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Analysis of Critical Thinking and Environmental Concern in SDGs Based STEM Learning

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Abstract : This study aimed to analyze students' critical thinking and environmental awareness in STEM learning based on SDGs. The research method used was a quasi-experimental design with a non-equivalent post-test-only control group design. The population consisted of 197 students, and a random sampling technique was used to select 75 students for the sample. The study employed a critical thinking test and an environmental awareness questionnaire as the instruments. Data were analyzed using SPSS 25 with a MANOVA test. The results showed that gender influenced students' critical thinking skills; however, it did not affect students' environmental awareness in STEM learning based on the SDGs. Furthermore, the learning method had an impact on both students' critical thinking skills and environmental awareness, indicating that STEM learning based on the SDGs is more effective than conventional methods. In conclusion, the learning method influences students' critical thinking skills and environmental awareness, whereas gender affects the level of critical thinking but does not influence environmental awareness at the junior high school level.

Keywords: Critical thinking; environmental concern; SDGs; STEM.



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基于可持续发展目标的 STEM 学习中的批判性思维和环境关注分析

摘要：本研究旨在分析学生在基于 SDGs 的 STEM 学习中的批判性思维和环境意识。所采用的研究方法是准实验设计，具有非等效后测对照组设计。总体为 197 名学生，样本是随机选取的，最终有 75 名学生作为样本。本研究使用了批判性思维工具和环境意识问卷。使用 SPSS 25 和 MANOVA 检验来分析数据。结果表明，性别影响学生的批判性思维能力，但性别并不影响学生在基于 SDGs 的 STEM 学习中的环境意识态度。然后，学习方法会影响学生的批判性思维能力和环境意识，这意味着基于 SDGs 的 STEM 学习比传统方法更好。综上所述，教学方法影响初中生的批判性思维能力和环境意识，性别影响批判性思维水平，但不影响环境意识态度。

关键词：批判性思维；环境关注；SDGs; STEM

1. Introduction

Education is one of the key pillars of sustainable development and is capable of shaping individuals who are aware of their responsibilities toward the environment [1], [2], [3]. In today's modern era, global challenges such as climate change, the depletion of natural resources, and pollution demand innovative solutions rooted in a deep understanding of science, technology, engineering, and mathematics (STEM). The implementation of STEM education based on Sustainable Development Goals (SDGs) is highly relevant to equip students with critical thinking skills and a strong sense of environmental awareness.

Critical thinking is the ability and willingness to evaluate a number of statements and make objective decisions based on sound judgment and supporting facts rather than on emotions [4], [5]. Based on this definition, students are not merely expected to accept all the information presented to them but are also required to assess it and provide solutions based on facts obtained through observation [6], [7]. In line with the goal of education to improve the quality of individuals, one of the key indicators of a person's quality is their ability to think critically [8].

However, several studies have shown that students' thinking skills remain low [9], [10], [11], [12], [13]. In addition, according to the Trends in International Mathematics and Science Study (TIMSS), which is conducted every four years, only 5% of secondary school students are able to solve problems that require critical thinking, whereas the remaining 95% solve problems based on memorization. This indicates that education is still largely conceptual and is yet to fully support learning that integrates critical thinking skills. Critical thinking is an essential competency required in the 21st century [14], [15].

Many studies have stated that the factors contributing to students' low critical thinking skills include: (1) students are not confident in expressing arguments, (2) students are not given enough opportunities to explore, (3) monotonous teaching methods are used, (4) classroom management is poor, (5) learning is based on memorization rather than conceptual understanding, and (6) students have not been trained to analyze problems based on facts [16].

Low critical thinking skills certainly have a negative impact on student development [17], [18]. Without critical thinking skills, students tend to make irrational or hasty decisions without thorough analysis, make mistakes that harm themselves, struggle to solve complex problems, and hinder cognitive progress for future learning [19].

In implementing an independent curriculum, students are encouraged to be more critical and active. Critical thinking is not only applied during lessons but also in daily life, such as in the attitude toward environmental awareness. In everyday life, critical thinking is needed to preserve the environment. This environmental awareness is not just limited to a concept but is more about the contextual application of critical thinking on how to protect the environment so that it can be utilized both in the present and in the future [20], [21].

This integration should begin with learning through a contextual problem-solving approach, one of which is STEM. The STEM approach trains students to develop problem-solving skills, critical thinking, and collaboration to understand phenomena occurring in their surroundings, thereby fostering curiosity and understanding the causes, impacts, and solutions to address them [16], [22], [23]. STEM can create human resources that are not only capable of addressing

environmental issues but also of reducing environmental damage in sustainable development [24], [25].

Learning that connects environmental issues and efforts to address them in the future is part of the objectives of the SDGs. Science education is one of the key subjects that support the achievement of SDGs or development aimed at maintaining the balance of the world without harming future generations [26], [27]. It can be said that science education plays an important role in the creation of Education for Sustainable Development (ESD) [28], [29]. Science education, which integrates the fields of Physics, Chemistry, and Biology, aligns with the principles of sustainable development and can provide a broad perspective for fostering curiosity and new ideas [28], [30].

To achieve this goal, learning media aligned with the SDGs based STEM approach are required. The STEM approach, with the principles of sustainable development, aims to enhance society's capabilities in science and innovative technological products to be globally competitive [31]. In this case, the STEM approach can prepare the younger generation to address the challenges they face in society [32]. The STEM approach also helps fulfill one of the SDGs, particularly Goal 4, which focuses on Quality Education and equipping society with 21st century skills [33].

