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Integrating the Sustainable Development Goals into STEM–Engineering Design Process Instruction to Enhance Senior High School Students' Critical Thinking Skills: Evidence from a Global Warming Unit

Nurah Muslihah[1]*, Muliati Syam[2], Abdul Hakim[3], Laili Komariyah[4]
[1,2,3,4] Physics Education Study Program, Mulawarman University, Samarinda, Indonesia
*Email: nurahmuslihah19@gmail.com

Abstract

This study aims to describe students' critical thinking skills before and after the implementation of SDGs through the STEM-EDP approach on global warming material, to determine the improvement and significant differences before and after treatment. This study uses a quantitative approach through a pre-experimental design in the form of a one-group pretest-posttest. The subjects studied were students of class X-D at SMA Negeri 1 Bontang with a sample size of 35 students. Data were obtained using a test technique, consisting of 14 multiple-choice questions and essays given before and after treatment. The results of the study indicate that there is an increase in students' critical thinking skills after the implementation of SDGs through the STEM-EDP approach. This data is proven by an increase in students' average score from 37.74 to 77.89, as well as an N-Gain value of 0.64, which is included in the moderate criteria, and an Asymp.Sig. (2-tailed) value of 0.000 <0.05, indicating a significant difference in students' critical thinking skills before and after treatment. After treatment, all critical thinking skill indicators improved, with the highest increase in likelihood and uncertainty analysis. This indicates that implementing the SDGs through the STEM-EDP approach to global warming is effective in enhancing students' critical thinking skills.

Keywords: Critical Thinking, Global Warming, SDGs, STEM-EDP

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INTRODUCTION

Issues related to global warming are closely associated with the Sustainable Development Goals (SDGs) (Malihah, 2022). Global warming is addressed under SDG 13, which focuses on climate change and its impacts (Putra et al., 2024). The three objectives of SDG 13 for addressing climate change are: (i) strengthening resilience and adaptive capacity to climate-related hazards and natural disasters; (ii) integrating climate change measures into national policies, strategies, and planning; and (iii) improving education, awareness, and the capacities of individuals and institutions in climate change mitigation, adaptation, impact reduction, and early warning related to climate change (Idrus & Nur, 2024).

Global warming and the climate change challenges faced by Indonesia require collective efforts from people around the world to mitigate their impacts (Putri et al., 2024). One way students can contribute is by studying global warming scientifically through physics learning, enabling them to understand the

ongoing phenomenon of global warming as well as methods to reduce its impacts and effects (Septaria et al., 2019). The teaching of global warming should not be underestimated, as it fosters environmental awareness among the younger generation and encourages creative thinking to develop innovations and mitigate the impacts of global warming (Hidayah & Permadi, 2023).

The implementation of the SDGs in education represents a concrete effort to achieve quality education through various initiatives, such as expanding equitable access to education, improving teacher quality, and developing inclusive educational policies (Anggraini & Nugraheni, 2024). This indicates that the implementation of the SDGs is not merely conceptual but has also been translated into educational policies and practices. Implementing the SDGs through environmental education can enhance students' awareness of sustainability issues and encourage them to become more concerned about their surrounding environment. Thus, implementing the SDGs in the learning process is directed not only toward developing students' knowledge but also toward fostering their attitudes and behaviors (Syarif et al., 2024).

The SDGs can be integrated into global warming instruction to maximize students' critical thinking skills. Critical thinking is an essential component of quality education (Rahayu et al., 2024). High-quality education can motivate individuals to become productive and innovative in promoting long-term sustainable development (Safitri et al., 2022). Quality education is one of the 17 Sustainable Development Goals, aiming to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (Humaida et al., 2020). Therefore, education is one of the key factors for achieving the SDGs.

