RESEARCH ARTICLE

Waste to energy: A STEM-ESD approach to improve student awareness and action in converting waste into eco-friendly energy

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Abstract: Waste management is a significant issue in Indonesia, and awareness and actions across all sectors, including school students, play a critical role. This study investigates the impact of educational interventions on students' awareness and actions regarding waste management and its potential as a source of environmentally friendly energy. The research used a quasi-experimental design, specifically a non-equivalent control group, involving a sample of 44 tenth-grade students in Bandung who were studying environmental change. Participants were selected through purposive sampling, and data were gathered via a questionnaire. Results indicate that the intervention significantly improved students' awareness of utilizing waste as an eco-friendly energy source ($p = 0.009 < \alpha = 0.05$), although it did not significantly influence their actions to apply this knowledge ($p = 0.201 > \alpha = 0.05$). This study provides an initial perspective on the potential of STEM-ESD project-based learning to enhance students' awareness and practical engagement in sustainable waste management practices.

Keywords: environmental awareness; sustainable energy; STEM-ESD education; student awareness

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Introduction

Waste management and utilization remain significant issues in Indonesia, largely due to low levels of awareness and engagement among the population (Aliman et al., 2019; Hidayah et al., 2021; Purnami, 2021). This lack of awareness contributes to high rates of environmental pollution across the country (Li et al., 2023; Olufemi et al., 2016; Wu et al., 2024). A critical component of this problem is the insufficient knowledge and concern for effective waste management. Students, as an important segment of society, also show a low level of awareness and concern regarding waste management, which is reflected in high pollution rates in both their schools and surrounding environments (Ali et al., 2017; Debrah et al., 2021; Purnami, 2021). Improving students' awareness and practices around waste management and utilization is essential for fostering environmental responsibility across generations (Debrah et al., 2021; Hidayah et al., 2021; Ilham et al., 2023; Labog, 2017). Teaching waste management in schools is a crucial step to enhance students' understanding of environmental issues and encourage active involvement. Environmental education aims not only to raise awareness but also to stimulate sustainable action among students (Arabaci & Okyay, 2023; Burke, 2017; Ilham et al., 2023; Kang & Hong, 2021; Moody-Marshall, 2023). Promoting sustainable behaviors in students can have long-term impacts, contributing to solutions for both local and global environmental issues.

Globally, energy challenges are increasingly urgent, and the use of fossil-based energy is recognized as a significant contributor to environmental degradation (Ho et al., 2021). Addressing this issue requires a shift towards sustainable practices and energy sources. Environmental sustainability and responsible energy use are essential for a healthy future, yet public awareness in Indonesia around the environmental impacts of fossil fuel consumption remains limited. Strengthening this awareness, particularly among students, can help drive a shift toward eco-friendly practices, including waste-to-energy initiatives that align with global sustainability goals.

As primary agents of environmental governance, humans are expected to act responsibly to minimize

their environmental impact. One promising approach to sustainable energy is the use of biomass and biogas from waste as eco-friendly energy sources. Harnessing energy from these renewable resources aligns with the United Nations Sustainable Development Goal (SDG) 7, which focuses on providing affordable and clean energy for all. SDG 7 highlights the need for accessible, modern energy to meet the growing demand, which continues to drive greater exploitation of natural resources.

In Indonesia, efforts to convert waste into energy have gained traction, particularly in response to the large quantities of waste generated in major cities. As a developing nation with one of the world's largest populations, Indonesia faces significant waste management challenges, ranking fourth globally in population and experiencing corresponding waste problems (Minghua et al., 2009). Waste materials, particularly from households, are often undervalued and can pose serious health and environmental risks (Dobiki, 2018). Addressing these issues requires a strong societal commitment to waste management and recycling practices. This includes educating communities, including school students, about waste types, management techniques, and the environmental consequences of waste mismanagement. Introducing waste awareness and recycling from an early age can foster a culture of responsible waste management. In particular, schools can instill awareness and action around organic waste management, addressing behaviors like littering and a lack of consideration for nature's carrying capacity (Debrah et al., 2021; Lanza et al., 2023; Olufemi et al., 2016; Pozo-Muñoz et al., 2023; Purnami, 2021). Household waste remains the most prevalent environmental problem in Indonesia, underscoring the need for increased public knowledge and awareness to maintain environmental stability.

Household waste is one of Indonesia's most persistent environmental challenges, largely due to low levels of awareness and concern among the public regarding waste management. This issue is also evident among students, who, although familiar with the types and examples of waste, show limited awareness of how waste can be utilized, particularly within their households (Purnami, 2021). This lack of awareness and action contributes significantly to pollution and other environmental issues. Additionally, research indicates that knowledge about converting waste into eco-friendly energy, such as biogas and biomass, remains limited among Indonesians (Fitriati et al., 2021; Ilham et al., 2023).

