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STEM-ESD Integration in E-Module to Improve Critical Thinking Skills

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ABSTRACT

Observations and literature reviews indicate that vocational school students' critical thinking skills remain low, even though these skills are important for vocational graduates. One reason is the limited availability of interactive teaching materials for the IPAS Project subject. This study aims to develop a STEM-ESD-based e-module for the IPAS Project on Soil Pollution to improve the critical thinking skills of Year 10 vocational school students. The study uses the Research and Development (R&D) method with the ADDIE model. The e-module was developed using Heyzine Flipbook. The validation results showed that the e-module was highly valid, with a score of 90% from subject matter experts, 92% from media experts, and 93% from language experts, as well as a very practical response from teachers (93%). The implementation of the e-module resulted in increased critical thinking skills, with an N-Gain score of 0.67 and very positive student responses. This e-module is suitable for use as an innovative teaching material that supports student-centred learning and sustainable education.

ARTICLE INFORMATION

Keywords:
21st century skills; ADDIE; Digital teaching materials; SMK IPAS project

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INTRODUCTION

The year 2045 marks 100 years of Indonesian independence, which is expected to be the momentum for the nation's second awakening through the realization of the Indonesian Golden Generation (Darman, 2017). In this context, the education sector plays a strategic role in realizing the Indonesian Golden Generation 2045 (Hamdani et al., 2022). Quality education is an important foundation for teachers to continue innovating in designing high-quality learning, increasing student engagement, and creating a creative and enjoyable learning atmosphere (Hamdani et al., 2022). To welcome the Golden Generation, students need to be equipped with 21st-century skills, including critical thinking (Putri et al., 2022), creativity, innovation, communication, teamwork, and global competitiveness.

Critical thinking is an individual's ability to consciously and purposefully assess information through the process of interpreting, analyzing, evaluating, and drawing conclusions, as well as providing reasons for the assessment (Møgelvang et al., 2023). Students who possess critical thinking skills will be able to analyze problems logically (Ariyanto et al., 2020) by examining various alternative solutions that are most appropriate and rational (Alsaleh, 2020). Critical thinking skills are very important for students to master because they play a role not only in an academic context but also in solving everyday problems (Sarip et al., 2022). For vocational high school (SMK) students, critical

thinking skills are essential in facing problems in the world of work and community life (Sarip et al., 2022). Employees with critical thinking skills contribute significantly to a company's success by solving complex work problems, generating more creative and innovative ideas (Kurniawan et al., 2021b), and making effective decisions (Rivas et al., 2023). A survey by the National Association of Colleges and Employers (NACE) shows that critical thinking skills are the most sought-after soft skills in the workplace. In line with this, the Job Outlook report (April 23, 2025) confirms that employers are currently seeking workers with strong communication, critical thinking, teamwork, and other career skills.

Although critical thinking skills are very important, various field studies indicate that students' critical thinking skills in Indonesia, especially at the vocational high school level, remain relatively low (Kurniawan et al., 2021a). This low achievement is a systemic challenge that could hinder students' readiness to meet the demands of the 21st-century workplace. This condition is influenced by various factors, one of which is the learning process, which is not yet optimal at facilitating skill development. In addition, dependence on conventional, passive, and context-free teaching materials also poses obstacles to developing these skills.

The rapid development of digital technology over the past few decades has brought significant changes across various fields, including education (Efendi, 2023). Following the COVID-19 pandemic, the world of education has undergone systemic reforms and innovations that have encouraged the transformation of classroom learning approaches (Rivas et al., 2023). Globally, various countries, especially in Europe, are increasingly strengthening the use of digital platforms, devices, and infrastructure to ensure the sustainability, flexibility, and inclusiveness of education (Knudstad & Paulsengaard, 2025). In line with this, UNESCO (United Nations Educational, Scientific and Cultural Organization), OECD (Organisation for Economic Co-operation and Development), and the European Commission emphasize the importance of equipping students with digital skills to prepare future generations for the digital age (Alam et al., 2025).

Therefore, in an effort to overcome low critical thinking skills and adapt learning to the times, this study aims to develop digital-based teaching materials in the form of e-modules. The development of digital-based teaching materials was chosen because they are more interactive, support innovative pedagogical strategies, are easily accessible anytime, anywhere, and are more durable than printed teaching materials, while still allowing lesson materials to connect with real-world issues relevant to students. Learning with digital teaching materials can improve the learning experience for students worldwide (Cohen et al., 2022) and accommodate diverse learning styles (Aligo & Prudente, 2025), thereby helping maintain student competitiveness globally.

The integration of STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD) in the development of digital teaching materials was chosen because STEM has been widely proven effective in developing students' critical thinking skills. Through STEM-ESD, students are also guided to develop awareness and take action on urgent environmental issues (Kopbossyn et al., 2025). STEM-based e-modules encourage students to shift from simply memorizing concepts to solving problems in an applied manner. A literature review shows that education systems across countries are increasingly encouraged to integrate STEM into education for sustainable development (Kopbossyn et al., 2025). This aligns with the Sustainable Development Goals (SDGs) through a global action program that has been running for a decade to continue enhancing SDG collaboration with ESD at all levels of education (Nguyen, 2023). The STEM approach, integrated with ESD, offers a strong framework for contextual learning that encourages students to solve complex problems, such as soil pollution, through interdisciplinary projects that hone their reasoning skills and foster concern for the environment.

Although the STEM-ESD approach has significant potential to strengthen sustainable education, studies on the development of STEM-ESD-based digital teaching materials that specifically focus on improving students' critical thinking skills in the IPAS Project subject in vocational schools remain relatively limited. Therefore, this study focuses on developing digital STEM-ESD-based e-modules on soil pollution to improve the critical thinking skills of Year 10 vocational high school students. The use of interactive flipbook-based e-modules is expected to be an effective medium in implementing the STEM-ESD approach, making learning more interesting, contextual, and student-oriented. Through the integration of sustainability issues in practice-based learning, this study is expected to make a real contribution to strengthening students' critical thinking skills and supporting the development of sustainable education in facing global challenges, such as climate change and natural resource depletion, which require the availability of STEM workers who are proficient in various disciplines and capable of designing sustainable solutions (Tarlochan et al., 2025).

METHOD

This study is a development study that applies the Research and Development (R&D) method, with development procedures based on the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) developed by Branch (2009) as a systematic framework. The ADDIE model was chosen for this study because it offers a systematic, structured approach and allows designers to return to a previous stage based on formative evaluation results (Ellerman, 2025). With these characteristics, the ADDIE model has proven to be efficient and effective in developing teaching materials (Shakeel et al., 2023).

