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Development of Stem-Esd E-Modules to Improve Students' Integrated Problem-Solving Competencies in Grade 10 Students'

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ABSTRACT
This study aims to develop a STEM-ESD (Science, Technology, Engineering, Mathematics - Education for Sustainable Development) e-module to train integrated problem-solving competencies in environmental change material. The method used is Research and Development (R&D) with the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) development model. The research subjects involved 62 grade 10 students from a school in Sukabumi City. Validation scores from material, language, and media experts were 98%, 92%, and 94% (very high), respectively. The effectiveness of the e-module was evaluated using an actual experiment with a pretest-posttest control group design. The theoretical implications of this study lie in the development of integrated STEM-ESD tools using the Engineering Design Process (EDP) approach, which remains limited in the context of the Independent Curriculum. The analysis results showed a significant increase in students' integrated problem-solving competency in the experimental class, with an N-Gain value of 0.62 (medium category), compared to the control class, which only achieved 0.22 (low category). Furthermore, user responses to the e-module showed excellent ratings in terms of appearance, language, ease of use, and visual appeal. Overall, the STEM-ESD e-module is practical and effective in enhancing learning outcomes and environmental awareness, while directly supporting SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). This module has the potential to serve as an innovative solution for sustainability-oriented learning in secondary schools. This e-module has the potential to be an innovative solution in supporting sustainability-oriented learning at the secondary school level.

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1. INTRODUCTION

The global environmental crisis has become a major barrier to achieving the Sustainable Development Goals (SDGs), with environmental damage largely caused by human activities such as fossil fuel use, deforestation, industrialization, and air pollution (Asif et al., 2021; Dagnachew & Hof, 2022; Raman et al., 2024; van Zanten & van Tulder, 2021). These activities have severely affected ecosystems and human life over the past decades, making sustainability-focused education increasingly urgent (Ahmed et al., 2020; Najwa & Suhartini, 2023).

In Indonesia, waste is one of the most critical contributors to environmental degradation. Household waste generation exceeds 32 million tons annually, with over 11 million tons unmanaged (KLHK, 2024). Food waste alone reaches 20.9 million tons per year (Kusumawardani et al., 2023), placing Indonesia as the 17th largest contributor globally despite ranking 70th in severe hunger levels. Mismanaged food waste in landfills produces methane (CH_4), a greenhouse gas more potent than CO_2, which worsens climate change and has even caused local disasters such as the 2005 Leuwi Gajah landfill explosion in West Java that killed hundreds (Moubareck et al., 2023). Low public awareness worsens this condition, as shown by the National Waste Management Information System (SIPSN), which reported that only 62.24% of waste was properly managed in 2023 while 37.76% remained untreated (KLHK, 2023). These challenges underscore the importance of Education for Sustainable Development (ESD) to foster environmentally friendly behaviour, support SDG 12 on responsible consumption and production, and equip students with eight key sustainability competencies that are transversal, multifunctional, and relevant across all SDGs (Hapsoro & Bangun, 2020; Kioupi & Voulvoulis, 2022; Purnamasari & Nurawaliyah, 2023; UNESCO, 2017; Vilmala et al., 2022).

The current education system is required to be able to face global challenges presented in every aspect of our lives. Education that is aligned with environmental, social, and economic conditions and needs is crucial to better prepare students for their future lives (Alismail & McGuire, 2015; Fathurohman et al., 2023; Marouli, 2021; OECD, 2024). Issues related to environmental damage and socio-scientific issues, in particular, can be addressed through the implementation of sustainable education (Gunamantha, 2010; Lubis et al., 2022; Suhendar et al., 2025; Tytler, 2012; Wang et al., 2018). One learning approach relevant to the Sustainable Development Goals (SDGs) is the STEM approach. STEM learning is an integration of Science, Technology, Engineering, and Mathematics learning that is expected to contribute to success in the 21st century (Solihah et al., 2024; Yuenyong et al., 2021). The Engineering Design Process (EDP) framework fosters iterative problem-solving, critical for STEM-ESD integration, and is considered the best approach to implementing ESD programs in schools. There are pedagogical principles in STEM that align with the characteristics of ESD, namely encouraging student participation in developing solutions to real-life problems (Abdurrahman et al., 2023; Firda et al., 2021; Gamage et al., 2022; Margot & Kettler, 2019; Martín-Sánchez et al., 2022; Rahman et al., 2023; Widarti & Roshayanti, 2021). However, the implementation of STEM-ESD in schools is often hampered by inadequate teaching materials.

Observations at a school in Sukabumi revealed that the implementation of learning was suboptimal due to the limited availability of teaching materials. This often presents challenges for teachers in implementing the curriculum, and more importantly, it impacts the quality of education for the students. Teachers often struggle to develop materials that meet students' needs, such as those related to environmental change. Research by Najwa & Suhartini (2023) found that the Merdeka Curriculum, a new curriculum implemented with limited preparation time, often presents challenges for teachers in its implementation. These challenges include unclear material boundaries and limited teaching materials. Developing e-modules to facilitate STEM-ESD is a pressing need to support optimal learning and ensure a better educational experience for the students.

The development of the STEM-ESD e-module has the potential to serve as a learning resource that encourages the development of students' integrated problem-solving competencies. Through the integration of STEM and education for sustainable development (ESD), this e-module presents science and technology-based materials and encourages student engagement in environmental issues. Learning addresses real-world problems (real-world problem-solving) that foster critical, creative, and collaborative thinking, making the learning experience practical and relevant. The advantage of STEM learning lies in the application of the Engineering Design Process (EDP), a systematic approach through the following stages: identifying problems, researching, idealizing, building, testing, and reflecting (Abdurrahman et al., 2023; Martín-Sánchez et al., 2022; Setiono & Windyariani, 2023), which guides students to think integratively and reflectively.

E-modules are designed digitally and interactively, providing flexible learning access. This advantage enables independent and contextual learning, allowing for adaptation to each student's learning style (Logan et al., 2021; Novianti et al., 2023; Santa et al., 2024). Interactive displays and engaging visuals enhance engagement and motivation. With these characteristics, e-modules have the potential to support the strengthening of higher-order thinking skills, meeting the demands of the independent curriculum and the challenges of 21st-century learning.

The explanation above demonstrates that e-modules are a potential learning medium for advancement. Adibah et al. (2023) highlighted that e-modules are highly effective for students, as they can significantly enhance the efficiency of independent learning and can be tailored to each individual's learning interests. E-modules also have the potential to help students better grasp the material, thereby contributing to improved learning outcomes (Lazuardi et al., 2023). Therefore, this study aims to develop a STEM-ESD e-module based on the Engineering Design Process (EDP), focusing on environmental change in the independent curriculum, and to examine its effectiveness in improving students' integrated problem-solving competencies. This is the first study to develop EDP-based STEM-ESD e-modules for Indonesia's Merdeka Curriculum, highlighting its novelty and contribution to sustainability-oriented education. Hence, there is an urgent need for further research to develop teaching tools that are not only relevant but also impactful for the learning process.