The use of learning media with the STEM approach certainly has more advantages and impacts the improvement of students' cognitive abilities and skills [17]. This is supported by numerous studies on the advantages of STEM, which have been identified as enhancing scientific literacy, thinking abilities, and creative thinking [34], [35], [36], increasing students' interest in pursuing careers in science [37], improving their attitudes toward science [38], and enhancing scientific literacy [39]. Furthermore, many researchers have conducted studies or developed learning media using the STEM approach to enhance higher-order thinking skills [40], train students' creativity through project-based STEM learning [41], and develop electrical installation prototype kits as STEM project media for junior high school students [42], [43].

A lesson on alternative energy will train students to be mindful of their environment, especially in terms of energy use in daily life, to prevent overconsumption. Learning takes place outside the classroom, where students build and assemble an alternative energy project related to energy from their surrounding environment. This SDGs based STEM project on alternative energy is connected to the use of energy for sustaining life in the future and, of course, helps students understand the scientific concepts behind the material they are learning.

The novelty of this study lies in the innovation of integrating STEM learning with the principles of SDGs, focusing on alternative energy, aimed at enhancing students' critical thinking skills and environmental awareness. This study addresses the need to develop educational methods that not only focus on cognitive and technical aspects, but also build awareness and environmental responsibility. Although previous studies [30], [44] have shown the benefits of STEM education, the SDGs based applications, particularly in the area of alternative energy, have not been extensively explored. Using a quasi-experimental approach and qualitative analysis, this study offers a significant new contribution to the educational literature and demonstrates that this integration can lead to meaningful improvements in critical thinking and environmental awareness among students.

Therefore, the research questions in this study are as follows: 1) Does the implemented learning approach affect students' critical thinking skills and environmental awareness based on gender?. 2) Do differences in the applied methods influence students' critical thinking skills and environmental awareness?.

2. Method

The study was conducted over a 10 month period in 2024. The research procedure is illustrated in Fig. 1.

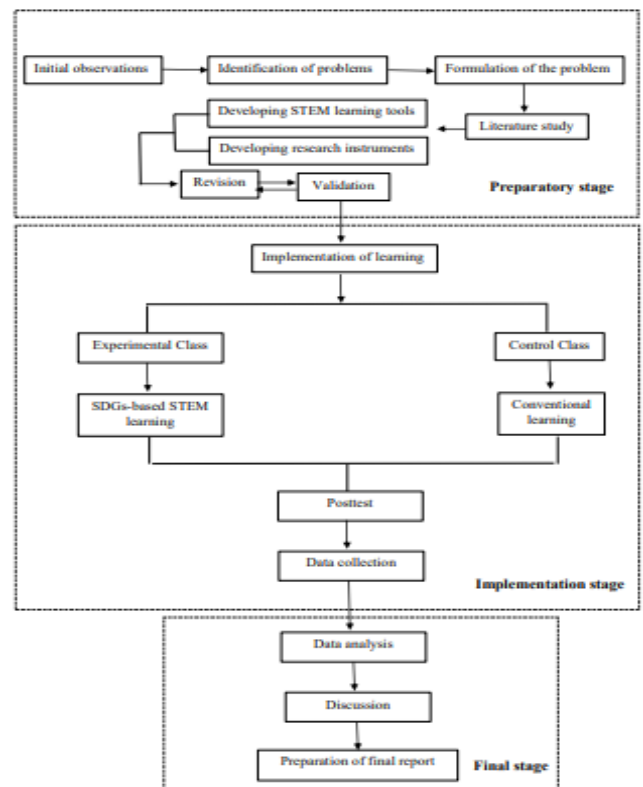


Figure 1. Research procedures (developed by the authors)

2.1 Population and Sample

This study was conducted at a junior high school in Riau, Indonesia. An independent curriculum was implemented as the official curriculum of this school. This study used a quasi-experimental research method with a non equivalent posttest only control group design [45]. There were two classes in this study: experimental and control. The experimental class was given treatment using STEM-based Alternative Energy Learning aligned with the Sustainable Development Goals, while the control class was treated with conventional teaching methods. The study was conducted at the Junior High School, 21 Pekanbaru, Riau, Indonesia.

The population of this study consists of 9th grade students aged 14–16 years.

The initial step in determining the sample was to conduct a normality test to assess whether the population distribution was normal. Next, a homogeneity test was conducted to determine whether there were groups with homogeneous variance. After identifying homogeneous groups, they were randomly selected using the lottery method. The sample for this study consisted of one control class and one experimental class. Figure 2 illustrates the procedure used to select the research sample.

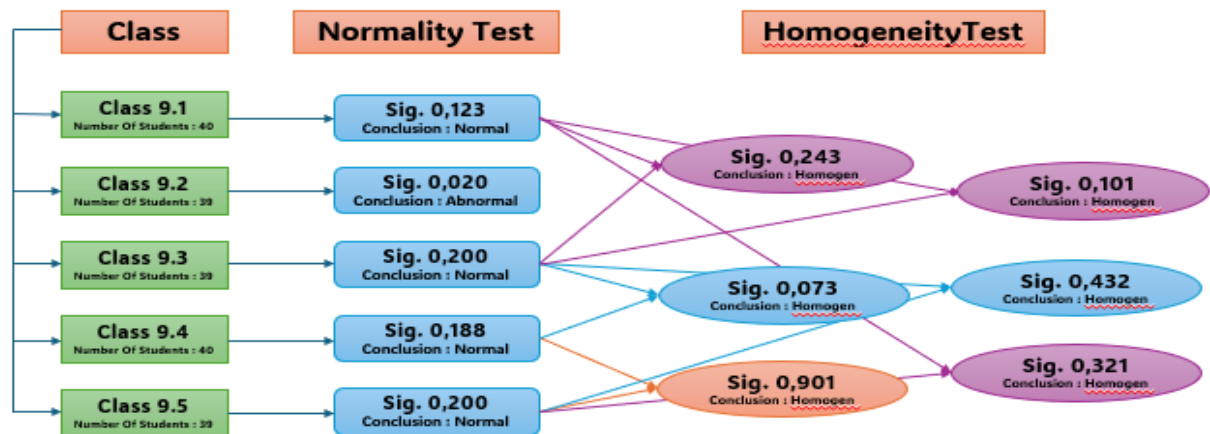


Figure 2. Sample selection procedure from the research population (developed by the authors)