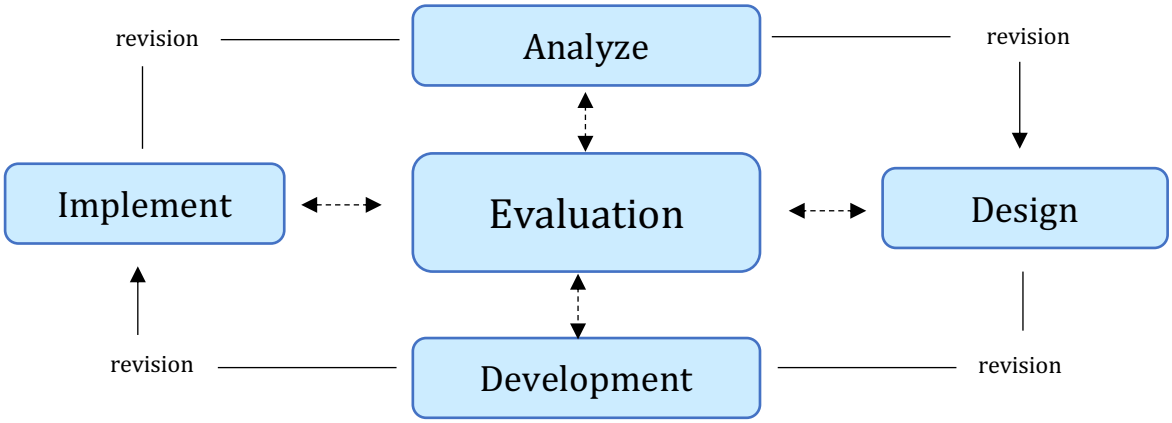


Figure 1. The ADDIE model iterative process (Source: (Drljača et al., 2017)

The initial stage of the research, namely the analysis phase, focused on analysing needs as the basis for learning design and the development of teaching materials (Zulkepli et al., 2024). The analysis was conducted through surveys, observations, and interviews to identify learners' needs in terms of knowledge, attitudes, and skills (Ellerman, 2025). At this stage, existing teaching materials and the suitability between learning outcomes and objectives were also assessed (Adriani et al., 2020). To improve data validity, interviews with teachers and observations of IPAS Project learning were conducted to identify learning problems and their impact on students' attitudes, behaviour, and skills related to environmental awareness.

During the design stage, an e-module framework was developed, including a concept map of the material, a storyboard, and validation instruments. Next, the development stage involved compiling the material and visual content in Canva, then packaging it into an interactive e-module based on the Heyzine Flipbook, equipped with competency tests via Genially and Quizizz. The developed product is

then tested for validity by subject-matter, media, and language experts, and for practicality by IPAS practitioner-teachers. Data are collected using a validation questionnaire and analysed descriptively and quantitatively to determine the level of feasibility, while qualitative input serves as a basis for refining the e-module until it is declared valid and suitable for learning. The feasibility level is qualified based on Khanan et al. (2024): 80-100& means valid and needs no revision, 60-79% means moderately valid and needs no revision, 40-59% means less valid and needs revision, and 0-39% means not valid and needs revision.

The practicality of the e-module was assessed by having teachers complete a Likert-scale questionnaire, which was then analysed using the Content Validity Ratio (CVR) method. This is an approach to testing content validity that assesses the suitability of each item within the domain being measured based on expert judgement (Shakeel et al., 2023). The CVR value obtained is then used in calculating the Content Validity Index (CVI). The CVI is calculated as the average CVR for each sub-question or instrument item, thereby reflecting the level of expert agreement with the instrument's content. According to Lawshe (1975), the CVI value is used to determine whether the instrument's overall validity is acceptable. The minimum CVR value indicating that an item is acceptable varies depending on the number of experts (respondents) involved in the assessment.

The CVR and CVI calculation results range from -1 to +1 and are used to determine the level of validity or expert agreement for each instrument item, according to the categories in Table 3. A CVR value close to +1 indicates that most experts consider the instrument item to be essential and relevant, while a CVR value close to 0 indicates a moderate level of agreement. Meanwhile, a negative CVR value indicates that most experts consider the item to be less relevant or non-essential. The CVI value describes the overall validity of the instrument based on the average CVR for each item. The higher the CVI value, the better the instrument's content is suited to the measurement objectives. Based on these criteria, instrument items with CVR and CVI values above the specified minimum threshold are declared valid and suitable for use. Conversely, items that do not meet the criteria need to be revised or eliminated in accordance with expert recommendations. Thus, CVR and CVI analysis play a crucial role in ensuring the quality and reliability of research instruments. CVI values are specified in the following category: Poor ($-1 < x < 0$), Good ($0 < x < 0{,}5$), and Excellent ($0{,}5 < x < 1$)

The instrument used was an essay test to measure critical thinking skills as proposed by Ennis (Rahmawati et al., 2016). Critical thinking skills are not innate abilities, but rather skills that need to be developed and trained systematically through a learning process. According to Ennis (1985; 2011), indicators of critical thinking skills are classified into five main aspects. First, providing simple explanations (elementary clarification), which includes the ability to focus questions, analyze arguments, and ask and answer questions that require explanation or clarification. Second, building basic skills (basic support), including the ability to assess the credibility of information sources and make judgments based on observations. Third, concluding (inference), which includes formulating and considering deductions, inductions, and making decisions based on reasoning. Fourth, providing advanced clarification, which includes the ability to identify terms, consider definitions, and recognize the assumptions underlying a statement. Fifth, organizing strategies and tactics, which involves determining appropriate actions and interacting effectively with others.

Critical thinking skill instruments are validated through two stages: expert judgment and empirical validation. Validity indicates the extent to which an instrument's measurement results are appropriate and relevant to the measurement objectives formulated (Wang et al., 2024). Empirical validation is obtained from the results of instrument trials that are analyzed statistically. Empirical validation aims to ensure that each instrument item measures critical thinking skills in accordance with the established theoretical construct. Through statistical analysis, the validity of each item can be determined, ensuring the instrument is truly feasible and accurate in assessing students' critical

thinking abilities. These validation results then become the basis for revising, retaining, or eliminating instrument items that do not meet the validity criteria. With instruments that are theoretically and empirically valid, the research data produced is expected to have a high level of reliability and accuracy in supporting the research objectives (Subhaktiyasa, 2024).