Knowledge is a critical precursor to action, as individuals are more likely to engage in sustainable practices when they understand the concepts and benefits behind them (Debrah et al., 2021; Michael et al., 2024; Michel & Zwickle, 2021; Wanchana et al., 2020). Therefore, all segments of society need to address the connections between waste and energy challenges in Indonesia. For students, early exposure to environmental issues can serve as a valuable stimulus for positive behavioral change. In this regard, the Merdeka Curriculum's emphasis on Environmental Pollution within Biology offers an effective platform to connect classroom learning with students' everyday lives. Engaging students in real-world environmental issues encourages them to develop an environmentally responsible mindset. Prior research supports that learning experiences closely tied to students' lives can effectively provide new knowledge, foster positive habits, and increase environmental awareness (Angelaki et al., 2024; Oliver & Adkins, 2020; Sapanova et al., 2024).

To actively engage students in addressing environmental issues, STEM-integrated project-based learning offers an effective approach. STEM learning encourages students to address real-world problems through a problem-solving framework, fostering critical thinking and innovative solutions (Castilla, 2024; Kirkland & Poppleton, 2021; Mater et al., 2020; Young et al., 2021). In particular, a Waste-to-Energy project within a STEM context enables students to collaborate and apply interdisciplinary knowledge to transform waste into eco-friendly energy, directly involving them in practical, impactful solutions. Research shows that STEM-based learning not only enhances collaboration but also equips students with problem-solving skills critical for tackling complex issues (Kartini et al., 2021; Priemer et al., 2020; Young et al., 2021). By engaging students in hands-on, technology-driven projects, STEM-based learning cultivates new habits of systematic problem-solving and the application of technology, which is especially relevant given the current low levels of public awareness about waste management in Indonesia.

This study will focus on a Waste-to-Energy STEM project to improve students' awareness and actions in utilizing waste as a sustainable energy source, addressing both educational and environmental needs. Through this approach, students can develop a deeper understanding of environmental responsibility and the role of technology in fostering sustainable practices.

Method

This research employed a quasi-experimental design using a non-equivalent control group format to evaluate the effectiveness of STEM-integrated Waste-to-Energy project-based learning on students' awareness and actions related to environmental sustainability. The study involved a sample of 44 tenth-grade students from a high school in Bandung, Indonesia, studying environmental change as part of their curriculum. Participants were selected through purposive sampling to ensure the inclusion of students with similar educational backgrounds and exposure to environmental topics, minimizing variability in prior knowledge. The sample was divided into two groups: an experimental group that received the Waste-to-

Energy STEM-integrated intervention and a control group that followed the standard curriculum without the specific project-based learning intervention.The learning model used is the STEM learning model. The STEM learning steps used can be seen in Table 1.

Table 1. Stages of the STEM learning model

Stages of learning model	Structure in students	Structure in teacher
Formulation of problem	Identify problems that can be solved by technology development	Presents a problem whose solution is the creation of technology
Think	Thinking of forms of technology that can be developed	Directs the form of technology that can be developed
Design	Design the technology to be created and developed	Guiding the design process
Create	Creating and developing technology	Directing students to evaluate the advantages and disadvantages of the technology that has been made.
Test	Identify the advantages and disadvantages of developed technology	Have students evaluate the strengths and weaknesses of the technology created.
Re-design	Improving technology design	Guiding design improvements

The instrument used in this study is an awareness instrument developed by Sen et al. (2021). The awareness instrument contains four indicators used to measure: 1) students' conceptual awareness, 2) awareness based on students' experiences, 3) students' awareness to engage, and 4) students' awareness to adapt. Meanwhile, the action instrument is a development of Hadjichambis and Paraskeva-Hadjichambi (2020) instrument. The action instrument contains three indicators, namely: 1) past and present actions, 2) competency achievements, and 3) future actions. Both instruments were measured using a questionnaire with a 4-point Likert scale calculation with the following options: strongly agree (SS), agree (S), disagree (TS), and strongly disagree (STS). The highest score on the choice is strongly agree with 4 points and the lowest score is strongly disagree with 1 point.
For data analysis, hypothesis testing was conducted using a t-test to determine whether there was a statistically significant difference between the control and experimental groups. The t-test was used to compare pre-and post-intervention scores between the two groups, with a p-value threshold of 0.05 set to determine significance. This analysis allowed us to assess the effectiveness of the Waste-to-Energy STEM project in enhancing students' environmental awareness and promoting action toward sustainable waste management practices.

Results and Discussion

Student Awareness

The findings from the Waste-to-Energy project-based learning intervention indicate a significant increase in student awareness of waste utilization as an eco-friendly energy source. As shown in Table 2, a t-test analysis yielded a p-value of 0.009, which is less than the significance level of $\alpha = 0.05$. This result confirms a statistically significant difference in awareness after the intervention, demonstrating that the Waste-to-Energy project positively influenced students' understanding and interest in waste management and renewable energy applications.