The figure shows that the research population consists of five classes (Class 9.1, 9.2, 9.3, 9.4, and 9.5). After conducting the normality test, four classes were found to be normally distributed (Classes 9.1, 9.3, 9.4, and 9.5), and one class was not normally distributed (Class 9.2). A homogeneity test was conducted on the four normally distributed classes, and all four were found to be homogeneous. Two classes were then randomly selected, resulting in Class 9.1 being assigned as the experimental class and Class 9.3 as the control class, both with a significance value of 0.101, indicating normal distribution. A total of 85 students were selected for the sample, with 38 and 37 students in the experimental and control classes, respectively. The distribution of the male and female students is shown in Figure 3.

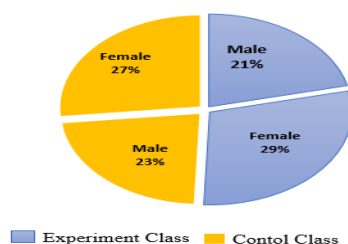


Figure 3. Percentage of male and female student samples

2.2 Research Instruments

Data were collected using tests and questionnaires. The environmental awareness questionnaire was designed to determine the extent of the students' environmental concerns. The test was used to measure students' critical thinking skills. The instrument used to assess critical thinking skills was developed in the form of multiple choice questions. Both instruments were developed by the researchers. Before conducting the study, the critical thinking instrument was validated by experts and tested in a trial. Validity and reliability tests were conducted after the trial. The following are the results of the expert validation of the critical thinking instrument:

Table 1. Expert validation results of critical thinking questions (developed by the authors)

Number	Aspects that are observed	Amount	Average Aspect	Category
1	Material Aspects	5	3,6	Very Valid
2	Construction Aspects	6	3,67	Very Valid
3	Linguistic Aspect	3	3,67	Very Valid
			Average	3,64 Very Valid

The validation results of the critical thinking skills test instrument from the two expert validators across all assessed aspects showed an average validation score of 3.62, which falls into the very valid category. Therefore, it can be concluded that the critical thinking skills test instrument developed for the topics of Dynamic Electricity and Alternative Energy Sources is appropriate for use as a teaching tool in the learning process. Subsequently, a test trial was conducted. Of the 20 test items, 16 were declared valid based on a validity test. According to [46], if each indicator aspect is still represented and a retest is not feasible, invalid items may be discarded. Of the 16 valid questions analyzed with SPSS 25, a Cronbach's alpha value of 0.747 was obtained, which falls into the reliable category.

Additionally, a trial of the environmental awareness questionnaire consisting of 30 statement items resulted in a Cronbach's alpha of 0.741, which was also categorized as reliable. These reliability results indicate that the instruments were suitable for measuring students' critical thinking skills and environmental awareness.

The media developed and implemented in this study consist of three learning tools: 1) a solar power generator, 2) a hydroelectric power generator, and 3) a wind power generator. These three tools are provided in a kit box containing puzzle-like components that students assemble into functional power plant models. The design of the STEM SDGs learning medium is shown in Figure 4.



Figure 4. STEM SDGs learning media

2.3 Data analysis

The research data were analyzed using descriptive and inferential methods. Descriptive analysis was conducted to obtain an overall picture of the variables analyzed. An inferential analysis was then performed,

beginning with tests for homogeneity and normality. Once these assumptions were met, a MANOVA test was conducted. The following table presents the types of data, data collection techniques, and data analysis methods.

Table 2. Types of data and data collection techniques

Number	Data type	Data collection technique	Data analysis techniques
1.	Teacher and student perceptions and needs	Providing perception questionnaires to respondents	Quantitative Descriptive Analysis: Frequency and Histogram
2.	Critical thinking skills of control and experimental class students	Providing critical thinking ability test questions for control and experimental class students	Quantitative Descriptive Analysis: Frequency and Histogram Inferential Test: using Manova Test
3.	Environmental concern attitude of control and experimental class students	Providing a questionnaire on environmental awareness attitudes of students in control and experimental classes	Quantitative Descriptive Analysis: Frequency and Histogram Inferential Test: using Manova Test

3. Results

The critical thinking skills data used in this study were based on four aspects of creative thinking skills: 1) elementary clarification, 2) basic support, 3) inference,

and 4) strategies and tactics. The descriptive analysis results are shown in table 2.

Table 3. Overall descriptive analysis

Indicator	Gender	Class	Mean	Std. Deviation	N
Critical thinking	Male	STEM_SDGs	65.81	8.788	16
		Conventional	50.59	8.522	17
		Total	57.97	11.499	33
	Female	STEM_SDGs	82.14	7.599	22
		Conventional	73.35	8.113	20
		Total	77.95	8.933	42
	Total	STEM_SDGs	75.26	11.437	38
		Conventional	62.89	14.116	37
		Total	69.16	14.181	75
Environmental Concern	Male	STEM_SDGs	74.56	6.593	16
		Conventional	68.29	5.742	17
		Total	71.33	6.854	33
	Female	STEM_SDGs	77.18	6.426	22
		Conventional	66.15	5.234	20
		Total	71.93	8.059	42
	Total	STEM_SDGs	76.08	6.540	38
		Conventional	67.14	5.503	37
		Total	71.67	7.509	75