Instruments that have met the validity criteria are then tested for reliability. In quantitative research, reliability refers to the degree of consistency and stability of an instrument's measurement results when used under relatively similar conditions at different times (Subhaktiyasa, 2024). A reliable instrument will produce the same or nearly the same scores when used to measure identical constructs in comparable situations (Heale & Twycross, 2015). Reliability testing can be carried out using several approaches, including stability (test–retest) reliability, internal consistency reliability, parallel-forms reliability, and inter-rater reliability. Test–retest reliability assesses the stability of measurement results over time by comparing scores obtained on two occasions separated by a specified time interval. If the measurement results show high consistency, the instrument is considered reliable. Common analysis techniques used in this test include Pearson's Correlation and the Intraclass Correlation Coefficient (ICC), with a coefficient value ≥ 0.70 indicating adequate reliability. Meanwhile, internal consistency reliability measures the extent to which items in an instrument are correlated with each other and consistently represent the same construct. This test is conducted in a single measurement, with one of the most widely used techniques being Cronbach's Alpha (α) coefficient. According to George and Mallery (2003), reliability can be interpreted based on alpha values as follows: excellent (≥ 0,90), good (0,80 – 0,89), acceptable (0,70 – 0,79), questionable (0,60 – 0,69), poor (0,50 – 0,59), and not reliable (< 0,50)

The next stage of the research was implementation, namely the use of e-modules in learning. The independent variable in this study was teaching materials, while the dependent variables were critical thinking skills and students' environmental literacy. This study involved Grade 10 students at SMKN 1 Gunungguruh, Sukabumi Regency, West Java Province, as the research population. There are a total of 16 Grade 10 classes with students in each class having the same level of ability. Therefore, the purposive sampling technique was used, which involves selecting students from one class with homogeneous abilities. As a result, the research subjects were Grade 10 DPIB students, totaling 30 students aged 15 to 16 years. Data collection was conducted through pre- and post-tests in the same class, using a one-group pretest-posttest design to measure students' critical thinking skills. The pre-test was conducted before the intervention to assess students' initial abilities, while the post-test was administered after the intervention to measure learning gains.

Table 1. One Group Pre-test Post-test Design Pre-experimental Method

Pretest	Treatment	Postest
O_1	X	O_2

(Source: Mack et al., 2019)

An initial analysis was conducted on the pre-test and post-test results using the Shapiro-Wilk normality test to determine whether the data were normally distributed. The results show that if the significance value (Sig.) or probability is > 0.05, the data are considered normally distributed. If the data are normal, the next analysis uses the Paired Sample T-Test to determine the difference in the average between the pre-test and post-test results. If the Sig (2-tailed) value is < 0.05, it can be concluded that there is a significant difference between the pre-test and post-test results, indicating that the e-module implementation improves students' critical thinking skills. The effectiveness of the critical thinking and environmental literacy instruments was analysed using the N-Gain calculation

(Coletta & Steinert, 2020), based on pre-test and post-test results, to determine the level of improvement in students' critical thinking skills. According to Sesmiyanti et al. (2019), effectiveness can be categorized based on N-Gain. N-Gain value > 0,7 means high, 0,3 ≤ N-Gain value ≤ 0,7 means medium, and N-Gain value < 0,3 means low.

In the final stage of the research, namely the evaluation phase, data were collected to determine students' and teachers' responses to the soil pollution e-module developed. Data collection from students was conducted through the distribution of questionnaires to measure the level of interest, ease of use, clarity of the material, and usefulness of the e-module in the learning process. Meanwhile, data from teachers were collected through interviews to explore their views on the suitability of the material, the feasibility of using the e-module, and its contribution to achieving learning objectives. The collected data were then analysed descriptively and quantitatively using percentage techniques. The results of the percentage analysis were used to assess the suitability and acceptance of the e-module against predetermined criteria. In addition, the findings from the evaluation stage were also used as material for reflection to identify the strengths and weaknesses of the developed e-module. Thus, the evaluation results were expected to provide a comprehensive picture of the soil pollution e-module's effectiveness in supporting the learning process. In the final stage of the research, namely the evaluation, data were collected on students' and teachers' responses to the soil pollution e-module through student questionnaires and teacher interviews. The results were analysed using percentage data: 80-100% is excellent, 66-79% is good, 56-65% is fair, 41-55 is not good, and <40 is poor.

RESULTS AND DISCUSSION

In the initial stage of the research, a preliminary analysis was conducted, including assessments of student characteristics, teaching material requirements, and the curriculum. Based on the analysis of student characteristics, students at SMKN 1 Gunungguruh belong to the digital generation, as is generally the case, who use smartphones as a daily necessity for communication, entertainment, transport booking, food ordering, etc., which has an impact on their learning style, as they tend to prefer visual-interactive learning related to technology rather than lecture methods. These characteristics indicate great potential for the application of digital learning media. Teachers are required to adapt to the times, necessitating pedagogical innovation and greater integration of technology in classroom learning (Rifai et al., 2024).

In addition, to assess students' thinking skills, an essay-based assessment was conducted. The results showed that most students were unable to provide in-depth analysis and logical arguments. The average score was only 38.3 out of 100, indicating that students' critical thinking skills remained low. This finding aligns with the results of the 2022 Programme for International Student Assessment (PISA), which showed that Indonesian students still generally have difficulty understanding complex texts, thinking critically, and applying scientific concepts in real-life contexts (Tanggur et al., 2022). Critical thinking skills do not develop naturally; they require training through learning that involves exploration, reflection, and contextual problem-solving (Alsaleh, 2020).

To reinforce these findings, a survey was conducted, with results shown in Figure 2, indicating that overall. However, students' discipline is already relatively good; aspects that support 21st-century skills, such as critical thinking, curiosity, confidence, and perseverance, still need to be further developed through the application of innovative, student-centred learning strategies. Therefore, a learning model is needed that challenges students to think critically and actively participate in solving real problems, one of which is through project-based learning with an ESD-oriented STEAM (Science, Technology, Engineering, Art, and Mathematics) approach (Habibaturrohmah et al., 2023).

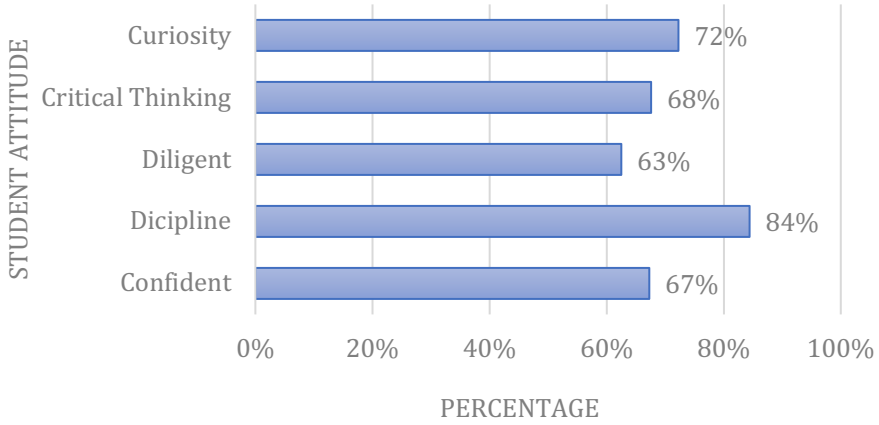


Figure 2. Profiles of Student Attitude

Data collection in the preliminary analysis stage was then conducted through interviews with several teachers of Natural and Social Sciences (IPAS) at the Vocational High School level. These interviews aimed to obtain information on problems encountered in the learning process, the teaching methods applied by teachers, and the availability of teaching media and the materials used. The results of interviews with IPAS teachers indicated that the critical thinking skills of Grade 10 students remained relatively low. This condition was characterised by students' tendency to passively accept information without evaluating its accuracy, limitations in constructing logical arguments, and difficulties in relating learning concepts to contextual problems (Sarip et al., 2022). In addition, students tend to rely on teacher guidance and show little initiative in exploring alternative solutions independently. As a result, many graduates lack the competencies required in the workplace, such as critical thinking and problem-solving skills (Kain et al., 2024).

