and critical thinking skills (AlAli, 2024; Mikušková, 2023). Beyond cognitive development, STEM learning environments promote active participation, collaboration, and problem-solving, which are essential foundations for self-regulated learning. In this context, STEM aligns with the needs of the Industrial Revolution 4.0, which emphasizes innovation, adaptability, and the ability to solve complex problems (Boltsi et al., 2024; Samaniego et al., 2024).

Alongside STEM, Education for Sustainable Development (ESD) has emerged as a critical educational framework that integrates environmental, social, and economic dimensions into learning. ESD aims to develop learners' knowledge, skills, and values to support sustainable development (Cheng et al., 2024). UNESCO (2017) emphasizes that ESD integration enables students to become agents of change who are aware of environmental issues and responsible decision-making. The socio-cultural, environmental, and economic perspectives of ESD are expected to foster holistic awareness of sustainability challenges (Fitroni et al., 2025). Previous studies confirm that ESD-based environmental education enhances students' awareness and understanding of environmental issues (Simamora et al., 2022).

However, previous studies indicate that the integration of STEM, ESD, scientific literacy, and independent learning in classroom practice remains limited and fragmented. Hanifah et al. (2025) assess that existing learning approaches often focus on content mastery without systematically integrating sustainability perspectives and self-directed learning skills, resulting in suboptimal development of scientific literacy and learning independence. This condition highlights a clear research gap regarding the need for learning resources that intentionally integrate STEM and ESD to simultaneously address cognitive and affective learning outcomes.

In the Indonesian context, the Merdeka Curriculum initiated by the Ministry of Education, Culture, Research, and Technology provides an opportunity to implement learner-centered and project-based learning. This curriculum allows teachers greater flexibility to design contextual and interactive learning experiences (Collins et al., 2021; Ariswari et al., 2024). The reduction of compulsory content by 30–40% enables educators to focus on developing students' competencies and character through meaningful learning activities (Naseer et al., 2025). Nevertheless, the implementation of the Merdeka Curriculum in regions such as Bengkayang Regency faces challenges, including limited facilities, insufficient learning resources, and a lack of teacher capacity to develop innovative STEM–ESD-based modules.

These challenges are closely related to Indonesia's persistent problem of low scientific literacy. Internationally, the 2018 PISA results show that Indonesian students achieved an average science literacy score of 396, significantly below the OECD average of 487 (Ministry of Education and Culture, 2020). The 2022 PISA cycle recorded a further decline of 13 points, indicating ongoing difficulties in understanding and applying scientific concepts. At the local level, education report card data from SMP Negeri 3 Sanggau Ledo show a 13.17% decrease in science literacy scores in 2023. Although both datasets indicate declining trends, it is important to note that PISA reflects international comparative performance, while the education report card represents school-level national assessment outcomes.

Low scientific literacy is often associated with limited learning resources, monotonous teaching methods, and teacher-centered instruction that minimizes student engagement (Januarti et al., 2024; Luah et al., 2025; Munandar et al., 2024). Such learning environments tend to position students as passive recipients of information, reducing opportunities for inquiry, experimentation, and reflection (Muliyadi et al., 2023). Consequently, students struggle to develop scientific reasoning skills and intrinsic motivation, which are essential for independent learning.

Independent learning is a crucial competency in 21st-century education. Liu (2025) defines independence as the ability to fulfill learning needs without excessive reliance on others, while Forbes-McKay et al. (2025) emphasize that independent learning is driven by internal motivation and self-regulation. STEM-based learning theoretically supports the development of self-regulated learning by engaging students in goal setting, problem analysis, decision making, and reflection. When combined with ESD, learning activities become more meaningful and value-oriented, strengthening students' internal motivation and sense of responsibility toward real-world problems. However, observations at SMP Negeri 3 Sanggau Ledo indicate that students still demonstrate low learning independence, characterized by passivity, lack of focus, and minimal initiative to learn beyond classroom activities.

This condition underscores the importance of developing integrated STEM–ESD learning modules as structured and contextual learning resources. Learning modules function as complete instructional units that enable students to learn independently and systematically (Holisoh et al., 2025). STEM-based

modules encourage critical and creative thinking through real-world problem solving, while ESD integration embeds sustainability values and social responsibility into learning experiences (Belkhir, 2020).

Therefore, the novelty of this research lies in the development of an integrated STEM–ESD science learning module that is specifically designed to address both scientific literacy and learning independence within the context of the Merdeka Curriculum and local educational challenges. This study is important as it provides an empirically tested learning solution that supports sustainable, student-centered learning while responding to declining scientific literacy and limited independent learning among junior high school students.