Based on Table 3, it can be seen that the critical thinking skills of students in the experimental group using SDGs based STEM in learning were male ($M=65.81$; $SD=8.878$) and female ($M=82.14$; $SD=7.599$), while in the conventional class, they were male ($M=50.59$; $SD=8.522$) and female ($M=73.95$; $SD=8.113$). The results show that there is a difference in critical thinking skills between male and female students, where descriptively, both in the experimental and conventional groups, female students had higher critical thinking skills than male students. Furthermore, it can be seen that the environmental concern results in the experimental group, for male students ($M=74.56$; $SD=6.593$) and female students ($M=77.18$; $SD=6.426$), while in the conventional class, male students ($M=68.29$; $SD=5.742$) and female students ($M=66.15$;

$SD=5.234$). The results can be descriptively analyzed that the average values in the experimental group are higher than in the control group. Additionally, when comparing the two groups of male and female students, it can be observed that the female student group has much higher environmental concern attitudes than the male student group. This aligns with several studies that state that STEM-based learning is more effective than conventional teaching [47], [48], [49].

After conducting descriptive analysis, inferential analysis was performed to determine whether the teaching method affects students' critical thinking skills and environmental concerns, as well as to assess the significance of the differences between the two. These differences are listed in Table 4.

Table 4. ANOVA analysis based on treatment group

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Gender	Critical thinking	7047.236	1	7047.236	104.596	.000
	Environmental Concern	1.042	1	1.042	.029	.866
Method	Critical thinking	2659.449	1	2659.449	39.472	.000
	Environmental Concern	1380.661	1	1380.661	38.183	.000
Error	Critical thinking	4783.696	71	67.376		
	Environmental Concern	2567.290	71	36.159		

a. R Squared = ,679 (Adjusted R Squared = ,665)

b. R Squared = ,385 (Adjusted R Squared = ,359)

Based on the ANOVA results, $F(1,71) = 104.596$, $p < .005$. This means that there was a significant difference in students' critical thinking skills based on gender. As shown in table 3, female students ($M = 77.95$; $SD = 8.933$) had much higher critical thinking skills than male students ($M = 57.97$; $SD = 11.499$). This is in line with studies by [50], [51], and [52], which state that female students have significantly higher critical thinking skills than male students. In terms of sex, males and females have different psychosocial aspects. There is a tendency to assume that male and female students have different abilities [53].

Environmental awareness is an important factor that needs to be considered. By adopting an environmental care attitude, one can contribute positively to maintaining sustainability and a healthy life on Earth (Ummi et al., 2023). Based on the results of the MANOVA test, $F(1,71) = 0.029$; $p > .005$, indicating that there was no significant difference in environmental care attitudes between male and female students. As shown in Table 3, female students ($M = 77.18$; $SD =$

6.593) had a high environmental care attitude, followed by male students ($M = 74.56$; $SD = 6.593$). From these results, it can be concluded that female students have a higher environmental care attitude than male students, although descriptively, the difference is not significant. This research is supported by other studies that state that female students have a better environmental care attitude than male students [55], [56].

The results of the MANOVA showed that $F(1,71) = 39.472$, $p < .005$. This result indicates that there was a significant difference in students' critical thinking skills based on the learning method used. The average critical thinking skill score for the group of students using the STEM-based SDGs learning method, as shown in Table 3 ($M = 75.26$; $SD = 11.437$), was higher than that of the group of students learning through conventional methods ($M = 62.89$; $SD = 14.116$). Therefore, it can be concluded that students who learn alternative energy materials using the STEM-based SDGs approach have better critical thinking skills compared to those who learn through conventional methods. This is clarified in the following sections.

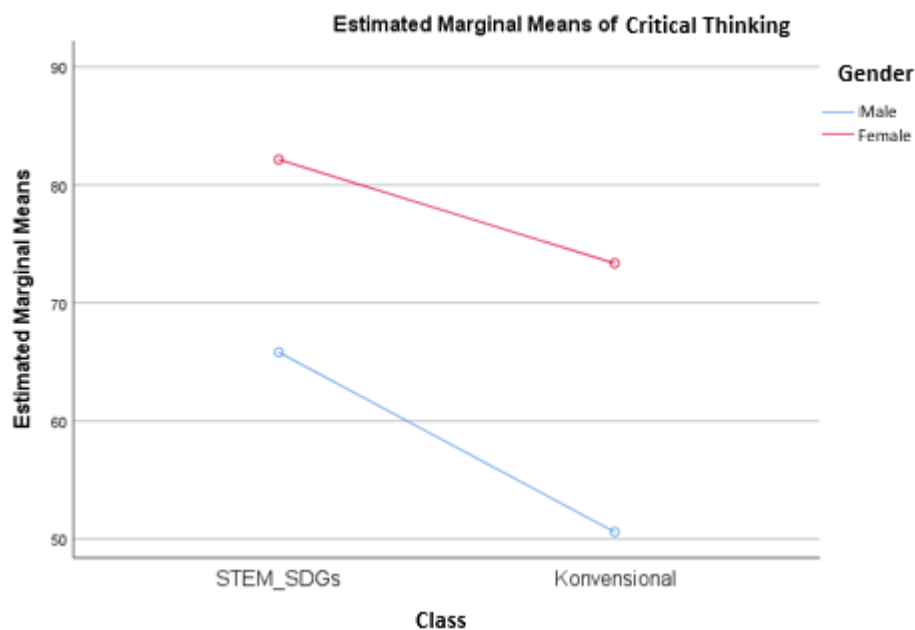


Figure 5. Interaction effect between gender and type of method on critical thinking

The interaction is evident in this graph because the pattern of the decrease in critical thinking scores from STEM SDGs to Conventional learning differs between males and females. These lines are not parallel, indicating that the effect of the learning method on critical thinking depends on gender. This shows the presence of an interaction between gender and learning method in critical thinking.