The review of learning materials and media identified limitations in the learning media, which were still in print form, which could be a factor hindering students' critical thinking. The available textbooks were considered too normative and had little relevance to students' real-life context. Conventional teaching materials tend to be less effective in stimulating active engagement and critical thinking skills among students (Sinaga & Firmansyah, 2024). Therefore, teachers emphasise the need to develop contextual, practice-based teaching materials that integrate ESD values, such as project modules or digital learning media. Digital learning materials align with constructivist learning theory by offering interactive tools that encourage exploration, critical thinking, and problem-solving (Aligo & Prudente, 2025).

In the context of the Merdeka Curriculum, the soil pollution material in the IPAS subject in Phase E is designed to develop fact- and data-based scientific understanding and environmental problem-solving skills. The integration of the STEM approach within the ESD framework aligns with the curriculum's objective of equipping students with 21st-century skills, particularly critical thinking, collaboration, and sustainability awareness (Marwah, 2025). Therefore, the development of STEM-ESD-based electronic IPAS project modules is a relevant and strategic innovation. Electronic modules not only facilitate understanding of scientific concepts but also encourage active student engagement through a series of project-based learning activities and real-world action (Nurjihan & Bunawan, 2025). This approach allows students to relate knowledge to environmental issues in their immediate surroundings, making learning more meaningful (Yuliati et al., 2025). Thus, ESD-oriented IPAS learning through STEM-ESD-based e-modules has the potential to be an effective solution for improving environmental literacy and critical thinking skills, and for fostering students' awareness and responsibility for environmental sustainability.

Next, in the design stage, researchers developed a conceptual framework for the e-module as a reference for product development. The framework included determining the scope of the learning materials presented in Table 9, developing visual storyboards, and planning the integration of the STEM–ESD approach into each section of the materials. In addition, at this stage, validation instruments were also designed to assess the feasibility of the e-module before implementation. The design results were then realised as a tangible product. This process included creating visual content in Canva and compiling systematic, easy-to-understand learning materials. Next, all components were assembled into an interactive e-module using the Heyzine Flipbook platform.

To increase student engagement and learning, the e-module was enriched with integrated competency tests across various digital platforms, including Genially, Quizizz, Google Forms, Wordwall, and Mentimeter. Thus, the design stage produced e-modules that are not only visually appealing but also support interactive and meaningful learning. Next, in the design stage, a conceptual framework for the e-modules was developed, covering the scope of material as shown in Table 9, visual storyboards, the integration of STEM-ESD, and the design of validation instruments. The results of the design were then realised through the creation of visual content in Canva, the compilation of materials, and the assembly of the final product into an interactive e-module using Heyzine Flipbook, enriched with competency tests from Genially, Quizizz, Google Forms, Wordwall, and Mentimeter.

Table 2. List of Activities in the STEM-ESD-based Soil Pollution E-module

Chapter	Description
Learning activity 1	Soil Pollution
Learning activity 2	Sources and Types of Soil Pollution
Learning activity 3	Impacts of Soil Pollution
Learning activity 4	Prevention and control of soil pollution
Real Action Activity	Organic waste processing

Each learning activity presented in the e-module contains systematically designed components, including learning objectives, observation activities on environmental issues, material descriptions, summaries, competency tests, STEM-ESD-based mini-projects, and reflections. These components are designed to help students gradually and deeply understand the material. The observation activities and mini-projects are designed to develop critical thinking skills and increase students' awareness of environmental pollution.

At the end, the e-module includes a glossary and competency test answer keys to help students verify their answers independently. In addition, the glossary is expected to help students understand important terms related to soil pollution. The STEM-ESD-based soil pollution e-module developed using the Flipbook application features attractive visuals, including images, illustrations, interactive quizzes, and educational videos. This aims to increase students' motivation to learn and their active involvement during the learning process. The overall design of the soil pollution e-module is presented in Figure 3.



Front cover



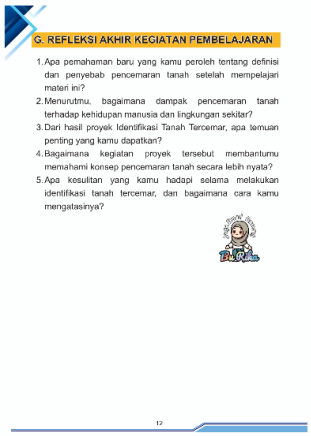
Material descriptions



STEM-ESD-based mini projects



Competency tests



Reflections



Back cover

Figure 3. Design of the e-module

To measure students' critical thinking skills, a test instrument was developed comprising 10 essay questions based on Ennis' critical thinking theory. This theory emphasizes that critical thinking skills include the ability to provide simple explanations, build basic skills, draw conclusions, provide further explanations, and organize strategies and tactics, as outlined in the question instrument grid in Table 10. Each question item is designed to represent these indicators proportionally. The question development process was carried out through the stages of basic competency analysis, determination of critical thinking indicators based on Ennis' framework, and the design of stimuli and questions that require logical reasoning, analysis, and evaluation of contextual problems (Nurdiyati et al., 2025). Thus, this instrument is expected to comprehensively and validly measure students' critical thinking skills in accordance with the learning objectives.

The developed e-module has undergone a series of validation processes involving subject matter experts, media experts, and language experts to ensure its suitability before implementation. This validation process aims to assess the suitability of the content, media display, and clarity and accuracy of language use in the e-module (Heale & Twycross, 2015). The assessment by subject-matter experts shows that the e-module is highly valid. The average score from subject-matter expert validation was 90%. This achievement indicates that the material presented aligns with the learning objectives and the characteristics of the learners. In addition, the material's structure is considered coherent and easy to understand. With these high validation results, the e-module is declared suitable for use in the next stage.