In 2022, Indonesia ranked 68th in the Programme for International Student Assessment (PISA), with an average science score of 383 points (OECD, 2023). Based on these findings, it can be concluded that Indonesian students' intellectual skills remain at a relatively low level (Rahmayani et al., 2024). PISA-based studies have shown that the indicators used in the PISA assessment are directly related to the components of critical thinking. For example, the ability to interpret data, explain scientific phenomena, and evaluate arguments constitutes part of the critical thinking skills assessed in the PISA framework. This indicates that PISA scores indirectly represent students' levels of critical thinking skills (Gomez & Suarez, 2020). PISA-based assessment tasks are highly relevant for measuring and developing 21st-century skills, particularly the 4Cs (Critical Thinking, Creativity, Communication, and Collaboration). Simanjuntak et al. (2024) reported that the use of PISA-based assessment tasks can profile and develop students' critical thinking skills in mathematics learning. This suggests that the better students perform on PISA-based tasks, the higher their critical thinking skills are likely to be. Prasetyo (2022) stated that one of the factors preventing students from meeting critical reasoning indicators is their lack of familiarity with higher-order thinking tasks, as they are more accustomed to solving relatively simple questions. Critical thinking is one of the higher-order thinking skills that is essential for developing 21st-century competencies (Rahardhian, 2022).

Critical thinking is a component of higher-order thinking skills (HOTS) (Oktavia et al., 2024). The indicators of critical thinking include cognitive processes such as understanding problems, formulating assumptions, providing logical reasoning, evaluating evidence, and making decisions (Hardika, 2020). Critical thinking is essential in science learning (Bahtiar et al., 2022). Physics is a branch of science that studies phenomena occurring in the universe (Wea et al., 2021). The application of critical thinking in physics learning is crucial because it trains students to analyze, interpret, and generate ideas to solve problems related to everyday life (Aripin et al., 2021).

One potential solution to address the issues described above is to implement a learning model that motivates students to think rationally in solving problems. The approach adopted in this study is the STEM–Engineering Design Process (STEM–EDP) learning approach (Ritonga & Zulkarnaini, 2021). Science, Technology, Engineering, and Mathematics (STEM) is an educational approach that aligns with the learning process to foster the development of the 4Cs (critical thinking, creativity, collaboration, and communication) (Fajrina et al., 2020). Integrating STEM with the Engineering Design Process (EDP) provides more meaningful learning experiences by engaging students in designing solutions to real-world problems. Triwulandari et al. (2022) found that EDP-based STEM learning on the topic of

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global warming effectively improved students' learning outcomes and received positive responses from students. The EDP stages, including problem identification, solution design, testing, and evaluation, directly promote students' critical thinking skills.

Syamsudin et al. (2026) also reported that the STEM–EDP approach has experienced rapid development in science education research and has been widely associated with improvements in critical thinking skills, problem-solving abilities, and project-based learning. These findings indicate that STEM–EDP is an innovative approach that is highly relevant to addressing the challenges of 21st-century education.

One of the essential components of STEM in the learning process is the Engineering Design Process (EDP) (Ulum et al., 2021). EDP is a structured problem-solving method that produces practical solutions through a systematic sequence of procedures (Syukri et al., 2023). Several studies have suggested that STEM can serve as an alternative approach for collaborative project-based learning within the Merdeka Curriculum (Latip et al., 2022). The curriculum currently implemented in Indonesian schools is the Merdeka Curriculum. Merdeka Belajar is an educational reform initiative introduced by the Ministry of Education and Culture of the Republic of Indonesia (Amalia, 2022).

This study contributes by providing an alternative instructional approach through STEM–EDP to enhance students' critical thinking skills. Specifically, this study aims to examine the improvement and significant differences in students' critical thinking skills before and after the implementation of the SDGs through the STEM–EDP approach in teaching global warming.

METHODS

The operational definitions of the variables used in this study are as follows. First, SDG implementation refers to the application of the principles of the Sustainable Development Goals, particularly SDG 4 (Quality Education) and SDG 13 (Climate Action), within the learning process. This implementation involves integrating sustainability concepts and environmental awareness into teaching and learning activities on the topic of global warming. Second, the STEM–Engineering Design Process (STEM–EDP) approach refers to an instructional approach that integrates science, technology, engineering, and mathematics with the Engineering Design Process (EDP). This process consists of the stages: Ask (identifying the problem), Imagine (generating possible solutions), Plan (designing a solution), Create (developing a prototype), and Improve (refining the solution), to address global warming issues creatively and innovatively. Third, critical thinking skills refer to students' critical thinking abilities measured before and after participating in physics instruction using the STEM–EDP approach on the topic of global warming. These skills comprise four indicators: hypothesis testing, argument analysis, likelihood and uncertainty analysis, and problem solving and decision making, which were assessed using a pretest and posttest consisting of 10 multiple-choice questions and 4 essay questions.