The results of the MANOVA showed that $F(1,71) = 38.183$, $p < .005$. This result indicates that there is a

significant difference in students' attitudes toward environmental concerns based on the learning method used. The average environmental concern scores of students who applied STEM-based SDGs learning, as shown in Table 3 ($M = 76.08$; $SD = 6.540$), were significantly higher than those of students who learned through conventional methods ($M = 67.14$; $SD = 5.503$). Therefore, it can be concluded that students' environmental concern attitudes who studied alternative energy using STEM-based SDGs learning were better

than those who learned through conventional methods. This is further clarified by the graph in Figure 3.

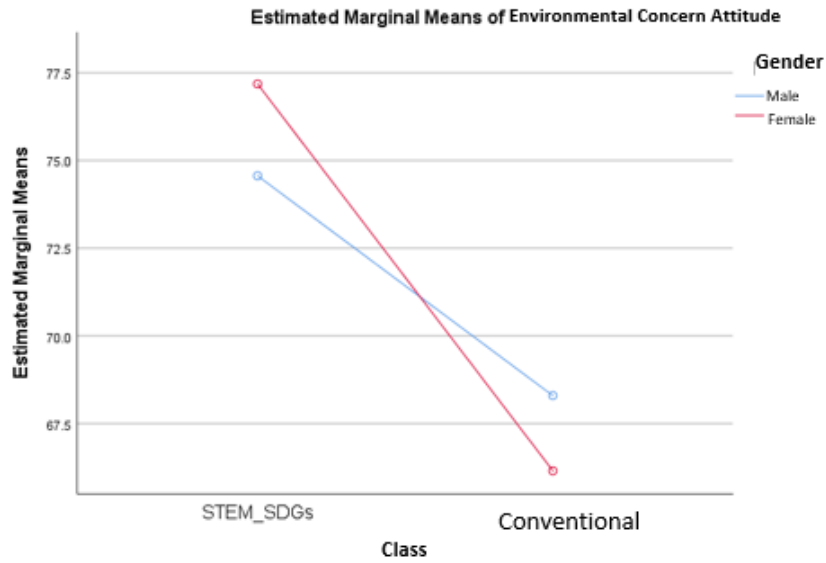


Figure 6. Interaction effect between gender and class type on environmental awareness

The figure shows the estimated marginal means of environmental concern based on gender (male and female) and class type (STEM SDGs and Conventional). In the STEM SDGs class, females had higher environmental concerns than males. However, in the Conventional class, both males and females showed a decline in environmental concern, with a sharper decrease observed in females. Eventually, in the Conventional class, females had lower environmental

concern scores than males, although the difference was not statistically significant. This differing pattern of decline indicates an interaction between gender and class type on environmental concerns, as seen from the non-parallel lines in the graph.

The students' critical thinking abilities for each indicator in the experimental and control groups are shown in Figure 3.

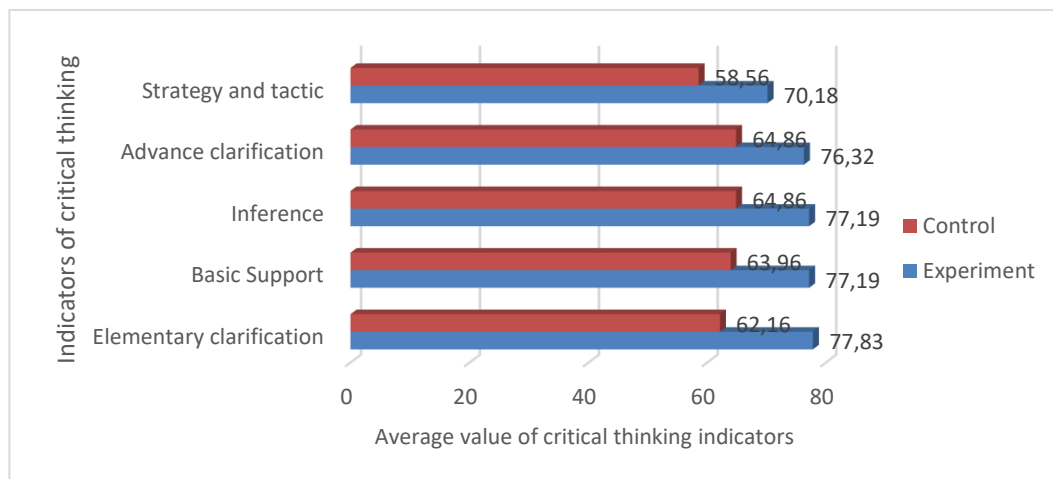


Figure 7. Average value of Critical Thinking Skills Indicator

The above graph shows a comparison of the average scores for critical thinking indicators between the control and experimental groups. The measured critical thinking indicators included elementary clarification, basic support, inference, advance clarification, strategy, and tactics. Overall, it is evident that the experimental group demonstrated higher

average scores across all indicators than the control group. This indicates that the intervention or treatment applied to the experimental group positively contributed to the improvement of students' critical thinking skills. The first indicator was elementary clarification, which showed a noticeable difference. The control group obtained an average score of 62.16 while the

experimental group achieved an average score of 77.83. This suggests that students in the experimental group were better able to understand and clarify basic information than those in the control group were. Next, for the basic support indicator, the control group had an average score of 63.96, while the experimental group scored the same as the previous indicator, 77.19. This indicates that the students in the experimental group were more proficient in providing basic support for arguments, such as using relevant facts or simple reasoning. There was also a significant difference in the Inference indicator. The experimental group achieved an average score of 77.19 much higher than the control group's 64.86. This shows that students in the experimental group were better at drawing conclusions based on the available evidence or information. For the advance clarification indicator, the experimental group scored an average of 76.32 higher than the control group's score of 64.86. This indicates that the students in the experimental group were more capable of further clarifying complex ideas or exploring arguments in greater depth. The final indicators were strategy and tactic, showing that the control group had an average

score of 58.56, while the experimental group reached 70.18. This demonstrates that the students in the experimental group were more skilled at designing effective strategies or problem-solving approaches.