2. RESEARCH METHOD

The type of research used is the Research and Development (R&D) research method. Research and Development (R&D) is a research method that aims to produce, develop, and test the effectiveness of a product (Novianti et al., 2023; Rustamana et al., 2024; Rustandi & Rismayanti, 2021). The R&D method facilitates the development and creation of products based on the data obtained (Rustamana et al., 2024). The use of the Research and Development (R&D) research method aims to produce a practical STEM-ESD e-module for grade 10 students, focusing on integrated problem-solving competencies in environmental change materials.

The research model used is the ADDIE development model developed by Dick & Carey (1996). This comprehensive model, used to develop educational programs and teaching materials, was first developed at the University of Florida in 1975 (Johnson-Barlow & Lehnen, 2021; Spatioti et al., 2022). The ADDIE model, with its five stages: Analysis, Design, Development, Implementation, and Evaluation, ensures a thorough and systematic approach to educational development (Ranuharja et al., 2021; Santa et al., 2024; Spatioti et al., 2022) (See Figure 1).

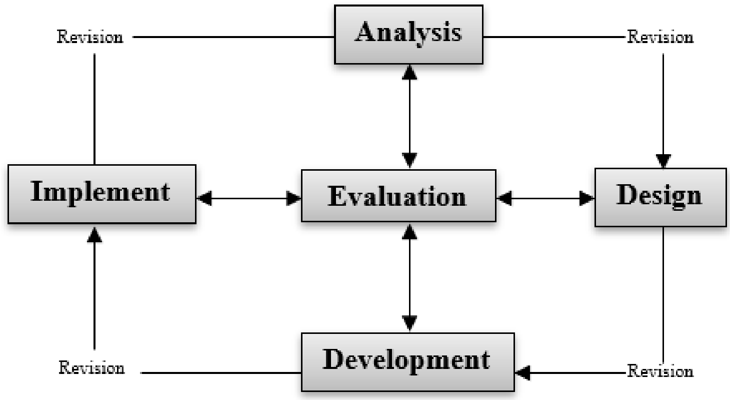


Figure 1. ADDIE development model (Santa et al., 2024)

The ADDIE stages carried out in this study to develop the STEM-ESD e-module are presented in detail in Table 1.

Table 1. ADDIE Stages (Santa et al., 2024; Spatioti et al., 2022)

Stage	Activities	Data Collection Techniques	Subject
Analysis	Analysis of curriculum, student characteristics, materials, teaching tools, teacher needs, and learning environment	Interviews and questionnaire	30 10th-grade students and two biology subject teachers at a high school in Sukabumi City.
Design	1. Preparation of materials 2. Design of e-modules 3. Preparation of data collection instruments		
Development	E-module design development		
	E-module Validation	Media expert validation	Media expert lecture
		Language expert validation	Language expert lecture
		Material expert validation	Material expert lecture
Implementation	Validity and reliability test	Effectiveness test instrument	20 10th-grade students in the school sample
	Readability test	Readability questionnaire for effectiveness test instruments	10 10th-grade students in the school sample
	Testing the Effectiveness of STEM-ESD E-modules in Training Competencies	Effectiveness test questions	62 10th-grade students in the school sample
	User response	User response questionnaire	31 10th-grade students in the school sample
Evaluation	Each stage is evaluated	Conduct revisions based on suggestions and input from expert lecturers, as well as the results of instrument testing.	

During the development stage, the e-module underwent validation by material, language, and media experts. Experts rated the e-modules using a 5-point Likert scale across multiple criteria, including content accuracy, language clarity, instructional design, and media quality.

The STEM-ESD e-Module will be used in conjunction with a pretest-posttest instrument to determine the product's effectiveness in training Integrated Problem-Solving competencies. The trial was conducted using a Pretest-Posttest Control Group Design, a method that ensures scientific rigor. Before being given treatment, students first took a pretest, followed by a posttest after the e-module was implemented. This design allows for a more objective comparison of learning outcomes before and after the intervention. In addition to measurements obtained through tests, students were also asked to complete a questionnaire to assess the effectiveness of the e-module that had been used. The research design is illustrated in Figure 2.

$$\begin{array}{cccc} R_1 & O_1 & & O_2 \\ & & X & \\ R_2 & O_1 & & O_2 \end{array}$$

Figure 2. pretest-posttest control group design

Explanation:
R_1 : Experiment class
R_2 : control class
O_1 : Pretest score (before treatment)
O_2 : Posttest score (after treatment)
X : Treatment

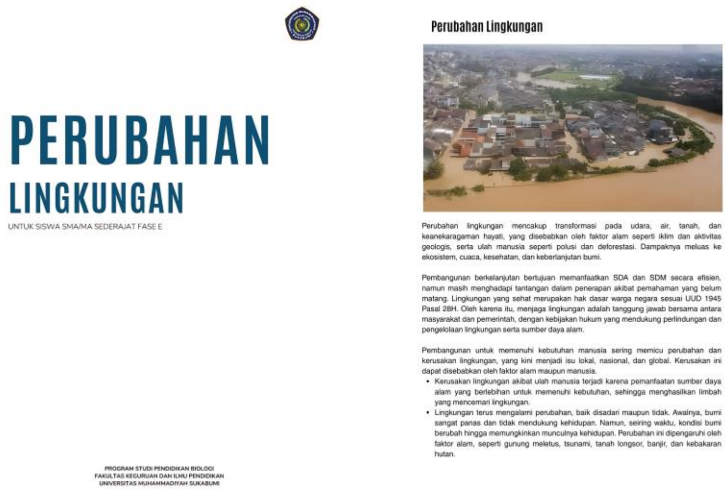
This stage aims to determine the extent to which the use of e-modules impacts students' integrated problem-solving competencies. Testing was conducted in a real classroom setting involving 62 students who were purposively sampled from SMAN 01 Sukabumi: 31 in the control class (not given e-modules but with the same learning materials) and 31 in the experimental class (given e-modules). The final stage in the ADDIE development model is evaluation. At this stage, an assessment is conducted based on the results of the response questionnaire and input from students and validators, which is used to measure the success of using the developed e-modules. This research, conducted with utmost ethical considerations, obtained official permission from the school that served as the research site, approval from the University Muhammadiyah Sukabumi Ethics Board, and informed consent from participating students and teachers. The data obtained were then analysed using the Statistical Package for the Social Sciences (SPSS) version 26, employing descriptive statistics, N-Gain analysis, normality and homogeneity tests, as well as an independent sample t-test to determine the effectiveness of the e-module.