This study employed a quantitative approach using a pre-experimental one-group pretest–posttest design. The sample consisted of a single class, in which the dependent variable was measured through a pretest administered before the intervention and a posttest administered after the implementation of the STEM–EDP approach. The study was conducted at SMA Negeri 1 Bontang from July to August 2025. The population comprised tenth-grade students at SMA Negeri 1 Bontang, while the sample consisted of 35 students from Class X-D. Purposive sampling was employed to select the sample based on several predetermined considerations.

Written tests were used as the primary data collection instrument in this study. The instrument for assessing critical thinking skills on the topic of global warming was adapted and re-evaluated based on a previous study conducted by Maharani et al. (2024). The test instrument had been piloted in six different schools in Samarinda City. The instrument consisted of 14 questions divided into two sections: 10 multiple-choice questions and 4 essay questions. The test was administered twice, before and after the implementation of SDG-based instruction using the STEM–EDP approach. According to Tiruneh et al. (2017), critical thinking skills consist of four indicators, as presented in Table 1.

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Table 1. Blueprint of the critical thinking skills test instrument

Critical Thinking Indicator	Multiple-Choice Items	Essay Items
Hypothesis Testing	4, 5	14
Argument Analysis	1, 8	–
Likelihood and Uncertainty Analysis	3, 6	11
Problem Solving and Decision Making	2, 7, 9, 10	12, 13

The scores obtained for each critical thinking indicator were analyzed using Equation 1.

$$Score = \left(\frac{Obtained\ score}{Maximum\ score}\right) \times 100$$

According to Razak (2017), students' pretest and posttest scores were classified into several performance categories, as presented in Table 2.

Table 2. Classification of pretest and posttest scores

Score Range	Category
80 ≤ x ≤ 100	Very Critical
70 ≤ x < 80	Critical
60 ≤ x < 70	Moderate
40 ≤ x < 60	Less Critical
0 ≤ x < 40	Very Less Critical

Data were analyzed using descriptive statistics to calculate the mean, maximum and minimum scores, and standard deviation. The analyses were performed using IBM SPSS Statistics 25 software. Descriptive analysis was used to describe students' critical thinking skills before and after the implementation of the STEM–EDP learning approach. The normalized gain (N-gain) test was employed to analyze the pretest and posttest data to determine the extent of improvement in students' critical thinking skills, while the paired-samples *t*-test was used to examine the differences in students' critical thinking skills before and after the implementation of the SDGs through the STEM–EDP approach. Prior to hypothesis testing, a normality test was conducted to ensure that the collected data were normally distributed.

RESULTS AND DISCUSSION

Results

The pretest results indicated that students' scores before the intervention ranged from 28 to 50. In contrast, the posttest scores obtained after the intervention ranged from 64 to 88. The descriptive statistics for the pretest and posttest scores are presented in Table 3.

Table 3. Descriptive statistics of students' critical thinking skills in the pretest and posttest

Descriptive Statistics	N	Minimum	Maximum	Mean	Std. Deviation
Pretest	35	28	50	37.74	5.777
Posttest	35	64	88	77.89	6.347
Valid N (listwise)	35				

Based on Table 3, students' mean critical thinking score increased substantially from 37.74 in the pretest to 77.89 in the posttest. The standard deviation was 5.777 for the pretest and 6.347 for the posttest. In addition, each indicator of critical thinking skills was observed throughout the implementation of the STEM–EDP approach during each learning session. The observation results are presented in Figures 1 and 2 as bar charts illustrating the differences in the mean pretest scores, posttest scores, and N-gain values for both the multiple-choice and essay questions across all measured critical thinking indicators.