Based on the overall data presented, it is clear that all the critical thinking indicators showed a significant increase in the experimental group. This indicates that the learning approach or method implemented in the experimental group was effective in enhancing the students' critical thinking skills. The differences in average scores between the groups serve as a basis to conclude that the innovative SDGs based STEM learning approach has a positive impact on the development of students' higher-order thinking skills. These findings highlight the importance of utilizing instructional strategies that promote exploration, problem solving, and reflection in teaching and learning processes. In addition to measuring students' critical thinking skills, this study also assessed their environmental awareness after implementing SDGs based STEM learning. The following is a breakdown of the results regarding students' environmental awareness.

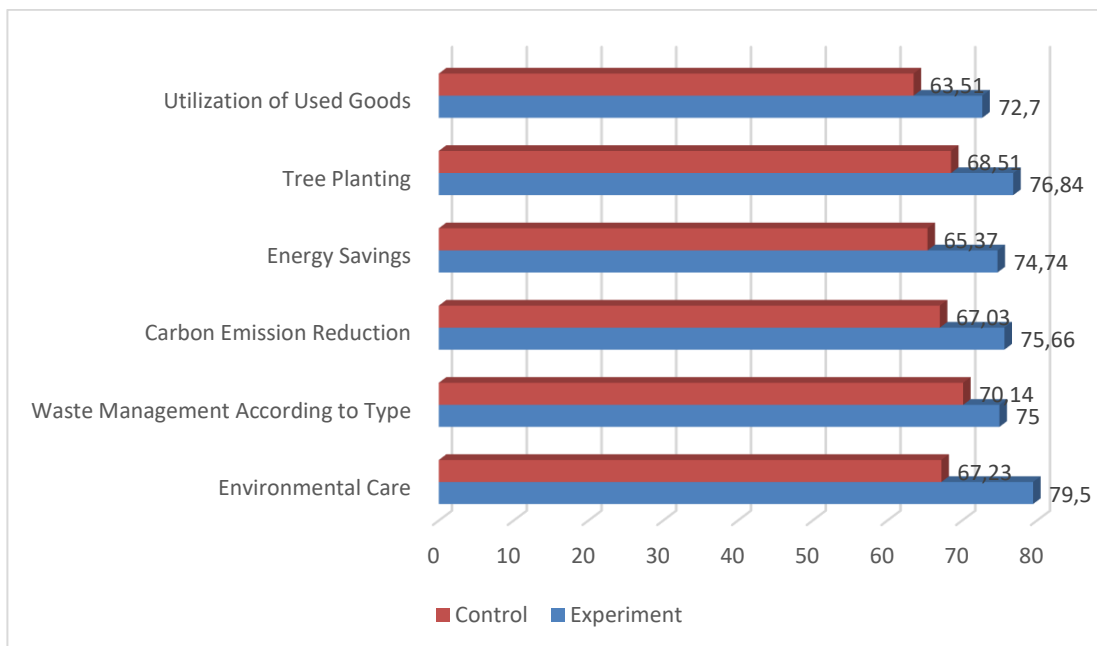


Figure 8. Average scores of environmental awareness indicators

The graph displays a comparison of the average scores for the six environmental awareness behavior indicators between the control and experimental groups. These indicators include the utilization of used goods, tree planting, energy savings, carbon emission reduction, waste management according to type, and environmental care. The average scores for all indicators were higher in the experimental group than in the control group. This suggests that the treatment or intervention provided to the experimental group had a positive effect on increasing students' environmental awareness and

pro-environmental behavior. The first indicator shows that the experimental group achieved an average score of 72.7, higher than the control group's score of 63.51. This indicates that students in the experimental group were more accustomed to and skilled in reusing used items such as recycling or repurposing goods for other useful purposes. The tree-planting indicator shows a notable difference with the control group averaging 68.51, and the experimental group reaching 76.84. Next, the Energy Savings indicator recorded an average score of 65.37 in the control group and 74.74 in the

experimental group. This difference suggests that students in the experimental group had greater awareness of the importance of conserving energy, such as turning off electronics when not in use or when using energy efficiently. For the carbon emission reduction indicator, the experimental group obtained an average score of 75.66, compared to the control group's 67.03. This suggests that students in the experimental group were more aware of and engaged in actions to reduce carbon emissions, such as using eco-friendly transportation and minimizing the use of fossil fuels. Waste management according to type indicator showed relatively high results in both groups, with 70.14 in the control group and 75 in the experimental group. This indicates that while waste management awareness was generally good among students, those in the experimental group showed better skills in sorting and managing waste based on its type (organic or inorganic). The final indicator was environmental care, which had the highest average score among all indicators in the experimental group at 79.5, compared to 67.23 in the control group. This suggests that students in the experimental group demonstrated more comprehensive concern for environmental issues and were more actively engaged in preserving nature. Overall, the graph indicates that the intervention or learning approach implemented in the experimental group effectively enhanced the students' understanding, awareness, and environmental actions. These findings highlight the importance of integrating environmental education into the learning process to foster sustainable and environmentally conscious character in students.