The validation results by media experts showed an average score of 92%, which falls into the highly valid category. This achievement indicates that the e-module meets the eligibility criteria for a digital learning medium. The ease of use aspect received the highest score, indicating that the e-module was designed with simple, clear navigation that is easy for users to operate. In addition, the usefulness aspect received an excellent rating, indicating that the e-module can support the learning process and help students achieve their learning objectives. However, the graphics aspect received the lowest score among the other aspects, although it is still within the valid range. This shows that the e-module's visual appearance is generally good and suitable for use.

Validation by language experts showed an average score of 93%, which falls into the highly valid category. These results indicate that the language used in the e-module meets the linguistic feasibility criteria. The aspects of sentence effectiveness and paragraph coherence received perfect scores, indicating that the language presentation is clear, coherent, and communicative. This makes it easier for students to understand the content without introducing ambiguity. In addition, the language used is considered appropriate for the developmental level and characteristics of vocational school students. Overall, the validation results show that the language in the e-module is suitable for use and supports optimal readability and comprehension for students.

The responses provided by practising teachers showed an average score of 93%, which falls into the highly category. These results indicate that the developed e-module is suitable for use in vocational education. The highest scores were obtained in the content suitability and language aspects. This shows that the material presented aligns with the vocational school curriculum requirements and is delivered in clear, easily understood language. In addition, the structure of the material presentation was found to be coherent and supportive of the classroom learning process. The usefulness aspect also received a high score, indicating that teachers considered this e-module to have a positive contribution to the learning process. The e-module was seen as helping teachers deliver material more engagingly and interactively. Thus, this e-module was considered effective in improving students' critical thinking skills.

Table 3. CVR and CVI results of teacher responses to the e-module

No	Aspect	CVR	CVI	Category
1	Content suitability	1,00	1,00	Valid
2	Linguistic suitability	1,00	1,00	Valid
3	Usefulness	1,00	1,00	Valid
4	Graphics	1,00	0,95	Valid
Average		1,00	0,99	Valid

Based on validity analysis using the Content Validity Ratio (CVR) and Content Validity Index (CVI) for responses from 15 teacher respondents, the CVR for each aspect was 1.00, and the CVI ranged from 0.95 to 1.00, with an average of 0.99. These values indicate that all aspects of content validity, language, usefulness, and graphics are valid. Because all CVR values are ≥ 0.49 and the CVI values are close to 1, it can be concluded that the STEM-ESD-based Soil Pollution e-module is highly valid and suitable for use in learning.

These validation results reinforce that the STEM-ESD-based soil pollution e-module is suitable for use as teaching material in vocational schools. The integration of accurate content, interactive media displays, and communicative language makes this e-module suitable for supporting project-based learning. STEM-based e-modules are practical for learning (Yuliati et al., 2025), with interactive e-modules considered highly feasible by experts and practitioners. Specifically, in terms of media, the relatively lower graphic value suggests that visual appeal still needs improvement to suit better the

characteristics of vocational school students, who tend to prefer dynamic displays. Overall, the validation score above 90% indicates that this e-module has great potential for implementation in STEM-ESD-based learning. These findings are consistent with research (Rachmadio et al., 2024) that indicates that interactive STEM-based e-modules have high validity, are practical to use, and are efficient in supporting 21st-century learning. Similar findings are also emphasised by Pertiwi et al. (2024), who found that interactive STEM-based e-modules enhance students' science literacy due to the suitability of the content, language, and communicative display.

From the perspective of media development, the interactive e-modules on basic motion patterns received media expert validation of 91.87% and subject matter expert validation of 95.83%, and were deemed highly suitable for use. STEAM-based modules on vibration and wave material obtained expert validation of up to 98% and media expert validation of 87.7%, with very positive student responses. Furthermore, STEM-PBL-based learning reinforced the finding that interactive learning media can significantly improve students' systematic thinking skills ($p < 0.05$). In line with this, STEM-based e-modules had an influence of 42.25% on student motivation and 39.69% on creativity, emphasising the importance of STEM integration in digital learning.

Thus, the results of this study indicate that the developed STEM-ESD-based e-modules are not only valid in terms of content, media, and language, but also relevant to the learning needs in vocational schools. Expert validation and teacher responses reinforce the evidence that the development of digital e-modules that integrate pedagogical, content, and technological aspects has the potential to improve students' critical thinking. Before being used in experimental classes, the question instruments were validated by experts, with results showing that critical thinking had a very high level of validity, averaging 95%.

Table 4. Results of the Validation of Critical Thinking Skills Question Instruments

No	Aspect	Critical Thinking Skills
1	Material	96%
2	Construction	97%
3	Language	92%
Average		95%

According to Arikunto (Kurniawan et al., 2021a), a research instrument can be considered valid if it is able to measure what it is supposed to measure. Validity is the degree of agreement between the data obtained and the actual data (Ellerman, 2025). Thus, validation results from instrument experts indicate that the questions compiled for both environmental literacy and critical thinking skills have met the requirements for content, construction, and appropriate language use. In terms of content, the validation score for critical thinking skills reached 96%. This indicates that the questions' content aligns with the learning indicators and can measure students' higher-order thinking skills. Who emphasise that a good assessment instrument must measure analytical, evaluative, and creative abilities in accordance with Bloom's revised taxonomy. In addition, integrating question content with the environmental context reflects the application of the principles of Education for Sustainable Development (ESD), in which learning is directed towards forming understanding and concrete actions on sustainability issues (Kioupi & Voulvoulis, 2019). Therefore, the question instrument is declared suitable for measuring the environmental literacy and critical thinking skills of vocational school students in the context of STEM-ESD-based learning.

The construction aspect scored 97% for critical thinking skills; these scores indicate that each item has been systematically and logically constructed in accordance with instrument development

principles. Good question construction is an important factor in maintaining internal validity, as it ensures that the instrument truly measures the competencies it is intended to measure. This also indicates that the questions have a strong relationship between the indicators, stimuli, and alternative answers. Furthermore, in terms of language, a 92% score was obtained for critical thinking skills. This shows that the language in the questions is communicative, does not cause ambiguity, and is appropriate for the students' developmental level. As stated by Sugiyono (2019), the language in the instrument must be clear and easy to understand to avoid interpretation bias that could affect measurement results. Overall, the validation results indicate that the developed instrument is highly valid and suitable for measuring students' critical thinking skills. The high validity also reinforces that the instrument has fulfilled the principles of integration between content, context, and construction in accordance with the STEM-ESD approach, which is oriented towards strengthening 21st-century skills through issue-based learning on the environment and applied science.