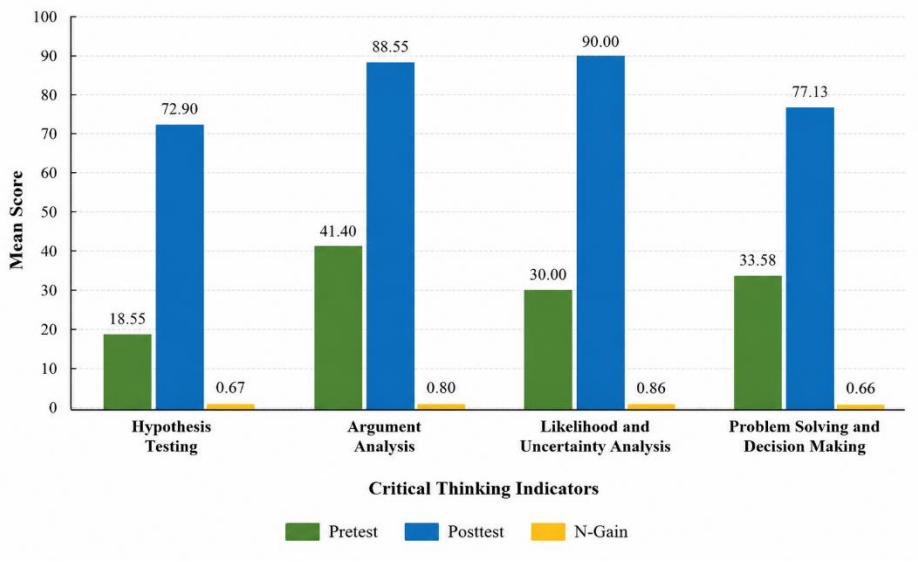


Figure 1. Mean scores for multiple-choice critical thinking indicators

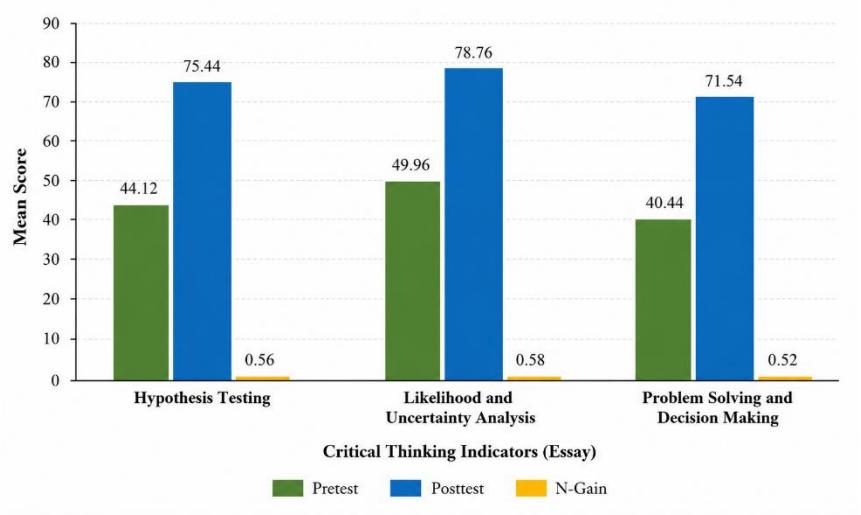


Figure 2. Mean scores for essay-based critical thinking indicators

Figures 1 and 2 present the mean scores for each critical thinking indicator on the multiple-choice and essay tests, respectively. The figures show that the mean scores for all critical thinking indicators were higher on the posttest than on the pretest. These findings indicate that implementing the SDGs through the STEM–EDP approach improved students' critical thinking skills across all measured indicators. The indicator that showed the greatest improvement following the implementation of the STEM–EDP approach was further analyzed using the normalized gain (N-gain) test.

The normalized gain (N-gain) test was used to determine the extent of improvement in students' learning outcomes from the pretest to the posttest. The results of the N-gain analysis are presented in Table 4.

Table 4. N-gain results

Mean Pretest	Mean Posttest	N-Gain	Category
37.74	77.89	0.64	Moderate

Based on the results presented in Table 4, the N-gain value for students' critical thinking skills was 0.64, which falls into the moderate category. This analysis was conducted to determine the improvement in each student's critical thinking skills. The distribution of students' N-gain categories is

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presented in Table 5.