4. Discussion

The results of this study show that the implementation of SDGs based STEM (Science, Technology, Engineering, and Mathematics) learning has a significant impact on improving students' critical thinking skills and environmental awareness. This is evident from the higher average scores across all indicators in both critical thinking and environmental awareness for the experimental group than for the control group. These findings indicate that integrating the STEM approach with SDG values can create more meaningful and contextual learning experiences that positively affect both students' cognitive and affective domains.

Critical thinking is a 21st century skill that plays a vital role in everyday life [57], [58]. In this study, critical thinking indicators such as elementary clarification, basic support, inference, advance clarification, and strategy and tactic showed higher results in the experimental class. This indicates that the SDGs based STEM approach encourages students to be more active in exploring information, analyzing problems, making decisions, and developing solutions based on logical

reasoning and data-driven arguments. The study also revealed that female students tended to demonstrate better critical thinking skills than male students. This finding is consistent with previous research stating that female students generally exhibit stronger critical thinking abilities than their male counterparts [59]. These differences in critical thinking skills are not solely due to biological factors, but are also largely influenced by social, emotional, and learning style differences between genders. One key factor is the learning style and attentiveness in analyzing information. Female students typically tend to be more meticulous in understanding concepts or solving problems [60], [61]. This makes them practice more in the critical thinking process, such as clarifying information, evaluating arguments, and making logical decisions. In addition, stronger verbal communication and expression skills, which are generally more pronounced in female students [62], play a role in developing critical thinking. Female students are often more active in discussions, expressing opinions, and listening to others' perspectives, which are essential to the critical thinking process. Moreover, female students frequently exhibit higher motivation to learn and a greater sense of responsibility for academic tasks. With this motivation, they tend to be more consistent in participating in learning, and more diligent when facing problems that require deep analysis. However, it is important to note that these differences are general trends and not absolute. A supportive learning environment, appropriate teaching approaches, and equal opportunities can help both male and female students develop critical thinking skills to the fullest extent. The following are the results of the analysis of each critical thinking indicator:

a. Elementary clarification

In the indicator of elementary clarification, the experimental class achieved a higher average score than the control class. This means that, with the implementation of STEM-based SDGs learning, students in the experimental class were able to provide simple and accurate explanations based on the statements given in the questions.

b. Inference

The Inference indicator in the experimental group falls into the critical category, whereas in the control group, it is categorized as moderately critical. The experimental group achieved a higher average score than did the control group. Through the implementation of SDGs based STEM learning, students in the experimental group were able to draw appropriate conclusions based on the information provided in the statements within the questions, or they were able to determine the accuracy of those conclusions. This is because SDG-based STEM learning allows students to

gather information through real-world actions, enabling them to better understand statements through personal experience. This aligns with [63], who states that students can correctly draw conclusions based on the information given. In contrast, students in the control group mostly struggled to evaluate the accuracy of the conclusions based on the information provided.

c. Basic support

The average basic support score of the students in the experimental class was significantly higher than that of students in the control class. This confirms that an STEM-based learning approach integrated with Sustainable Development Goals (SDGs) can improve students' basic abilities more effectively than conventional methods. Previous studies also support this finding [64], which found that the integration of technology and problem-based projects in learning can significantly enhance students' basic skills and critical thinking skills. This research strengthens the argument that using innovative learning methods, such as STEM, is more effective in developing students' critical thinking skills than traditional approaches.

d. Advance clarification

The advance clarification indicator in critical thinking refers to an individual's ability to provide deeper elaboration or more detailed explanations of a topic, concept, or argument. The experimental class, which used an STEM-based learning approach integrated with the SDGs, showed a significant improvement in critical thinking skills compared to the control class, which used conventional teaching methods. This can be observed from the difference in the average critical thinking scores, where the experimental class outperformed the control class. Research by [65] also supports this finding, stating that project-based learning integrated with the SDGs provides students with opportunities to further explore and elaborate on information, ultimately enhancing their critical thinking skills.

e. Strategy and tactics

This indicator refers to an individual's ability to design, implement, and evaluate effective methods or approaches to solving problems or achieving specific goals. Based on the research findings, students in the experimental class that applied SDGs based STEM learning demonstrated higher critical thinking skills in the strategy and tactic indicators compared to students in the control class who used conventional learning methods. This suggests that an integrative and contextual learning approach can enhance students' critical thinking skills, particularly strategies and tactics. Research by [66] also shows that an STEM-based approach not only improves conceptual understanding

but also encourages students to develop more effective problem-solving strategies.

Critical thinking skills play an important role in shaping environmental awareness, as individuals who think logically and analytically tend to be more reflective of the impact of their actions on the environment. Environmental awareness reflects an individual's consciousness of protecting and preserving the environment. This attitude is not only formed through a conceptual understanding of environmental issues but also through direct involvement in learning activities that require active participation and critical reflection on environmental problems. In this context, the implementation of SDGs based STEM learning provides opportunities for students to explore environmental issues in an interdisciplinary manner and design solutions through scientific and technological approaches.

One of the key aspects of STEM learning is to provide students with opportunities to identify and solve real-world problems through a project-based approach. In this context, projects are aligned with the Sustainable Development Goals (SDGs). Through these activities, students not only learn science and technology concepts but also develop critical awareness of their surrounding environment. As shown in the research findings graph, all environmental awareness indicators in the experimental class showed significant improvement compared to those in the control class. Indicators such as the utilization of used goods, energy savings, tree planting, carbon emission reduction, waste management, and overall environmental care all recorded higher scores in the experimental group. This indicates that students who learn through the STEM SDGs approach not only understand the importance of environmental preservation, but are also more motivated to take real action.