3. RESULT AND DISCUSSION

The target of this research is to develop an effective STEM-ESD E-Module that trains students in grade X in integrated problem-solving competencies related to environmental change materials. The integration of STEM (Science, Technology, Engineering, and Mathematics) with ESD (Education for Sustainable Development) is expected to foster a comprehensive understanding of environmental issues in the context of sustainable development, particularly regarding the concept of ecological change. The research model used is based on the ADDIE development model, developed by Dick & Carey (1996). The ADDIE model is a framework for developing educational programs and teaching materials (Johnson-Barlow & Lehnen, 2021; Spatioti et al., 2022).

The first stage in e-module development is problem analysis. The purpose of this analysis is to identify the needs and problems associated with learning. At this stage, the curriculum, subjects, student characteristics, teaching materials, and learning modules are analysed and evaluated. A needs analysis was conducted on 30 students and two biology teachers at SMAN 01 Sukabumi City. Based on the analysis, the learning media used were deemed ineffective, too theoretical, boring, and not relevant to real life or environmental issues. Furthermore, the learning media used tended to be one-way, lacked visuals, and did not support independent learning. As a result, learning became boring and tended to decrease student interest and motivation (Chalupa, 2021; Santa et al., 2024; Vonitsanos et al., 2024). In today's modern era, students not only need engaging learning materials but also those that can increase their enthusiasm for learning (Santa et al., 2024; Zulfira et al., 2024). Teaching materials for educators and students can be provided in the form of e-modules. The use of e-modules continues to increase due to their flexibility, adaptability to independent learning needs, encouragement of active student engagement, and ubiquitous use (Alyusfitri et al., 2024; Santa et al., 2024; Setianingsih et al., 2025).

The second stage in e-module development is the design stage. The e-module was developed based on Core Competency 3.4, which analyses data on environmental change, its causes, and impacts on life, and formulates solutions for environmental conservation. The e-module not only covers Core Competencies, learning objectives, materials, and evaluation but is also designed interactively. This module aims to enrich and support the achievement of learning objectives by drawing on material from various references, including books, articles, and other online sources. Planning and utilizing technology-based learning media is crucial in education because it has been proven to increase efficiency, effectiveness, ease of access, and support flexibility in the learning process (Isnaeni et al., 2021; Santa et al., 2024). The STEM-ESD e-module trial design is illustrated in **Figure 3**.



a. Cover Design **b.** Content design

Figure 3. STEM-ESD e-Module design blueprint

During the development phase, the STEM-ESD e-module was developed according to the design until it was completed. The e-module was then validated by several experts, based on media, language, and material aspects. The validation process is a crucial step in e-module development, ensuring that the content, display, and language are appropriate and suitable for use by students. The involvement of experts at this stage significantly impacts the refinement of the e-module, resulting in a product that is both effective and suitable for use in the learning process (Aslik et al., 2022; Atikah et al., 2021; Fawaid et al., 2025; Hendrawensi et al., 2024; Melanie Utamy & Hufri, 2024; Santa et al., 2024). Material experts evaluated the e-module by considering aspects of material feasibility, material accuracy, and STEM integration. Validation by material experts is presented in Table 2.

Table 2. Material expert validation

No	Aspects	Value of each aspect	Max score	Percentage	Criteria
1	Material suitability	31	32	96	Valid
2	Material accuracy	43	44	97	Valid
3	STEM integration	12	12	100	Valid
	Overall Score	86	88	98	Valid

Linguists evaluated the e-module by assessing several aspects, including language suitability, the cohesiveness of thought flow, the use of easily understood language, and compliance with PEUBI. Validation from linguists is evident in Table 3.

Table 3. Language expert validation

No	Aspect	Value of each aspect	Max score	Percentage	Criteria
1	Language suitability	16	16	100	Valid
2	Cohesiveness of thought flow	19	20	95	Valid
3	Use of easy-to-understand language	11	12	91	Valid
4	Compliance with PUEBI	13	16	81	Valid
	Overall Score	59	64	92	Valid

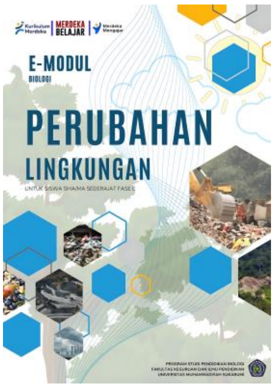
Media experts evaluated the e-module, considering aspects of appearance, content completeness, and instruction clarity. Validation from media experts is evident in Table 4.

Table 4. Media expert validation

No	Aspect	Valie of each aspect	Max score	Percentage	Criteria
1	E-Module appearance	20	20	100	Valid
2	Content completeness	28	28	100	Valid
3	Media instruction clarity	16	20	80	Valid
	Ovelall score	64	68	94	Valid

The results of expert validation indicate that the developed STEM-ESD e-module meets the criteria in three aspects: material, language, and media. Based on the results in Table 2, validation from material experts yielded a percentage of 98%, indicating that the material is valid. These. These results suggest that the content, accuracy, and implementation of STEM in the e-module are of excellent quality. Validation from language experts yielded a percentage of 92%, indicating that the language used in the e-module is valid (as shown in Table 3). This demonstrates that the language used is clear, follows the rules, and is easy to understand. Based on the results in Table 4, validation by media experts confirms the validity of the criteria, with a percentage of 94%. These results indicate that the appearance, aesthetics, interactivity, and presentation of the e-module are perfect and can support the learning process. The validation results from each expert indicate valid outcomes, demonstrating that the STEM-ESD e-module is deemed feasible and ready for use in the learning process. The developed STEM-ESD e-module has met the established criteria, thus improving functionality and effectiveness in the learning process. These positive outcomes of the validation process should instill optimism about the potential of the STEM-ESD e-module (Nikmah et al., 2019; Risniawati et al., 2020; Santa et al., 2024).

The developed e-module (Figure 4) is a comprehensive resource, comprising 48 pages. It was created using the Canva application and then converted into Flip PDF format via the Flipping Book platform. This STEM-ESD e-module consists of two learning activities, with the first activity titled "Let's observe the surrounding environment" and the second activity "Let's make use of waste around us." Each activity includes several stages, namely: Identify Problems and Constraints, Research, Ideate, Analyse Ideas, Build, Test and Refine, and Communicate and Reflect. All stages refer to the STEM learning process through the Engineering Design Process (EDP) approach Both activities are linked to SDGs Learning Objective 12 on Responsible Consumption and Production and SDGs 13 on Climate Change (UNESCO, 2017; Zuhaida et al., 2024).



a. E-module cover

b. content of environmental changes

Figure 4. The developed STEM-ESD E-Module design.

The next stage is the fourth stage, namely, implementation. The STEM-ESD e-module was developed using environmental change materials, including analysing environmental change data, its causes, and impacts on life, as well as formulating solutions for environmental conservation. This e-module is designed for 10th-grade students at SMAN 01, Sukabumi City. The trial was conducted in two classes, namely the control and experimental classes. There was no difference in learning between the two classes; however, only in the experimental class was the STEM-ESD e-module given. The trial was conducted over five meetings. The first meeting was filled in the pre-test. The second meeting involved several stages, namely: Identifying the Problem and Constraint, Researching, Ideating, and Analysing ideas. The third meeting involved two stages for students, namely Build, Test, and Refine. The fourth meeting was conducted in the Communicate and Constraint stages; the fifth meeting involved data collection, specifically completing the post-test.

a**.** Identify Problem and Constraint

b. Build, Test and Refine

Figure 5. Implementation stage.