To determine the extent of improvement in student learning outcomes after the implementation of the STEM-ESD-based Soil Pollution e-module, an improvement analysis was conducted using the Normalised Gain (N-Gain) calculation. This analysis measured the effectiveness of the e-module in improving students' environmental literacy and critical thinking skills. The N-Gain calculation was performed by comparing the pre-test and post-test scores for each aspect measured. Thus, the extent of improvement in students' abilities after participating in learning using the e-module could be determined. The N-Gain values obtained were then classified into specific improvement categories. This classification was used to interpret the level of success of the learning intervention provided. The N-Gain calculation results are then analysed descriptively to provide an overview of the improvement in student learning outcomes. A summary of the N-Gain calculation results is presented in Table 5.

Table 5. Students' Critical Thinking Skills N-Gain Values

Description	Pre-test	Post-test
Lowest value	30	72,5
Highest score	45	92,5
Average	38,64	79,85
Standard deviation	5,23	6,37
Variance	27,38	40,60
N-Gain	0,68	Moderate Category

Based on testing the instrument with students, a comparison of pre-test and post-test scores was obtained, as shown in Table 17. The lowest student score increased from 30 on the pre-test to 72.5 on the post-test, while the highest score increased from 45 to 92.5. This increase indicates a significant improvement in understanding and mastery of the material after the implementation of STEM-ESD-based learning. The students' average score also increased significantly, from 38.64 on the pre-test to 79.85 on the post-test. These results show that the developed learning improved students' abilities by almost double compared to before the treatment. According to Hake (1998), improvements in learning outcomes can be measured using the normalised gain (N-Gain) score, which describes the effectiveness of learning in enhancing students' understanding of the taught concepts. An N-Gain value of 0.68 falls into the moderate category, according to Hake's criteria, namely: $g > 0.7$ (high), $0.3 \leq g \leq 0.7$ (moderate), and $g < 0.3$ (low). This indicates that implementing project-based learning with a STEM-ESD approach has a positive impact on students' critical thinking, though there is still room for improvement.

In terms of data distribution, the standard deviation increased from 5.23 to 6.37, and the variance from 27.38 to 40.60. This increase indicates that, after the treatment, students had a more diverse range of abilities, still within a generally improved achievement range. Project-based learning provides opportunities for students to develop independent thinking and problem-solving skills, leading to variations in performance among individuals. Overall, the analysis shows that STEM-ESD-based learning is effective in improving student learning outcomes, including cognitive aspects and higher-order thinking skills. The significant increase in post-test scores reinforces the idea that this approach can link science, technology, and environmental concepts in context, thereby encouraging active engagement and deeper conceptual understanding.

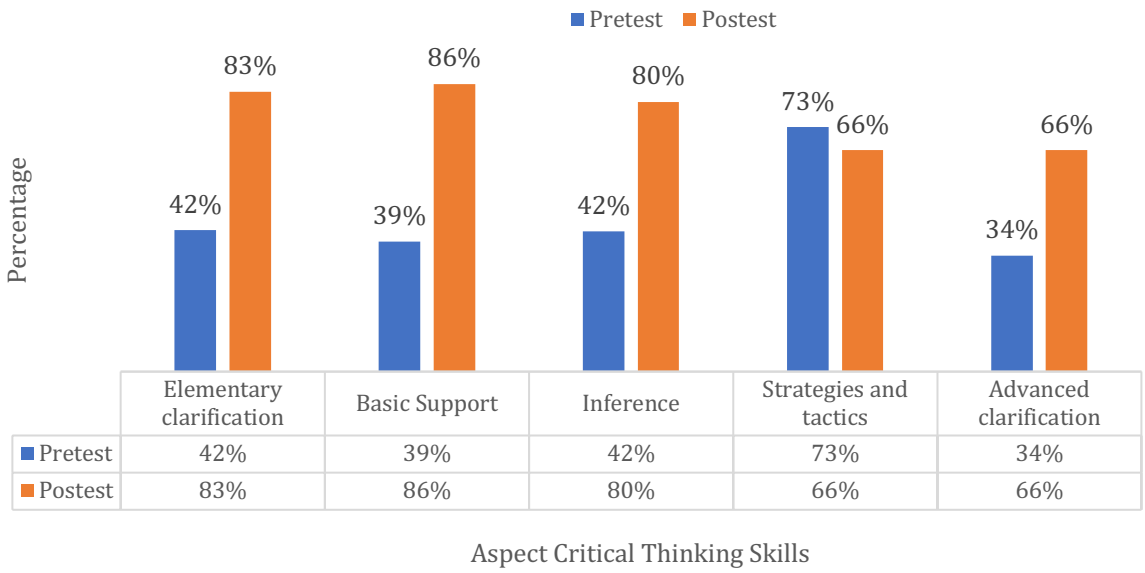


Figure 4. Results of Pre-test and Post-test of Students' Critical Thinking Skills

Based on Figure 4, there is a noticeable difference in students' critical thinking skills before and after the implementation of the STEM-ESD-based Soil Pollution e-module. In terms of elementary clarification, students' abilities improved significantly, indicating that they are increasingly able to focus on problems and provide accurate initial explanations. Improvements were also observed in the basic support aspect, indicating that students became more skilled at providing basic support by considering sources and observing results. The inference component also improved, indicating an increase in students' ability to draw logical conclusions from the information obtained.

Meanwhile, in terms of strategies and tactics, it was found that learning outcomes after the lesson did not show optimal improvement compared to before the e-module was used. This indicates that students' ability to organise strategies and determine actions still needs further attention. On the other hand, the advanced clarification aspect improved, indicating that students were beginning to provide further explanations and identify the terms and assumptions underlying a problem. Overall, these results indicate that the use of STEM–ESD-based e-modules contributes positively to improving most aspects of students' critical thinking skills, although further reinforcement is still needed in certain aspects.

Overall, this study's results indicate that the STEM-ESD approach is effective in improving students' critical thinking skills. The integration of science, technology, and real-world environmental contexts makes students more actively engaged, think analytically, and have an awareness of environmental sustainability. Thus, STEM-ESD-based learning not only improves cognitive learning outcomes but also shapes scientific thinking relevant to the demands of 21st-century education. To

provide an overview of students' acceptance and perceptions of the use of STEM-ESD-based Soil Pollution e-modules, student response questionnaires were administered. These questionnaires were designed to reveal students' assessments of the quality and usefulness of e-modules in the learning process. The student response instrument covered five main aspects: STEM–ESD content and learning; media display and feasibility; environmental literacy; critical thinking skills; and learning motivation and engagement. The assessment of each aspect aimed to determine the extent to which the e-module met students' learning needs. The student response data obtained was then analysed descriptively using percentage techniques. The results of this analysis were used to assess the level of suitability and acceptance of the e-module from the students' perspective. These findings also served as evaluation material to identify the strengths and weaknesses of the developed e-module. The results of student responses to the STEM-ESD-based Soil Pollution e-module are presented in Table 6.