The integration of SDGs into science education adds the dimension of values and ethics to the learning process. Students are not only encouraged to understand scientific concepts, but also to reflect on their impact on society and the environment. Incorporating SDGs into STEM learning is a strategic step toward creating a generation that is environmentally conscious and prepared to face future challenges. This study also found that female students demonstrated a higher level of environmental awareness than did male students. This finding aligns with previous research suggesting that females tend to exhibit greater environmental concern than males [67]. The following presents the results of the analysis of students' environmental awareness based on each indicator.

a. Environmental care

Thus, environmental care is an important indicator of environmental awareness. In this study, the results for environmental care between the experimental class, which used the STEM SDGs approach, and the control class, which used the conventional method, showed a significant difference. The experimental class scored 79.50, which was higher than that of the control class, which scored only 67.23. This indicates that the implementation of the STEM SDGs method was more effective in increasing students' environmental awareness. The STEM SDGs method, which integrates concepts from science, technology, engineering, and mathematics with the goals of sustainable development, provides a more contextual and applicable approach. This motivates students to become more concerned about environmental issues. By contrast, conventional methods tend to be more theoretical and less likely to encourage students' direct involvement in environmental care activities. Therefore, the use of the STEM-SDG method can enhance students' understanding and promote real actions to preserve the environment.

b. Waste management according to type

The research results showed that the environmental care indicator related to waste management by type was higher in the experimental class (75.00) than in the control class (70.14). This difference indicates that the intervention applied in the experimental class had a positive impact on increasing students' awareness of waste sorting. This improvement may be attributed to the more interactive and hands-on learning method used, which helped the students better understand the importance of waste separation. Although the difference was not very large, these findings demonstrate that the instructional strategy used in the experimental class was more effective in fostering students' awareness of proper waste management.

c. Carbon emission reduction

The results show that the environmental care indicator related to carbon emission reduction was higher in the experimental class (75.66) than in the control class (67.03). This difference indicates that the intervention applied in the experimental class was effective in raising students' awareness of carbon emissions reduction. Factors such as project-based learning methods and the STEM approach likely contributed to the improvement in students' understanding and behavior regarding eco-friendly concepts. Additionally, active participation in emission mitigation activities, such as reducing fossil fuel usage and improving energy efficiency, played a role in the better results observed in the experimental class compared with the control class.

d. Energy savings

The research results showed a significant difference in the environmental care indicators related to energy savings between the experimental and control classes. The experimental class achieved an average score of 74.74 while the control class only reached 65.37. This indicates that the intervention applied in the experimental class was more effective in raising awareness and promoting energy-saving practices than the teaching methods used in the control class. This difference may be attributed to the more interactive approach, such as discussions, simulations, or action-based projects, implemented in the experimental class. Therefore, innovative teaching strategies play a key role in instilling energy-saving habits in students.

e. Tree planting

The research results showed a significant difference in the environmental care indicators related to tree planting between the experimental and control classes. The experimental class achieved an average score of 76.84 while the control class only reached 65.51. This difference indicated that the intervention applied in the experimental class was more effective in raising awareness and encouraging student participation in tree-planting activities. This can be attributed to the more interactive and experience-based teaching methods used in the experimental class, which helped the students better understand the importance of reforestation. Meanwhile, the control class, which used conventional methods, was less effective in fostering environmental awareness among the students.

f. Utilization of used goods

The indicator for the utilization of used goods showed a significant difference between the experimental and control groups. The experimental group, which applied the STEM SDGs method, scored 72.70 higher than the control group, which scored 63.51. This indicates that the STEM SDGs method is more effective in encouraging students to reuse used goods creatively. The integrative approach, which combines the concepts of science, technology, and sustainability, provides a deeper understanding of the importance of recycling and waste reduction. Using this method, students are more motivated to apply the concept of reusing goods in their daily lives.

5. Conclusion

Based on the research results, there was a difference in critical thinking skills and environmental care attitudes, with female students exhibiting higher levels than male students. Additionally, the use of learning methods influences students' critical thinking skills and environmental care attitudes, and STEM SDG-based learning is more effective than conventional learning.

Compared to previous research, STEM is generally integrated into other learning models used to enhance 21st century skills. Therefore, this study provides novel insights by integrating STEM with SDGs to improve students' critical thinking skills and environmental care attitudes, which are crucial for facing future challenges. This study makes a significant contribution to the STEM education field, where STEM is integrated with SDGs, and has a positive impact on improving critical thinking skills and environmental care attitudes at the junior high school level. This study innovates by integrating the STEM approach and SDGs principles in science learning, specifically in the topic of alternative energy. This study not only assesses cognitive aspects through critical thinking skills, but also evaluates affective aspects, such as environmental care attitudes, which are rarely studied together. With a quasi-experimental design involving valid and reliable instruments and MANOVA statistical analysis, the results provide strong empirical evidence that SDGs based STEM learning can shape students who are critical thinkers and environmentally friendly, in line with the demands of 21st century education and sustainable development. The limitation of this study is that it only involved a sample from one school; therefore, the results may not be generalizable to a wider population. Future research should involve more schools with diverse backgrounds to make these findings more generalizable. The implementation of STEM-based SDGs learning should be more widely integrated across various education levels to foster students' critical thinking skills and environmental care attitudes. Future research could expand the participant scope from different regions and explore other aspects, such as collaboration, creativity, and the influence of digital learning media on the success of this approach.

Declarations

Author Contributions

Conceptualization, Y.Y. S.P and S.W.; methodology, Z.Z and Y.Y; software, Y.Y, S.P, I.L.; validation, Z.Z and Y.Y; formal analysis, Y.Y and I.L.; investigation, Y.Y and S.P.; resources, Y. Y.; data curation, Y.Y and Z.Z.; writing—original draft preparation, Y.Y and I.L.; writing—review and editing, Y.Y.; visualization, Y. Y. and Z. Z.; supervision, Y.Y.; project administration, Y.Y. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies, have been completely observed by the authors.

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