The research was conducted in the 10th grade on environmental change. The e-module, developed based on real-world problems, focused on household waste, providing a tangible and relevant context for the students. Students were given a case study of a waste problem in their environment, then asked to discuss and design a solution through a collaborative approach. This process led them to develop an environmentally friendly product, in the form of eco-enzymes, as illustrated in Figure 5. This activity is part of implementing the engineering design process (EDP) stages, which are integrated into the STEM-ESD e-module.

This study aims to measure the effectiveness of using STEM-ESD e-modules by involving one class as an experimental class that utilizes e-modules, and comparing it with a control class that does not use e-modules in the learning process. Data were analysed using the N-Gain test to assess the impact of using STEM-ESD e-modules on learning effectiveness. The results of the effectiveness test are presented in Table 5 and illustrated in Figure 6, which compares the pretest and posttest scores of the experimental and control classes.

Table 5. N-Gain results of pretest-posttest values

Kelas	Pretest	Posttest	N-Gain	Criteria
Control	43,33	56,29	0,22	Low
Experiment	44,28	79,23	0,62	Medium

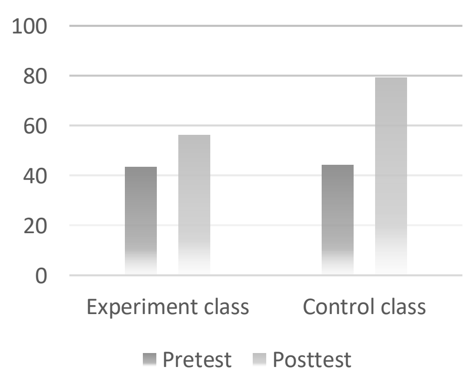


Figure 6. Comparison of pretest and posttest scores

The N-gain values of the two classes differ. The N-gain value in the experimental class is higher than that in the control class. The N-gain value of the experimental class is 0.62, categorized as medium, while the control class is 0.22, categorized as low. This is in line with the analysis conducted by Meltzer (2002), as cited in Frahasta et al. (2023), which categorizes N-gain scores into three levels, as shown in **Table 6**.

Tabel 6. N-Gain score criteria

Criteria	N-Gain Score
High	g > 0.7
Medium	0.3 < g ≤ 0.7
Low	G ≤ 0.3

Additionally, normality and homogeneity tests were conducted on the pre-test and post-test results of both classes as a preliminary requirement for performing parametric analysis. The normality test aims to determine whether the data in the population is normally distributed. Once normally distributed, the next step is to conduct a homogeneity test to determine whether the data variance is homogeneous. Once the data meet the normality and homogeneity criteria, the necessary parametric analysis tests can be conducted. One such analysis is the independent sample t-test, which is used to test hypotheses using parametric methods. In this study, post-test data from the experimental and control classes were used in the hypothesis test. The analysis and hypothesis testing process was carried out using the robust and reliable SPSS version 26 software. The summary results of the analysis are shown in **Table 7** below.

Table 7. Summary of Normality Test, Homogeneity Test, and Hypothesis Test

Test	Class	Description	Value (Sig.)	Note
Normality Test (Shapiro-Wilk)	Experiment	*Pretest*	0,559	Normally distributed data
		Posttest	0,783	
	Control	*Pretest*	0,722	
		Posttest	0,332	
Homogeneity Test	Experiment and Control	*Based on mean*	0,98	Homogeneously distributed data
		Based on median	0,981	
		Based on the median with adjusted	0,981	
		Based on trimmed mean	0,976	
Hypothesis Test (Independent Sample T-test)	Experiment dan Control	*Pretest*	0,685	Significanly different
		Posttest	0	

Based on the data in Tables 5 and 7, the N-Gain results indicate an increase in learning outcomes in both classes, but with varying levels of effectiveness. The control class showed an N-Gain value of 0.22, which falls within the low criteria, indicating that the increase in integrated problem-solving competency in that class was not statistically significant. Meanwhile, the experimental class showed an N-Gain value of 0.62, which falls within the medium category, indicating that the use of the STEM-ESD e-module has a greater impact on integrated problem-solving competency compared to conventional learning. Our N-Gain (0.62) exceeds the outcome reported by [Study X] (0.45), underscoring the efficacy of applying the Engineering Design Process (EDP) framework in enhancing problem-solving competencies. The STEM-ESD e-module provides learning materials and media that are easily accessible and contextualized, enabling students to use them independently and deepen their understanding of the subject (Maison & Wahyuni, 2020). This e-module features an attractive and user-friendly interface, fostering a sense of empowerment and control in students. This increases students' learning interest and encourages their reading skills (Abed, 2019; Santa et al., 2024).

In the experimental class, there was a significant increase in integrated problem-solving competency. Active student involvement in solving contextual problems through the Engineering Design Process stages is a significant factor in increasing integrated problem-solving competency. The stages of the Engineering Design Process include: Identify Problems and Constraints, Research, Ideate, Analyze Ideas, Build, Test and Refine, and Communicate and Reflect, facilitating in-depth critical thinking, problem-solving, and collaborative processes (Setiono & Windyariani, 2023). Martín-Sánchez et al. (2022) stated that engineering design process-based learning within the STEM-ESD framework is effective in increasing student participation and reflective abilities on sustainability issues. Furthermore, the use of interactive e-modules with attractive visual designs and accessibility through digital platforms also contributes to encouraging student motivation and learning independence. This is reinforced by the findings of Alyusfitri et al. (2024), who stated that digital e-modules can adapt to individual learning needs and significantly increase cognitive engagement.

The next stage is the evaluation stage, which aims to determine the success of the STEM-ESD e-Module. This is done by analyzing the results of the user response questionnaire and collecting input from students and teachers. The response questionnaire was used to measure the effectiveness of the STEM-ESD e-module on environmental change material. The questionnaire was administered to 31 participating students. The results of the questionnaire analysis are presented in Table 8.