Table 6. Student Responses to the STEM-ESD-based Soil Pollution e-module

No	Aspect	Student Response
1	STEM-ESD content and learning	88%
2	Media display and feasibility	85%
3	Environmental Literacy	87%
4	Critical Thinking Skills	86%
5	Motivation and Learning Engagement	82%
Average		86%

The analysis of student responses shows that the STEM-ESD-based Soil Pollution e-module received very positive feedback. In general, all assessed aspects had percentages above 80%, indicating that this e-module is very feasible and interesting for learning. The high response to the content and STEM-ESD learning aspects shows that students consider the material presented to be relevant to real life, integrative between disciplines, and capable of fostering a holistic understanding of soil pollution. STEM-based learning emphasizes the interconnection among science, technology, engineering, and mathematics in authentic contexts, thereby increasing the relevance and meaning of learning for students.

The appearance and usability of the media also received high praise, indicating that the e-module's attractive, interactive, and easy-to-use design contributed to students' comfort and motivation in learning. Multimedia Learning, which asserts that a combination of text, images, and interactive activities can improve information processing and knowledge retention. The positive response to the critical thinking aspects of these e-modules shows that they not only convey knowledge but also encourage students to understand environmental issues in depth and develop higher-order thinking skills. This supports the OECD's (2018) view that sustainable education development is an important 21st-century competency related to reflective thinking and sustainable decision-making.

Meanwhile, the strong response to aspects of motivation and learning engagement indicates that e-modules can create active and meaningful learning experiences. STEM-ESD-based learning encourages students to engage in real-world problem solving, collaboration, and innovation in an environmental context. Thus, these results reinforce the self-determination theory, which emphasizes that learning that provides autonomy, competence, and relevance will increase students' intrinsic motivation. Overall, the high student response indicates that STEM-ESD-based e-modules are highly effective in improving critical thinking skills and learning motivation. This proves that integrating

STEM and ESD principles can be an innovative strategy for environmental education to shape a generation that thinks scientifically, cares, and is responsible for ecosystem sustainability.

CONCLUSION

This study shows that the STEM-ESD-based Soil Pollution e-module is highly valid and effective, and it receives positive responses from both teachers and students. Expert validation results indicate a very high level of feasibility across materials, construction, and language. The application of the e-module can improve students' critical thinking skills, as indicated by moderate N-Gain scores on learning outcomes. In addition, student responses to the e-module were also very good, especially in terms of content, appearance, and learning motivation. Thus, the STEM-ESD-based e-module is suitable as an innovative learning medium to support the development of 21st-century skills and sustainable environmental awareness.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

Adriani, D., Lubis, P., & Triono, M. (2020). Teaching Material Development of Educational Research Methodology With Addie Models. In *3rd International Conference Community Research and Service Engagements, IC2RSE 2019, 4 December 2019, North Sumatra, Indonesia*.

Alam, T. M., Stoica, G. A., Sharma, K., & Özgöbek, Ö. (2025). Digital Technologies in the Classrooms in the Last Decade (2014–2023): A Bibliometric Analysis. *Frontiers in Education, 10*(February).

Aligo, B. L., & Prudente, M. (2025). Effectiveness of Digital Learning Materials on Students' Achievement in Science: A Meta-Analysis. *Journal of Global Education and Research, 9*(1), 55–69.

Alsaleh, N. J. (2020). Teaching Critical Thinking Skills: Literature Review. *The Turkish Online Journal of Educational Technology, 19*(1), 21–39.

Ariyanto, S. R., Lestari, I. W. P., Hasanah, S. U., Rahmah, L., & Purwanto, D. V. (2020). Problem Based Learning dan Argumentation sebagai Solusi dalam Meningkatkan Kemampuan Berpikir Kritis Siswa SMK. *Jurnal Kependidikan: Jurnal Hasil Penelitian dan Kajian Kepustakaan di Bidang Pendidikan, Pengajaran, dan Pembelajaran, 6*(2), 197–205.

Cohen, A., Soffer, T., & Henderson, M. (2022). Students' Use of Technology and Their Perceptions of Its Usefulness in Higher Education: International Comparison. *Journal of Computer Assisted Learning, 38*(5), 1321–1331.

Coletta, V. P., & Steinert, J. J. (2020). Why Normalized Gain Should Continue to Be Used in Analyzing Preinstruction and Postinstruction Scores on Concept Inventories. *Physical Review Physics Education Research, 16*(1), 10108.

Darman, R. A. (2017). Mempersiapkan Generasi Emas Tahun 2045 Melalui Pendidikan Berkualitas. *Jurnal Edik Informatika Penelitian Bidang Komputer Sains dan Pendidikan Informatika, 3*, 73–87.

Drljača, D., Latinović, B., Stanković, Ž., & Cvetković, D. (2017). ADDIE Model for Development of E-Courses. In *Proceedings of the International Scientific Conference-Sinteza* (Vol. 2017, pp. 242–247).

Efendi, P. M. (2023). Keterampilan Abad 21 Kaitannya dengan Karakteristik Masyarakat di Era Abad 21. *Caruban: Jurnal Ilmiah Ilmu Pendidikan Dasar, 6*(1), 78.

Ellerman, D. (2025). International Journal of Education and Social Science Research. *SSRN Electronic Journal, 8*(4), 327–343.

Habibaturrohmah, Z., Kaniawati, I., Solihat, R., & Nirbayati, W. F. (2023). How to Integrate ESD (Education for Sustainable Development) Into STEM Education?: A Systematic Literature Review. *Journal of Natural Science and Integration, 6*(2), 270–282.

Hamdani, A. D., Nurhafsah, N., & Silvia, S. (2022). Inovasi Pendidikan Karakter dalam Menciptakan Generasi Emas 2045. *JPG: Jurnal Pendidikan Guru, 3*(3), 170–178.

Heale, R., & Twycross, A. (2015). Validity and Reliability in Quantitative Studies. *Evidence-Based Nursing, 18*(3), 66–67.

Kain, C., Koschmieder, C., Matischek-Jauk, M., & Bergner, S. (2024). Mapping the Landscape: A Scoping Review of 21st Century Skills Literature in Secondary Education. *Teaching and Teacher Education, 151*(December 2023), 104739.

Kioupi, V., & Voulvoulis, N. (2019). Education for Sustainable Development: A Systemic Framework for Connecting the SDGs to Educational Outcomes. *Sustainability (Switzerland), 11*(21).

Knudstad, H., & Paulsengaard, L. (2025). Public Policy Response in Expanding National Digital Education Access in Norway. *International Journal of Education and Digital Learning (IJEDL), 3*(6), 262–269.