Table 5. Distribution of students' N-gain categories for critical thinking skills

N-gain	Category	Frequency	Percentage
N-gain ≥ 0.70	High	10	28.57%
0.70 > N-gain ≥ 0.30	Moderate	25	71.43%
N-gain < 0.30	Low	0	0%

As shown in Table 5, students' N-gain scores were classified into the moderate and high categories. The majority of students (71.43%) achieved a moderate level of improvement, while 28.57% achieved a high level. No students fell into the low category. This finding may be attributed to the collaborative and project-based nature of the learning activities, which provided students with opportunities to discuss, construct arguments, and solve problems collaboratively. The percentage distribution of students across the N-gain categories is illustrated in Figure 3.

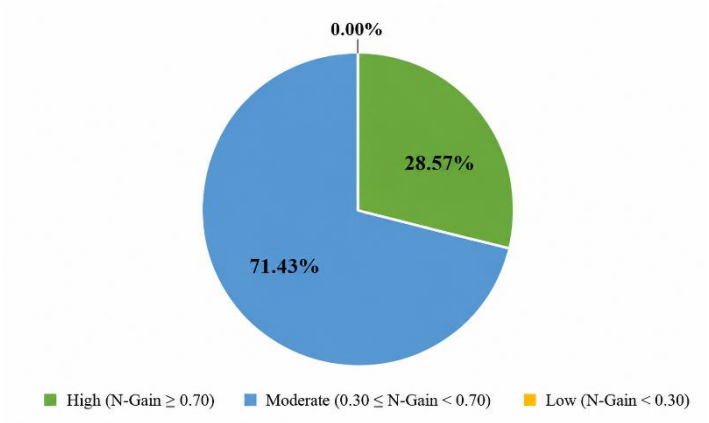


Figure 3. Distribution of students across N-gain categories

The N-gain analysis was also conducted to examine the improvement in each measured critical thinking indicator. The N-gain results for each indicator were obtained from two types of assessment instruments: multiple-choice and essay tests. The N-gain results for the multiple-choice test are presented in Table 6, while those for the essay test are presented in Table 7.

Table 6. N-gain results for critical thinking indicators in the multiple-choice test

Critical Thinking Indicator	Mean Pretest	Mean Posttest	N-Gain	Category
Hypothesis Testing	18.55	72.90	0.67	Moderate
Argument Analysis	41.40	88.55	0.80	High
Likelihood and Uncertainty Analysis	30.00	90.00	0.86	High
Problem Solving and Decision Making	33.58	77.13	0.66	Moderate

Table 7. N-gain results for critical thinking indicators in the essay test

Critical Thinking Indicator	Mean Pretest	Mean Posttest	N-Gain	Category
Hypothesis Testing	44.12	75.44	0.56	Moderate
Likelihood and Uncertainty Analysis	49.96	78.76	0.58	Moderate
Problem Solving and Decision Making	40.44	71.54	0.52	Moderate

Tables 6 and 7 show that all critical thinking indicators were classified within the moderate and high categories. The Likelihood and Uncertainty Analysis indicator demonstrated the greatest improvement, with an N-gain score of 0.86 for the multiple-choice test and 0.58 for the essay test. In contrast, the Problem Solving and Decision Making indicator showed the lowest improvement, with an N-gain score of 0.66 for the multiple-choice test and 0.52 for the essay test. These findings indicate that the

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implementation of the SDGs through the STEM–EDP approach on the topic of global warming effectively improved the critical thinking skills of tenth-grade students at SMA Negeri 1 Bontang, particularly in the Likelihood and Uncertainty Analysis indicator.

Before conducting the paired-samples *t*-test, the assumption of normality was examined using the Shapiro–Wilk test. The data were considered normally distributed when the significance value exceeded 0.05 ($p > 0.05$). The results of the normality test for the pretest and posttest scores are presented in Table 8.

Table 8. Results of the normality test for the pretest and posttest scores

Test of Normality	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pretest	.085	35	.200*	.968	35	.401
Posttest	.145	35	.062	.952	35	.132

[a] *Liliefors Significance Correction.*

For the pretest data, the significance value was 0.401, whereas the posttest data yielded a significance value of 0.132. Since both significance values were greater than 0.05, the data were considered to be normally distributed. Therefore, hypothesis testing was conducted using the paired-samples *t*-test, and the results are presented in Table 9. As shown in Table 9, the significance value (Sig. 2-tailed) was 0.000. Since this value was less than 0.05 ($p < 0.05$), it can be concluded that there was a statistically significant difference in students' critical thinking skills before and after the implementation of the SDGs through the STEM–EDP approach.