Table 8. User Response Questionnaire Results

No	Indicator	Score (%)	Criteria
1	Presentation/Display	90,2 %	Very Good
2	Language	91, 4 %	Very Good
3	Ease of use	91, 1%	Very Good
4	Media usability	91,6 %	Very Good
5	Attractiveness and usability of visual communication	92,9 %	Very Good

The questionnaire results in Table 8 indicate that the STEM-ESD e-module received a very positive response from users, with scores of 90.2% for the display aspect, 91.4% for the language aspect, and 91.1% for ease of use. This indicates that the module is engaging, communicative, and easy to operate. The learning media was rated as easy to access with a score of 91.6%, and the visual communication was rated as very effective with a score of 92.9%. Overall, the module was rated as very good in supporting the learning process. The STEM-ESD e-module encourages students to learn independently and work individually, thus gaining both general and professional knowledge (Amalia et al., 2024; Dinu & Petre, 2018; Santa et al., 2024). Learning media in digital form also have their advantages. E-modules can be accessed in various places, and their ability to display a wide range of content, including images, videos, and animations, makes this medium effective in increasing student engagement, interest, motivation, and learning outcomes (Miranda & Wibowo, 2023; Najwa & Suhartini, 2023). However, the generalizability of these findings is constrained by the relatively small and context-specific sample, which limits the extent to which the results can be applied to broader educational settings.

4. CONCLUSION

The study's results demonstrated that the development of the STEM-ESD e-module was effective in training Education for Sustainable Development (ESD) competencies in 10th-grade students, particularly in the area of environmental change. The development process followed the ADDIE model, which includes Analysis, Design, Development, Implementation, and Evaluation. Validation by experts demonstrated that the e-module met the eligibility criteria for discussion materials and media, achieving a high validity score. The results of the effectiveness test, conducted through a one-group pretest-posttest approach and a comparison between the experimental and control classes, showed a significant increase in students' understanding of environmental issues, with a medium N-Gain value in the experimental class and a low one in the control class.

The developed e-module combines the STEM approach and ESD principles, is designed interactively through a digital platform, and supports students' independent learning. With its attractive appearance, communicative language, and contextual and relevant content, the e-module was highly rated by students in various aspects, including attractiveness, ease of use, and visual effectiveness. The use of this e-module not only improves learning outcomes but also fosters problem-solving skills and environmental awareness in students. This demonstrates that the integration of STEM-ESD in digital media has great potential as an innovative solution to support sustainable education in schools.

This study is limited by its implementation timeframe and limited scope, which only covered environmental change. Therefore, careful interpretation and generalization of the findings are essential. Policymakers should prioritize teacher training in EDP-based STEM-ESD design to enhance classroom implementation and scalability. Further research is recommended to develop STEM-ESD e-modules for other SDG themes and test them at various educational levels to obtain more comprehensive and applicable findings. Future studies should also extend implementation to both urban and rural schools, as well as investigate potential gender and cultural influences on learning outcomes.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Abdurrahman, A., Maulina, H., Nurulsari, N., Sukamto, I., Umam, A. N., & Mulyana, K. M. (2023). Impacts of integrating engineering design process into STEM makerspace on renewable energy unit to foster students' system thinking skills. *Heliyon*, *9*(4), e15100. https://doi.org/10.1016/j.heliyon.2023.e15100

Abed, E. K. (2019). Electronic Learning and its Benefits in Education 1. *EURASIA Journal of Mathematics, Science and Technology Education*, *15*(3). doi: 10.29333/ejmste/102668

Abubakar, I. R., Maniruzzaman, K. M., Dano, U. L., AlShihri, F. S., AlShammari, M. S., Ahmed, S. M. S., Al-Gehlani, W. A. G., & Alrawaf, T. I. (2022). Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South. *International Journal of Environmental Research and Public Health*, *19*(19). https://doi.org/10.3390/ijerph191912717

Adibah, B., Yovita, Y., & Zein, M. (2023). Evaluasi Penggunaan E-Module di Kalangan Mahasiswa: Studi Pengembangan di UIN Suska Riau. *Milenial: Journal for Teachers and Learning*, *3*(2), 84–91. https://doi.org/10.55748/mjtl.v3i2.139

Ahmed, Z., Asghar, M. M., Malik, M. N., & Nawaz, K. (2020). Moving towards a sustainable environment: The dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Resources Policy*, *67*(January), 101677. https://doi.org/10.1016/j.resourpol.2020.101677

Alismail, H. A., & McGuire, P. (2015). 21st Century Standards and Curriculum: Current Research and Practice. *Journal of Education and Practice*, *Vol.6*, *No.*(ISSN 2222-1735), 150–154. https://files.eric.ed.gov/fulltext/EJ1083656.pdf

Almaududi, S. (2024). Blue Economy Dalam Pemberdayaan Masyarakat Mencapai Sustainable. *Jurnal Review Pendidikan Dan Pengajaran (JRPP), 7(3)*, *7*, 12057–12061. https://journal.universitaspahlawan.ac.id/index.php/jrpp/article/download/33376/22055/110005

Alyusfitri, R., Gistituati, N., Yerizon, Fauzan, A., & Yarman. (2024). The Effectiveness and Relationship of Student Responses toward Learning Outcomes Using Interactive Multimedia-Based E-Modules in Elementary Schools. *International Electronic Journal of Elementary Education* , *16*(5), 573–584. https://doi.org/10.26822/iejee.2024.354

Amalia, S., Safrida, S., & Ulva, S. M. (2024). *Differentiated Learning Integrated with Social Emotional Awareness and Digital Learning Media in Improving the Students Motivation and Learning Outcomes*. *10*(1), 239–244. https://doi.org/10.29303/jppipa.v10i1.5354

Amegah, A. K., & Jaakkola, J. J. K. (2016). Pollution de l'air domestique et objectifs de développement durable. *Bulletin of the World Health Organization*, *94*(3), 215–221. https://doi.org/10.2471/BLT.15.155812

Anzolin, G., & Lebdioui, A. (2021). Three Dimensions of Green Industrial Policy in the Context of Climate Change and Sustainable Development. *European Journal of Development Research*, *33*(2), 371–405. https://doi.org/10.1057/s41287-021-00365-5

Asif, M., Saleem, S., Tariq, A., Usman, M., & Ul Haq, R. A. (2021). Pollutant Emissions from Brick Kilns and Their Effects on Climate Change and Agriculture. *ASEAN Journal of Science and Engineering*, *1*(2), 135–140. https://doi.org/10.17509/ajse.v1i2.38925

Aslik, M., Karyono, H., & Gunawan, W. (2022). Pengembangan E-Modul IPA Berbasis Literasi untuk Mendukung Pembelajaran Daring Bermakna. *JINOTEP (Jurnal Inovasi Dan Teknologi Pembelajaran): Kajian Dan Riset Dalam Teknologi Pembelajaran*, *9*(1), 56–67. https://doi.org/10.17977/um031v9i12022p056

Atikah, N., Gistituati, N., Fitria, Y., & Syarifuddin, H. (2021). Validitas E-Modul Matematika Sekolah Dasar Berbasis Pendekatan Realistic Mathematics Education (RME). *Jurnal Basicedu*, *5*(6), 6103–6109. https://doi.org/10.31004/basicedu.v5i6.1799

Bhakta, H., Raja, K., Samal, B., & Cheela, V. R. S. (2020). Circular economy approach in solid waste management system to achieve UN-SDGs Solutions for post-COVID recovery. *Science of the Total Environment*, *January*. https://www.sciencedirect.com/science/article/pii/S0048969721046805/pdfft?md5=5638abb6445276996ec2e1b47c8ca34b&pid=1-s2.0-S0048969721046805-main.pdf