Kopbossyn, A., Laiskhanov, S., Aksoy, B., Tokbergenova, A., Nametkulov, M., & Kozybakova, A. (2025). Integrated STEM for Sustainability in School and Early Teacher Education: A Systematic Review (2019–2025). *Frontiers in Education, 10*(October).

Kurniawan, N. A., Hidayah, N., & Rahman, D. H. (2021a). Aseptabilitas Panduan Bimbingan Kelompok untuk Meningkatkan Kemampuan Berpikir Kritis Siswa SMK. *Nusantara of Research: Jurnal Hasil-Hasil Penelitian Universitas Nusantara PGRI Kediri, 8*(1), 35–43.

Kurniawan, N. A., Hidayah, N., & Rahman, D. H. (2021b). Analisis Kemampuan Berpikir Kritis Siswa SMK. *Jurnal Pendidikan: Teori, Penelitian, dan Pengembangan, 6*(3), 334.

Mack, M. R., Hensen, C., & Barbera, J. (2019). Metrics and Methods Used to Compare Student Performance Data in Chemistry Education Research Articles. *Journal of Chemical Education, 96*(3), 401–403.

Marwah, S. S., Anisah, A. S., & Nurzakiah. (2025). Inclusive Education in the 21st Century: Challenges, Strategies, and Innovations. *Eduscape: Journal of Education Insight, 3*(2), 96–109.

Møgelvang, A., Vandvik, V., Ellingsen, S., Strømme, C. B., & Cotner, S. (2023). Cooperative Learning Goes Online: Teaching and Learning Intervention in a Digital Environment Impacts Psychosocial Outcomes in Biology Students. *International Journal of Educational Research, 117*, 102114.

Nguyen, T. P. L. (2023). Integrating Circular Economy Into STEM Education: A Promising Pathway Toward Circular Citizenship Development. *Frontiers in Education, 8*(March), 1–9.

Nurdiyati, N., Novita, M., & Patonah, S. (2025). Analisis Keterampilan Berpikir Kritis Siswa dalam Pengembangan Modul Ajar Berdiferensiasi Berorientasi Education for Sustainable Development pada Materi Green Chemistry. *Didaktika: Jurnal Kependidikan, 14*(1 Februari), 167–178.

Nurjihan, D. S., & Bunawan, W. (2025). Peningkatan Hasil Belajar Peserta Didik Melalui Penerapan LKPD Berbasis Discovery Learning. *Jurnal Pendidikan MIPA, 15*(3), 1120–1127.

Pertiwi, N. P., Saputro, S., Yamtinah, S., & Kamari, A. (2024). Enhancing Critical Thinking Skills Through STEM Problem-Based Contextual Learning: An Integrated E-Module Education Website With Virtual Experiments. *Journal of Baltic Science Education, 23*(4), 739–766.

Putri, R. D. R., Ratnasari, T., Trimadani, D., Halimatussakdiah, H., Husna, E. N., & Yulianti, W. (2022). Pentingnya Keterampilan Abad 21 dalam Pembelajaran Matematika. *Science and Education Journal (SICEDU), 1*(2), 449–459.

Rachmadio, R. E., Joko, J., Lastriyani, I., & Nugraha, D. (2024). School Principal Leadership and Sustainable Governance: A Systematic Review of International Practices. *Eduscape: Journal of Education Insight, 2*(4), 186–194.

Rahmawati, I., Hidayat, A., & Rahayu, S. (2016). Analisis Keterampilan Berpikir Kritis Siswa SMP pada Materi Gaya dan Penerapannya. *Prosiding Seminar Nasional Pendidikan IPA Pascasarjana UM, 1*(1), 1112–1119.

Rifai, N. A. K., Herlina, M., Nurhadryani, Y., & Agustina, R. (2024). Literasi digitalisasi data untuk mengatasi kesenjangan digital di masyarakat pedesaan di Desa Dayeuhkolot, Subang. *Empowerment*, *7*(03), 285-291.

Rivas, S. F., Saiz, C., & Almeida, L. S. (2023). The Role of Critical Thinking in Predicting and Improving Academic Performance. *Sustainability (Switzerland), 15*(2), 1–10.

Sarip, N., Kaharuddin, K., & Palloan, P. (2022). Analisis Keterampilan Berpikir Kritis Peserta Didik Kelas X di SMAN 10 Makassar. *Jurnal Sains dan Pendidikan Fisika, 18*(3), 291.

Sesmiyanti, S., Antika, R., & Suharni, S. (2019, August). N-Gain Algorithm for Analysis of Basic Reading. In *Proceedings of the 2nd International Conference on Language, Literature and Education, ICLLE* (pp. 22–23).

Shakeel, S. I., Al Mamun, M. A., & Haolader, M. F. A. (2023). Instructional Design With ADDIE and Rapid Prototyping for Blended Learning: Validation and Its Acceptance in the Context of TVET Bangladesh. *Education and Information Technologies, 28*(6), 7601–7630.

Sinaga, W. M. B. B., & Firmansyah, A. (2024). Perubahan Paradigma Pendidikan di Era Digital. *Jurnal Teknologi Pendidikan, 1*(4), 10.

Subhaktiyasa, P. G. (2024). Prosedur Penelitian: Suatu Pendekatan Praktik. *Journal of Education Research, 5*(4), 5599–5609.

Tanggur, F. S., Feka, V. P., & Benufinit, Y. A. (2022). Pelatihan Pembuatan dan Praktik Penggunaan Alat Peraga Pembelajaran Tematik Bagi Guru di Sdk Sta. Familia Kota Kupang. *Pemimpin*, *2*(1), 53-59.

Tarlochan, F., Alduais, A., Chaaban, Y., & Du, X. (2025). Integrating Sustainability Into STEM Education and Career Development: A Scientometric and Narrative Review. *International Journal of STEM Education, 12*(1).

Wang, A., Duan, Y., Norton, P. G., Leiter, M. P., & Estabrooks, C. A. (2024). Validation of the Maslach Burnout Inventory-General Survey 9-Item Short Version: Psychometric Properties and Measurement Invariance Across Age, Gender, and Continent. *Frontiers in Psychology, 15*(July), 1–17.

Yuliati, D., Dwi, P., Putra, A., & Ahmad, N. (2025). Pengembangan E-Modul Berbasis STEM-SDGs untuk Meningkatkan Scientific Communication Siswa. *Jurnal Pendidikan dan Kebudayaan, 15*(3), 260–267.

Zulkepli, N., Albakri, I. S. M. A., Khalid, P. Z. M., & Ishak, M. F. F. (2024). Using the ADDIE Model to Develop an Online Professional Development Program for Non-Specialist ESL Teachers. *Arab World English Journal, 2024-July*(Special Issue), 302–313.