Table 9. Results of the paired-samples *t*-test

Paired Samples Test	Mean Difference	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
				Lower	Upper			
Pretest – Posttest	-40.143	7.758	1.311	-42.808	-37.478	-30.612	34	.000

Discussion

SDG-based learning is more effective than conventional instruction and can foster students' critical thinking skills. Students are encouraged to understand environmental issues from the perspectives of science, technology, engineering, and mathematics, and to solve problems through the stages of the Engineering Design Process (EDP) (Yennita et al., 2025). STEM learning implemented through the EDP stages actively engages students in the learning process, promoting two-way interactions and collaborative discussions among peers (Sulaeman et al., 2021).

Chen (2024), in a study published in a reputable international journal, reported that integrating the Engineering Design Process into STEM instruction has a positive effect on the development of higher-order thinking skills, including critical thinking, because students are trained to evaluate alternative solutions and consider the consequences of each decision they make. Therefore, based on these previous studies, it can be concluded that the STEM–EDP approach is an effective instructional strategy for enhancing students' critical thinking skills, particularly in the topic of global warming, which requires analytical, evaluative, and problem-solving skills within real-world contexts.

Rahmawati et al. (2024) also reported that STEM–EDP-based learning is effective in improving students' critical thinking skills because it connects scientific concepts with authentic environmental issues, thereby encouraging students to think reflectively and develop solution-oriented thinking. Students' understanding of global warming throughout the learning process was demonstrated by their ability to complete the student worksheets (LKPD) during each lesson. These worksheets were designed based on critical thinking indicators and aligned with the stages of the STEM approach through the Engineering Design Process (EDP).

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Figure 4. Student worksheet (LKPD) on global warming

During the first stage, Define (defining the problem), the lesson began by presenting a video on global warming, as outlined in the student worksheet (LKPD), which introduced facts about environmental changes resulting from global warming. At this stage, students engaged in critical thinking by identifying problems related to the events presented in the video. This activity primarily fostered the likelihood and uncertainty analysis indicator, as students predicted the factors contributing to global warming. In addition, students demonstrated the argument analysis indicator by identifying relevant information and evaluating the credibility of information sources.

During the second stage, Learn (learning the scientific concepts related to the problem), students studied the causes and impacts of global warming. They collected information from the instructional video provided in the LKPD and identified the knowledge required to answer the questions presented in the worksheet. This activity primarily promoted the problem-solving and decision-making indicator, as students learned to understand the characteristics of a problem and develop appropriate solution plans based on the identified issues.

During the third stage, Plan (planning an appropriate solution), students worked collaboratively in groups to answer the questions in the LKPD, discuss project design ideas, and begin planning their projects. At this stage, students designed a miniature environmentally friendly and flood-resistant house. The planning process included determining an elevated house design to prevent floodwater from entering the building and selecting environmentally friendly materials, such as wooden sticks, cardboard, and used plastic straws. This activity primarily developed the likelihood and uncertainty analysis indicator, as students identified strategies to mitigate the impacts of global warming.

During the fourth stage, Try (developing and testing the proposed solution), students constructed the planned project and refined it based on the results of the initial trial. At this stage, they evaluated whether the miniature house design was both environmentally friendly and resistant to flooding. This activity primarily strengthened the problem-solving and decision-making indicator, as students analyzed alternative solutions and made appropriate decisions based on evidence.

During the fifth stage, Test (testing the solution), students presented and evaluated their completed projects. In this phase, the environmentally friendly and flood-resistant miniature house was tested by placing it in a container filled with water to determine whether the design could withstand flooding while remaining stable without collapsing. This activity primarily developed the hypothesis testing indicator, as students determined whether causal principles could be applied to explain the observed outcomes.