Method

This study employed a Research and Development (R&D) approach aimed at producing a science learning module based on the STEM approach integrated with Education for Sustainable Development (ESD) and examining its validity, practicality, and effectiveness in improving students' scientific literacy and learning independence. The development model used was ADDIE, which consists of the stages of analysis, design, development, implementation, and evaluation. During the analysis stage, a needs assessment was conducted covering science learning conditions, student characteristics, the Merdeka Curriculum, and issues related to scientific literacy and learning independence. The design stage involved formulating learning objectives, learning materials, STEM–ESD-based learning activities, and research instruments. The development stage included module production, validation by subject matter experts and media experts, and product revision based on validator feedback. The implementation stage consisted of limited trials, wider trials, and operational field trials, while the evaluation stage was conducted to determine the final feasibility of the developed product.

Product trials were conducted in stages after the module was declared valid by experts. The limited trial aimed to identify the initial readability and practicality of the module and involved ten seventh-grade students representing high, medium, and low academic abilities, as well as two science teachers. Data at this stage were collected using readability and practicality questionnaires, which served as the basis for product refinement. The wider trial was conducted in one non-sample class using a one-group pretest–posttest design to obtain an initial overview of learning implementation and student responses before applying the module in the operational field trial.

The operational field trial aimed to examine the effectiveness of the module in improving students' scientific literacy and learning independence. At this stage, a quasi-experimental design employing a nonequivalent control group pretest–posttest design was used with three groups: one experimental class using the STEM–ESD integrated module, one control class using a STEM-based module without ESD, and one control class using an ESD-based module without STEM. Each group was given a scientific literacy pretest and posttest, as well as measurements of learning independence before and after the learning process.

The research subjects were seventh-grade students of SMP Negeri 3 Sanggau Ledo in the odd semester of the 2025/2026 academic year. The sampling technique used was purposive sampling, considering the equivalence of academic characteristics and classroom conditions. After selecting the classes, experimental and control classes were determined through random class assignment to ensure that differences in learning outcomes could be attributed to the applied treatments.

The independent variable in this study was the STEM-based science learning module integrated with ESD, while the dependent variables were students' scientific literacy and learning independence. Data were collected using test and non-test techniques. The test technique was employed to measure scientific literacy through validated essay-type written tests. Non-test techniques included interviews, observations, and questionnaires. A learning independence questionnaire with a four-point Likert scale was used to measure students' learning independence in both experimental and control classes. Observations were conducted to assess learning implementation and students' independent learning behavior during the learning process. In addition, readability and practicality questionnaires were used to evaluate the ease of module use from the perspectives of students and teachers.

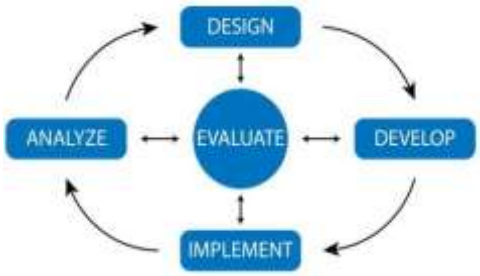

Figure 1. Flowchat method

Data analysis was conducted to assess the validity, practicality, and effectiveness of the developed module. Module validity and practicality were analyzed using the Guttman scale and the Percentage of Agreement (PA) method, with the module considered feasible and

practical if the PA value reached at least 70%. Module effectiveness was analyzed using paired sample t-tests to examine within-group improvements and Multivariate Analysis of Variance (MANOVA) to compare differences in scientific literacy and learning independence improvements between experimental and control groups. If parametric assumptions were not met, the non-parametric Kruskal–Wallis test was applied. In addition, effect size was calculated using Cohen's f to determine the magnitude of the influence of the STEM–ESD integrated science learning module on students' scientific literacy and learning independence.

Result and Discussion

Initial Product Development Results

The learning module developed is a digital module with a STEM (Science, Technology, Engineering, and Mathematics) approach that is integrated with ESD (Education for Sustainable Development) and equipped with a virtual laboratory. This module is designed to improve science literacy and independent learning among seventh-grade junior high school students on the subject of environmental pollution.

The module design was created using Canva, downloaded in PDF format, and then converted into an interactive flipbook via Heyzine.com so that it can be easily accessed via students' smartphones. This digital feature makes learning more contextual and in line with the characteristics of the digital generation. The module structure consists of: (1) an introduction containing competencies, concept maps, and learning objectives; (2) presentation of material that integrates the concept of environmental pollution with the STEM approach; (3) project and experiment activities such as eco terrariums, simple water filters, and bioplastic production; (4) reflection and evaluation; and (5) reinforcement of ESD values in the form of environmental awareness, social responsibility, and conservation of natural resources.