Cattaneo, A., Federighi, G., & Vaz, S. (2021). The environmental impact of reducing food loss and waste: A critical assessment. *Food Policy*, *98*(August 2019), 101890. https://doi.org/10.1016/j.foodpol.2020.101890

Chalupa, C. (2021). Increasing Motivation among Language Learners through Individualized Assessment. *Central European Journal of Educational Research*, *3*(2), 1–13. https://dea.lib.unideb.hu/bitstreams/e991d137-f2fb-4375-affc-e08ea767d472/download

Dagnachew, A. G., & Hof, A. F. (2022). Climate change mitigation and SDGs: modelling the regional potential of promising mitigation measures and assessing their impact on other SDGs. *Journal of Integrative Environmental Sciences*, *19*(1), 289–314. https://doi.org/10.1080/1943815X.2022.2146137

Dick, W., & Carey, lou. (1996). *The systematic design of instruction* (4th ed). HarperCollins College Publisher.

Dinu, C., & Petre, V. C. (2018). Educational Platform for Developing and Prototyping Electronic Assemblies. *International Conference and Exposition on Electrical And Power Engineering (EPE)*, 27–30. https://ieeexplore.ieee.org/abstract/document/9044167

Djirong, A., Jayadi, K., Abduh, A., Mutolib, A., Mustofa, R. F., & Rahmat, A. (2024). Assessment of Student Awareness and Application of Eco-Friendly Curriculum and Technologies in Indonesian Higher Education for Supporting Sustainable Development Goals (SDGs): A Case Study on Environmental Challenges. *Indonesian Journal of Science and Technology*, *9*(3), 657–678. https://doi.org/10.17509/ijost.v9i3.74385

Fathurohman, I., Amri, M. F., Septiyanto, A., & Riandi. (2023). Integrating STEM based Education for Sustainable Development (ESD) to Promote Quality Education: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 1052–1059. https://doi.org/10.29303/jppipa.v9i11.4430

Fawaid, Faulina, R., & Sari, D. I. (2025). Pengembangan E-Modul Berbasis Etnomatematika Pada Materi Bangun Ruang Sisi Datar Di Mts Nurul Karomah. *Numeracy*, *12*(1), 51–66. https://doi.org/10.46244/numeracy.v12i1.3092

Fields, V., Educational, A., & Lemon, H. A. (2024). IJOTIS Is Climate Change a curse ? Causing Huge Effect on. *Indonesian Journal of Teaching in Science (IJoTIS)*, *4*(1), 85–96. https://ejournal.upi.edu/index.php/IJoTis/article/view/68758

Firda, R.-, Kaniwati, I., & Sriyati, S. (2021). STEM Learning in Sustainability Issues to Improve Sustainability Consciousness of Junior High School Students. *Paedagogia*, *24*(1), 53. https://doi.org/10.20961/paedagogia.v24i1.54212

Frahasta, R. I., Juhanda, A., & Nuranti, G. (2023). Implementation of Game-Assisted Interactive Demonstration on Students ' Problem-Solving Skills and Digital Literacy in the Immune System. *BIOEDUKASI: Jurnal Biologi Dan Pembelajarannnya*, *21*(3), 287–298. https://doi.org/10.19184/bioedu.v21i3.41213

Gamage, K. A. A., Ekanayake, S. Y., & Dehideniya, S. C. P. (2022). Embedding Sustainability in Learning and Teaching: Lessons Learned and Moving Forward-Approaches in STEM Higher Education Programmes. *Education Sciences*, *12*(3). https://doi.org/10.3390/educsci12030225

Gunamantha, I. M. (2010). Pendidikan Untuk Pembangunan Berkelanjutan : Mengapa, apa dan bagaimana. *Pendidikan Dan Pengajaran*, *43*(3), 215–221. http://download.garuda.kemdikbud.go.id/article.php?article=2676608&val=1324&title=PENDIDIKAN UNTUK PEMBANGUNAN BERKELANJUTAN MENGAPA APA DAN BAGAIMANA

Hapsoro, N. A., & Bangun, K. (2020). Perkembangan Pembangunan Berkelanjutan Dilihat Dari Aspek Ekonomi Di Indonesia. *Lakar: Jurnal Arsitektur*, *3*(2), 88. https://doi.org/10.30998/lja.v3i2.7046

Hendrawensi, Hidayati, A., Yeni, F., & Zurwina. (2024). Development of Electronic Module (E-Module) Based on Case Method in Science Subjects at Junior High School. *Jurnal Penelitian Pendidikan IPA*, *10*(6), 3486–3492. https://doi.org/10.29303/jppipa.v10i6.6796

Hsieh, Y. L., & Yeh, S. C. (2024). The trends of major issues connecting climate change and the sustainable development goals. *Discover Sustainability*, *5*(1). https://doi.org/10.1007/s43621-024-00183-9

Ibrahim, I. M., Suryadi, K., & ... (2024). Examining Climate Change Issues for Improving Cross-Generation Awareness in 21st Century Agenda: A Bibliometric Approach. *Asean ...*, *3*(2), 173–182. https://ejournal.bumipublikasinusantara.id/index.php/ajsed/article/view/491

Isnaeni, W., Sujatmiko, Y. A., & Pujiasih, P. (2021). Analysis of the Role of Android-Based Learning Media in Learning Critical Thinking Skills and Scientific Attitude. *Jurnal Pendidikan IPA Indonesia*, *10*(4), 607–617. https://doi.org/10.15294/jpii.v10i4.27597

Jakhongir, S., Khayrilla, K., Muhabbat, H., & Salim, K. (2023). Analyzing Climate Policy Utilizing Financial and Energy Industry Models. *ASEAN Journal of Economic and Economic Education*, *2*(2), 125–138.

Johnson-Barlow, E. M., & Lehnen, C. (2021). A scoping review of the application of systematic instructional design and instructional design models by academic librarians. *Journal of Academic Librarianship*, *47*(5), 102382. https://doi.org/10.1016/j.acalib.2021.102382

Kioupi, V., & Voulvoulis, N. (2022). Education for Sustainable Development as the Catalyst for Local Transitions Toward the Sustainable Development Goals. *Frontiers in Sustainability*, *3*(July), 1–18. https://doi.org/10.3389/frsus.2022.889904

KLHK. (2023). *Sistem Informasi Pengelolaan Sampah Nasional (SIPSN)*.

KLHK. (2024). *Sistem Informasi Pengelolaan Sampah Nasional (SIPSN)*.