During the sixth stage, Decide (deciding and communicating whether the proposed solution is appropriate or requires improvement), students presented the projects they had designed and tested. This activity fostered critical thinking through the reasoning indicator, as students interpreted the results of the discussions they had conducted. In addition, students demonstrated the argument analysis

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indicator by drawing valid conclusions from the data provided. These indicators were evident when students responded to the LKPD presentations of other groups by providing suggestions, critiques, and questions.

The greatest improvement in critical thinking skills was observed in the likelihood and uncertainty analysis indicator. This improvement can be attributed to the implementation of the SDGs through the STEM–EDP approach, which directly engaged students in collecting and analyzing data related to authentic real-world problems. Global warming, as a learning topic closely connected to real-life situations, involves considerable scientific uncertainty and probabilistic reasoning. Consequently, it provides students with greater opportunities to develop their likelihood and uncertainty analysis skills compared with the other critical thinking indicators.

However, this does not imply that the STEM–EDP approach was less effective in developing the other critical thinking indicators. Several factors may explain why these indicators showed smaller improvements than likelihood and uncertainty analysis, such as the limited instructional time devoted to activities specifically targeting those indicators. As a result, students had fewer opportunities to practice and receive feedback on skills such as making appropriate decisions based on information presented in tables or graphs.

To verify whether the observed improvement was statistically significant, statistical analyses were performed. The prerequisite analysis began with the Shapiro–Wilk normality test, which indicated that both the pretest and posttest data were normally distributed. Subsequently, a paired-samples *t*-test was conducted to determine the significance of the improvement. The results showed a significance value (*Sig.* 2-tailed) of 0.000, which was lower than 0.05. Based on the decision criterion ($p < 0.05$), the null hypothesis (H_0) was rejected, and the alternative hypothesis (H_a) was accepted. Therefore, it can be concluded that there was a statistically significant difference in students' critical thinking skills before and after the implementation of the SDGs through the STEM–EDP approach.

CONCLUSION

Based on the results of the data analysis conducted with Class X-D students at SMA Negeri 1 Bontang, it can be concluded that the mean critical thinking score increased from 37.74 before the implementation of the STEM–EDP approach to 77.89 after the intervention. The implementation of the Sustainable Development Goals (SDGs) through the STEM–EDP approach in teaching global warming resulted in a significant improvement in students' critical thinking skills. This finding was supported by an N-gain score of 0.64, which falls within the moderate category. The greatest improvement was observed in the likelihood and uncertainty analysis indicator, with N-gain scores of 0.86 for the multiple-choice test and 0.58 for the essay test. Furthermore, a significant difference was found in students' critical thinking skills before and after the implementation of the SDGs through the STEM–EDP approach on the topic of global warming. This was confirmed by the paired-samples *t*-test result, which yielded a significance value of 0.000 ($p < 0.05$).

Based on the findings of this study, the STEM–EDP approach can serve as an effective alternative instructional strategy for developing students' knowledge and enhancing their critical thinking skills in classroom learning. However, the time allocated for implementing the STEM–EDP approach was relatively limited, preventing each stage of the Engineering Design Process (EDP) from being explored in sufficient depth. Consequently, some students were unable to fully understand the relationships among physics concepts, the SDG context, and the engineering design solutions they developed. Future studies are therefore recommended to allocate more instructional time to enable students to engage more deeply in each stage of the EDP and strengthen the integration of physics concepts with sustainable development contexts.

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Conflict of Interest

The authors declare that they have no conflict of interest related to this study.

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Author Contributions

N.M. contributed to conceptualization, methodology, investigation, data curation, formal analysis, and writing the original draft. M.S. contributed to methodology, validation, supervision, and reviewing and editing the manuscript. A.H. contributed to investigation, validation, and reviewing and editing the manuscript. L.K. contributed to supervision and reviewing and editing the manuscript. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for their contributions.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate

Formal ethics approval was not required for this study in accordance with the applicable institutional requirements. The study was conducted with permission from SMA Negeri 1 Bontang. Participation was voluntary, and informed consent was obtained from the participants and/or their legal representatives, as applicable.

Generative AI Declaration

During the preparation of this manuscript, the authors used Google Gemini to assist with language editing, grammar correction, improving clarity and readability, and refining sentence structure. The authors critically reviewed and edited all AI-assisted content and take full responsibility for the accuracy, originality, integrity, and final content of the manuscript.

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