The development process refers to the ADDIE model, which includes the stages of analysis, design, development, implementation, and evaluation. The results of the needs analysis show that science learning in schools is still teacher-centered and learning resources are limited to textbooks, so students are less active in relating science concepts to environmental issues. Therefore, a module that integrates the STEM approach and ESD values was developed to address these needs.

Analyse

The analysis stage was conducted to identify the needs and problems in science learning in grade VII at SMP Negeri 3 Sanggau Ledo. The results of the analysis showed that learning was still teacher-centered and only used textbooks as learning resources, so students tended to be passive. Through analysis of the material and media needs, it was determined that the development of an integrated ESD STEM learning module on environmental pollution was the right solution because it allowed students to learn independently according to their respective abilities and speeds. The integration of material with videos and observation activities was also considered effective in improving students' science literacy. In addition, this stage also established Learning Outcomes (CP), Learning Objectives (TP), and Learning Objective Flow (ATP) in accordance with the independent curriculum applicable in schools.

Design

At the design stage, activities began with the selection of Canva as the module development platform. Next, a concept map, content, learning activities, module usage instructions, and evaluation questions were compiled. The module layout design includes the cover, background, font, and page layout, which are tailored to the ESD-oriented STEM approach. This stage ends with a self-review to ensure the consistency and attractiveness of the module layout from start to finish. The cover design can be seen in the following image.

Figure 2. Cover

Development

During the development stage, teaching materials and learning videos relevant to environmental pollution were created. Learning activities were designed in three STEM-based projects/practical's, namely the creation of an Eco Terrarium, a water filter, and bioplastics. After the module was completed, it was tested for validity by media experts and subject matter experts using an assessment questionnaire. The experts provided

feasibility scores, comments, and suggestions for improvement, which were used to revise the module to make it more optimal. The results of the revision showed that the module and learning videos were deemed suitable for use in the learning process. The following are the results of the assessment by two validators (lecturers).

Construction Aspects

Based on the feasibility test results of the STEM-based ESD-oriented learning module product on environmental pollution, it can be concluded that the average score obtained by respondents was 4.4 out of a maximum average score of 5.0. The result was 88%. Based on the categorization, it can be said to be very feasible. Therefore, the module can be said to be feasible in terms of construction for use in the next stage.

Content Aspects

Based on the feasibility test results of the STEM-based ESD-oriented learning module product on environmental pollution, it can be concluded that the average score obtained by respondents was 4.2 out of a maximum average score of 5.0. The result was 84%. Based on the categorization, it can be said to be very feasible. Therefore, the module can be said to be feasible in terms of content for use in the next stage.

Language Aspects

Based on the results of the feasibility test of the STEM-oriented ESD-oriented learning module product on environmental pollution material, it can be concluded that the average score of the results obtained by respondents is 4.3 out of a maximum average score of 5.0. Then the results are 86%. Based on the categorization, it can be said to be very feasible. Therefore, the module can be said to be feasible in terms of language for use in the next stage. Based on the results of the feasibility test of the STEM-oriented ESD-oriented learning module product on environmental pollution material, it can be concluded that the average score of the results obtained by respondents is 4.3 out of a maximum average score of 5.0. Then the results are 86%. Based on the categorization, it can be said to be very feasible. Therefore, the module can be said to be feasible in terms of language for use in the next stage.

Implementation

In this implementation stage, 2 stages of limited scale testing and large scale testing were carried out. For the limited scale test, the respondents were 10 students of class VII of SMP Negeri 3 Sanggau Ledo and for the large scale test, the respondents consisted of 2 science teachers and 60 students of class VII of SMP Negeri 3 Sanggau Ledo.

Limited Scale Test Results

Based on the results of a limited scale feasibility test conducted by 10 student respondents of the STEM-based learning module product oriented to ESD on environmental pollution material, it can be concluded that the score obtained by the respondents was 306 out of a maximum score of 340. Then the results obtained were 90% based on the categorization, which can be said to be very feasible.

Table 1. Limited Scale Test Assessment Results

Indicator	Score
Presentation	38
Language	54
Material	56
Appearance	52
Benefit	52
Ease of Use	54
Score	306

Large Scale Test Results

Based on the results of a large-scale feasibility test conducted by 60 student respondents of the STEM-based learning module product oriented to ESD on environmental pollution material, it can be concluded that the score obtained by the respondents was 1832 out of a maximum score of 2040. Then the results obtained were 89.8% based on the categorization, which can be said to be very feasible.

Table 2. Result. Large Scale Test

Indicator	Score
Presentation	216
Language	322
Material	316
Appearance	318
Benefit	336
Ease of Use	324
Score	1832

Evaluation

The evaluation stage is conducted to determine whether the developed product or media meets the desired objectives. The type of evaluation used in this study is formative evaluation, which assesses or measures the product being developed during the ongoing stages. This includes validation by content/learning materials experts, learning media experts, and teacher and student trials. No improvements were made to the teachers or students. Based on these results, the STEM-based ESD-oriented learning module product with environmental pollution material for seventh-grade junior high school students is feasible and practical for use in improving scientific literacy and student learning independence.