Kurniawan, A., Wulan, T. R., & Muslihudin, M. (2023). Pengembangan Potensi Desa Wisata di Banyumas Menuju Pembangunan Perdesaan Berkelanjutan. *Jurnal Ilmiah Membangun Desa Dan Pertanian*, *8*(5), 169–181. https://doi.org/10.37149/jimdp.v8i5.334

Kusumawardani, D., Hidayati, N. A., Martina, A., Agusti, K. S., Rahmawati, Y., Amalia, Y. Y., & Ramdaniyah, N. F. (2023). Household Food Waste in Indonesia: Macro Analysis. *Polish Journal of Environmental Studies*, *32*(6), 5651–5658. https://doi.org/10.15244/pjoes/163157

Lazuardi, M. A., M, A. S., Haryandi, S., & Ibrahim, M. A. (2023). The Effectiveness of Electronic Modules on Problem-Solving Oriented Work and Energy Topics to Improve Student Learning Outcomes. *Jurnal Ilmiah Pendidikan Fisika*, *7*(1), 137. https://doi.org/10.20527/jipf.v7i1.7311

Logan, R. M., Johnson, C. E., & Worsham, J. W. (2021). Development of an e-learning module to facilitate student learning and outcomes. *Teaching and Learning in Nursing*, *16*(2), 139–142. https://doi.org/10.1016/j.teln.2020.10.007

Lubis, S. P. W., Suryadarma, I. G. P., Paidi, & Yanto, B. E. (2022). The Effectiveness of Problem-based learning with Local Wisdom oriented to Socio-Scientific Issues. *International Journal of Instruction*, *15*(2), 455–472. https://doi.org/10.29333/iji.2022.15225a

Maison, & Wahyuni, I. (2020). Guide inquiry science e-module development for improving junior high school students ' scientific literacy Guide inquiry science e-module development for improving junior high school students ' scientific literacy. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/1876/1/012089

Manullang, T. I. B., Nandiyanto, A. B. D., Suryadi, A., Rochyadi, E., Haerudin, D., Muspita, R., Sumiroh, E., & Manullang, L. S. (2021). Improving students with intellectual disabilities science process skills through photosynthesis experiment in enhancing climate change awareness. *Journal of Engineering Science and*

Technology, *16*(3), 2368–2377.

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: a systematic literature review. *International Journal of STEM Education*, *6*(1). https://doi.org/10.1186/s40594-018-0151-2

Marouli, C. (2021). Sustainability education for the future? Challenges and implications for education and pedagogy in the 21st century. *Sustainability (Switzerland)*, *13*(5), 1–15. https://doi.org/10.3390/su13052901

Martín-Sánchez, A., González-Gómez, D., & Jeong, J. S. (2022). Service Learning as an Education for Sustainable Development (ESD) Teaching Strategy: Design, Implementation, and Evaluation in a STEM University Course. *Sustainability (Switzerland)*, *14*(12). https://doi.org/10.3390/su14126965

Mason, L. R., Melton, C. C., Gray, D., & Swallow, A. L. (2022). Climate Change, Social Work, and the Transition Away from Fossil Fuels: A Scoping Review. *Sustainability (Switzerland)*, *14*(12). https://doi.org/10.3390/su14127086

Melanie Utamy, D., & Hufri, H. (2024). Validasi E-Modul Interaktif Berbasis Saintifik Pada Materi Kalor dan Termodinamika. *Jurnal Pendidikan Tambusai*, *8*(2), 27567–27577. https://doi.org/10.31004/jptam.v8i2.17248

Meltzer, D. E. (2002). The relationship between mathematics preparation and conceptual learning gains in physics: A possible "hidden variable" in diagnostic pretest scores. *American Journal of Physics*, *70*(12), 1259–1268. https://doi.org/10.1119/1.1514215

Miranda, D., & Wibowo, Y. (2023). Pengembangan Media Berbasis Aplikasi Android pada Materi Sistem Pernapasan Kelas XI SMA. *JURNAL EDUKASI BIOLOGI*, *9*(1), 77–89. https://journal.student.uny.ac.id/index.php/jeb/article/view/18146/17732

Mochtar, N. E., Seta, A. K., Gasim, H., Hendarman, & Indrastuti, N. (2014). Pendidikan untuk Pembangunan Berkelanjutan (Education for Sustainable Development) di Indonesia. In *Kementrian Pendidikan dan Kebudayaan* (Issue 9). Komisi Nasional Indonesia untuk UNESCO (KNIU).

Moubareck, C. A., Alawlaqi, B., & Alhajeri, S. (2023). Characterization of physicochemical parameters and bacterial diversity of composted organic food wastes in Dubai. *Heliyon*, *9*(6), e16426. https://doi.org/10.1016/j.heliyon.2023.e16426

Najwa, H. A., & Suhartini. (2023). Development of E-Module Integrated with Education for Sustainable Development (ESD) on Enviromental Change Material. *Jurnal Penelitian Pendidikan IPA*, *9*(12), 12130–12138. https://doi.org/10.29303/jppipa.v9i12.6105

Nikmah, C., -, T., & Nasrudin, H. (2019). Validation of Learning Media Using Argument Driven Inquiry (ADI) Learning Model. *International Journal of Scientific and Research Publications (IJSRP)*, *9*(11), p9509. https://doi.org/10.29322/ijsrp.9.11.2019.p9509

Novianti, R., Suhendar, S., & Ratnasari, J. (2023). Pengembangan E-Module Berbasis Education for Sustainable Development untuk Melatihkan Kompetensi Berpikir Kritis pada Siswa. *Bioscientist : Jurnal Ilmiah Biologi*, *11*(1), 639. https://doi.org/10.33394/bioscientist.v11i1.7986

OECD. (2024). Pisa 2022. In *Perfiles Educativos* (Vol. 46, Issue 183). https://doi.org/10.22201/iisue.24486167e.2024.183.61714

Purnamasari, S., & Nurawaliyah, S. (2023). Studi Literatur: Penilaian Kompetensi Keberlanjutan dan Hasil Belajar Education for Sustainable Development (ESD). *Jurnal Pendidikan UNIGA*, *17*(1), 686. https://doi.org/10.52434/jpu.v17i1.2553

Rahman, A. A., Kaniawati, I., Riandi, R., & Hendayana, S. (2023). Secondary Science Teachers Perception on STEM Learning for Sustainable Development. *Jurnal Penelitian Pendidikan IPA*, *9*(3), 1297–1303. https://doi.org/10.29303/jppipa.v9i3.2776

Raman, R., Manalil, S., Dénes, D. L., & Nedungadi, P. (2024). The role of forestry sciences in combating climate change and advancing sustainable development goals. *Frontiers in Forests and Global Change*, *7*(October), 1–15. https://doi.org/10.3389/ffgc.2024.1409667

Ranuharja, F., Ganefri, G., Fajri, B. R., Prasetya, F., & Samala, A. D. (2021). Development of Interactive Learning Media Edugame Using Addie Model. *Jurnal Teknologi Informasi Dan Pendidikan*, *14*(1), 53–59. https://doi.org/10.24036/tip.v14i1.412

Risniawati, M., Serevina, V., & Delina, M. (2020). The development of E-learning media to improve students' science literacy skill in Senior High School. *Journal of Physics: Conference Series*, *1481*(1). https://doi.org/10.1088/1742-6596/1481/1/012075

Rustamana, A., Hasna Sahl, K., Ardianti, D., Hisyam, A., Solihin, S., Sultan, U., Tirtayasa, A., Raya, J., No, C., & Banten, S. (2024). Penelitian dan Pengembangan (Research & Development) dalam Pendidikan. *Jurnal Bima: Pusat Publikasi Ilmu Pendidikan Bahasa Dan Sastra*, *2*(3), 60–69. https://doi.org/10.61132/bima.v2i3.1014

Rustandi, A., & Rismayanti. (2021). Penerapan Model ADDIE dalam Pengembangan Media Pembelajaran di SMPN 22 Kota Samarinda. *Jurnal Fasilkom*, *11*(2), 57–60. https://doi.org/10.37859/jf.v11i2.2546

Santa, S., Lathifah, S. S., Aulia, D. N., & Meyradhia, A. G. (2024). Development of A Smart Module on Hydrological Cycle Based on SDGs as A Source of Science Studies for Primary School Students. *Jurnal Penelitian Pendidikan IPA*, *10*(3), 1492–1499. https://doi.org/10.29303/jppipa.v10i3.6515

Setianingsih, D. A., Handoyo, E., & Wardani, S. (2025). *The Effect of Using PJBL-Based Interactive E-Modules on Improving Learning Outcomes A . Introduction*. *6*(2), 1179–1198.

Setiono, S., & Windyariani, S. (2023). *Development of Online STEM Learning Program for the Preparation of Prospective 21 st Century Biology Teacher*. *21*(3), 181–188. https://doi.org/10.19184/bioedu.v21i3.40383

Shayan, N. F., Mohabbati-Kalejahi, N., Alavi, S., & Zahed, M. A. (2022). Sustainable Development Goals (SDGs) as a Framework for Corporate Social Responsibility (CSR). *Sustainability (Switzerland)*, *14*(3), 1–27. https://doi.org/10.3390/su14031222

Solihah, P. A. S., Kaniawati, I., Samsudin, A., & Riandi, R. (2024). Need Analysis of STEM-ESD Based Development on Teaching Materials and Instrument Test. *Jurnal Penelitian Pendidikan IPA*, *10*(3), 1124–1133. https://doi.org/10.29303/jppipa.v10i3.6516

Spatioti, A. G., Kazanidis, I., & Pange, J. (2022). A Comparative Study of the ADDIE Instructional Design Model in Distance Education. *Information (Switzerland)*, *13*(9), 1–20. https://doi.org/10.3390/info13090402

Suhendar, S., Widodo, A., Solihat, R., & Riandi, R. (2025). Students' future thinking skills: Implications for school education programs. *Journal of Pedagogical Research*, *9*(1), 254–273. https://doi.org/10.33902/JPR.202534029

Tytler, R. (2012). Socio-Scientific Issues, Sustainability and Science Education. *Research in Science Education*, *42*(1), 155–163. https://doi.org/10.1007/s11165-011-9262-1

UNESCO. (2017). Education for Sustainable Development Goals: learning objectives. In *Education for Sustainable Development Goals: learning objectives*. https://doi.org/10.54675/cgba9153

van Asselt, H. (2023). The SDGs and fossil fuel subsidy reform. *International Environmental Agreements: Politics, Law and Economics*, *23*(2), 191–197. https://doi.org/10.1007/s10784-023-09601-1

van Zanten, J. A., & van Tulder, R. (2021). Towards nexus-based governance: defining interactions between economic activities and Sustainable Development Goals (SDGs). *International Journal of Sustainable Development and World Ecology*, *28*(3), 210–226. https://doi.org/10.1080/13504509.2020.1768452

Vandyck, T., Ebi, K. L., Green, D., Cai, W., & Vardoulakis, S. (2022). Climate change, air pollution and human health. *Environmental Research Letters*, *17*(10). https://doi.org/10.1088/1748-9326/ac948e

Vilmala, B. K., Karniawati, I., Suhandi, A., Permanasari, A., & Khumalo, M. (2022). A Literature Review of Education for Sustainable Development (ESD) in Science Learning: What, Why, and How. *Journal of Natural Science and Integration*, *5*(1), 35. https://doi.org/10.24014/jnsi.v5i1.15342

Vonitsanos, G., Moustaka, I., Doukakis, S., & Mylonas, P. (n.d.). Transforming Education in the Digital Age : Exploring the Dimensions of Education 4 . 0. *IEEE Global Engineering Education Conference (EDUCON)*.

Wan Mahari, W. A., Azwar, E., Li, Y., Wang, Y., Peng, W., Ma, N. L., Yang, H., Rinklebe, J., Lam, S. S., & Sonne, C. (2020). Deforestation of rainforests requires active use of UN's Sustainable Development Goals. *Science of the Total Environment*, *742*. https://doi.org/10.1016/j.scitotenv.2020.140681

Wang, H. H., Hong, Z. R., Liu, S. C., & Lin, H. S. (2018). The impact of socio-scientific issue discussions on student environmentalism. *Eurasia Journal of Mathematics, Science and Technology Education*, *14*(12). https://doi.org/10.29333/ejmste/95134

Widarti, R., & Roshayanti, F. (2021). Potensi Implementasi STEAM (Science, Technology, Engineering, Art and Mathematic) berorientasi ESD (Education for Sustainable Development) dalam Pembelajaran Fluida. *Unnes Physics Education Journal*, *10*(3), 291–295.

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. S. (2023). Circular economy strategies for combating climate change and other environmental issues. *Environmental Chemistry Letters*, *21*(1), 55–80. https://doi.org/10.1007/s10311-022-01499-6

Yuenyong, C., Nam, N. D., Buan, A., Suwono, H., Wekke, I. S., & Buang, N. A. (2021). The 2ndInternational Annual Meeting on STEM education (IAMSTEM 2019). *Journal of Physics: Conference Series*, *1835*(1), 2019–2022. https://doi.org/10.1088/1742-6596/1835/1/011001

Zandonadi, R. P., Maisa, L., Raposo, A., & Cortez, V. (2021). Food waste on foodservice: an overview through the perspective. *Foods*, *10*(1175), 1–14.

Zuhaida, A., Widodo, A., Prima, E. C., & Solihat, R. (2024). *STEM-ESD dalam Pembelajaran IPA* (A. Zuhaida (ed.)). CV Pustaka Egaliter.

Zulfira, R., Halim, A., Khaldun, I., Mahzum, E., Nazar, M., & Kasli, E. (2024). Effect of Interactive Learning Media Using Visual Basic for Application Excel Spreadsheet to Reduce Misconception in Physics Learning. *Jurnal Penelitian Pendidikan IPA*, *10*(1), 28–36. https://doi.org/10.29303/jppipa.v10i1.6387