Overall, it is in the Very Feasible category. This can be seen from the expert test which showed 2 experts said it was very feasible, 2 teachers said it was very feasible, 60 student respondents said it was very practical. Therefore, it can be concluded that the STEM-based learning module product, ESD-oriented with environmental pollution material for grade VII of junior high school, is feasible and practical to use in order to improve scientific literacy and student learning independence.

Table 3. Results of the Feasibility and Practicality Test of Learning Media

Respondents	Score	Max Score	Percentage	Category
Validator 1	76	85	89.4%	Very Worthy
Validator 2	70	85	82.4%	Very Worthy
Teacher	170	200	85%	Very Practical
Student	1832	2040	89.8%	Very Practical

Extensive Trial Science Literacy Results

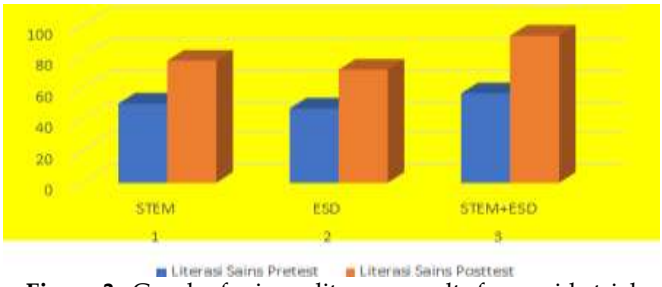

Figure 3. Graph of science literacy results from wide trial

Based on Figure 3, it can be seen that in learning using the STEM approach learning module oriented to ESD, the learning outcomes in scientific literacy skills have a better or higher increase compared to the STEM approach module alone and the ESD-oriented module alone. This shows that there is a difference in the results of scientific literacy skills before and after treatment, but with the best results in the experimental class that uses the STEM approach module and ESD-oriented environmental pollution material.

Learning Independence Scores on the Extensive Trial

This table shows a comparison of the learning independence scores achieved by students in the three treatment groups. In the first group, which used the STEM Module without ESD, the average score was 826 out of a maximum score of 1600. This equates to a learning independence percentage of 51.625%.

The second group, which used the ESD Module without STEM, achieved a slightly lower average score of 805 out of the same maximum score (1600). Their learning independence percentage was 50.3%. The third group, the experimental group and using the ESD-integrated STEM Module, demonstrated significantly higher results. This group achieved an average score of 1416, which is 88.4% of the maximum score.

Overall, the data in this table indicates that the use of learning modules that simultaneously integrate STEM and ESD resulted in the highest level of learning independence among the three groups. This indicates that the integration of these two approaches significantly contributes to improving student learning independence.

Table 4. Result Learning Independence Scores on the Extensive Trial

Respondents	Score	Max Score	Percentage	Category
Teacher	170	200	85%	Very Practical
Student	1832	2040	89.8%	Very Practical

Practicality Analysis of the Module

Based on the questionnaire data analysis, the average practicality score was in the "Very Practical" category. This indicates that the module can be used effectively without requiring excessive guidance from either teachers or other instructors.

Table 5. Practically Analysis Module

Class	Learning Independence Score	Maximum Score	Presentation
1 (STEM Module without ESD)	826	1600	51.625%
2 (ESD Module without STEM)	805	1600	50.3%
3 (STEM Module integrated ESD)	1416	1600	88.4%

Conclusion

In conclusion, this study demonstrates that the STEM-based science learning module integrated with Education for Sustainable Development (ESD) on environmental pollution is valid, practical, and effective within the context of seventh-grade students at SMP Negeri 3 Sanggau Ledo. Expert validation confirmed high validity in terms of content, construction, and language, while teacher and student responses indicated that the module was very practical and easy to implement in classroom learning. The effectiveness of the module was empirically supported by inferential statistical analyses, in which paired sample t-tests showed significant pretest–posttest improvements, and MANOVA results indicated that students who used the STEM–ESD integrated module achieved significantly higher gains in scientific literacy and learning independence compared to students using STEM-only or ESD-only modules ($p < 0.05$). Notably, the most

important finding of this study is the synergistic effect of integrating STEM and ESD, which resulted in a substantially higher level of learning independence, reaching 88.4%, compared to the control groups. These findings suggest that the combined STEM–ESD approach offers added pedagogical value beyond single-approach modules, although the generalization of results is limited to contexts with similar student characteristics and learning conditions.

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