Table 2. Mean score of pre-test and post-test of students' awareness

Group	Pre-test	Post-test	p-value
Experiment	69.46	73.90	0.009
Control	66.46	67.29	

This result aligns with previous research suggesting that hands-on, project-based learning fosters greater interest and awareness among students by involving them directly in real-world issues (Bergman, 2016; Ercan & Bilen, 2014; Khasanah et al., 2020; Lin et al., 2022). The project used in this study actively engaged students in problem-solving activities, where they tackled the challenges of waste management and explored renewable energy options. In the Waste-to-Energy project, students were involved in selecting, managing, and recycling waste to create an environmentally friendly energy source. This process encouraged a hands-on approach that allowed students to develop scientific attitudes and critical thinking skills, as reported in similar studies on problem-solving and experiential learning.

As part of the STEM-based learning process, students conducted field observations to assess the local environmental impact of waste. This observation phase aimed to stimulate an environmental consciousness by allowing students to experience firsthand the issues surrounding waste pollution. According to Zaizay et al. (2024), direct engagement in fieldwork promotes a scientific attitude, as students gain a deeper understanding through real-world observation. Through this hands-on approach, students began to recognize the environmental consequences of waste mismanagement and appreciated the need for sustainable practices. The project effectively enhanced students' environmental awareness, as evidenced by their responses and solutions during discussions with the teacher. Students acknowledged the need for proactive waste management and emphasized that waste should be recycled and managed to prevent pollution. This increased awareness highlights the project's success in making students more conscious of their role in environmental stewardship.

The results of this study underscore the value of STEM-integrated project-based learning in addressing environmental challenges and promoting sustainable behaviors among students. Environmental pollution due to waste mismanagement remains a pressing issue in Indonesia, largely because of low public awareness and limited understanding of waste utilization (Castilla, 2024; Yusuf & Fajri, 2022). Prior studies have found that many students lack awareness regarding waste recycling and its potential benefits (Ali et al., 2017; Debrah et al., 2021). By introducing students to sustainable practices through direct engagement, this study demonstrates that experiential, problem-oriented learning can cultivate both knowledge and proactive attitudes toward environmental care.

Student Conceptual Awareness

The results of this study indicate that the Waste-to-Energy project-based learning approach significantly enhanced students' conceptual awareness of environmental issues, particularly concerning waste management and sustainable energy solutions. After completing the project, students demonstrated an increased understanding of the causes and impacts of environmental pollution, as well as the importance of proactive responses to these issues (Sen et al., 2021). This increase in awareness is visually represented in Figure 1, which shows the average conceptual understanding scores for both the experimental and control groups, highlighting a noticeable improvement in the experimental group following the intervention. Statistical analysis further confirmed this, with a significant p-value of 0.015 ($\alpha = 0.025$), demonstrating that the Waste-to-Energy project had a measurable impact on students' conceptual awareness.

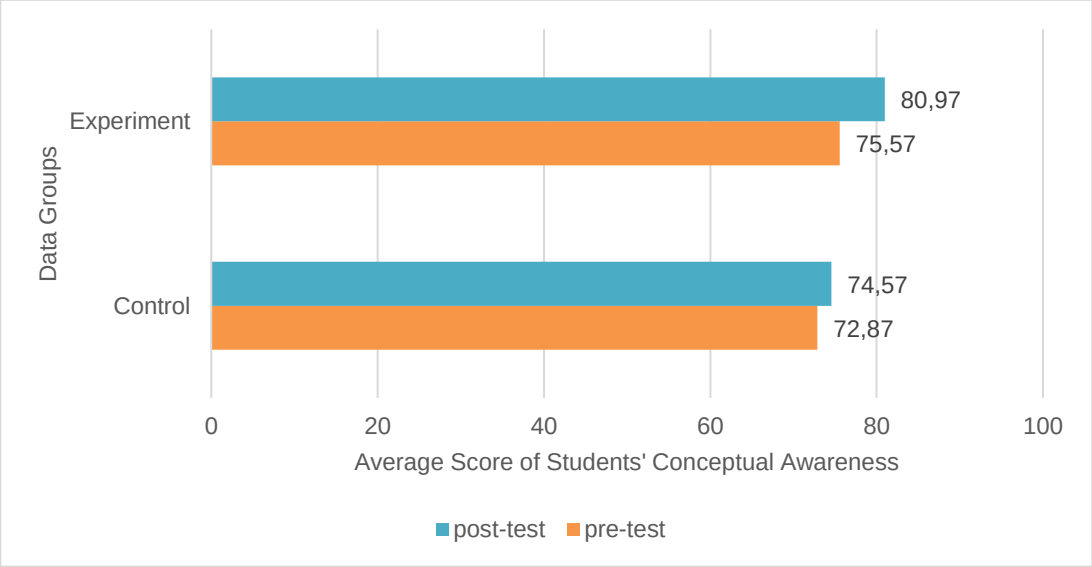

Figure 1. Average score of students' conceptual awareness

Key to this increase in conceptual awareness was the hands-on, STEM-based approach, which encouraged students to actively engage in identifying, analyzing, and solving real-world environmental problems through technological applications. The direct involvement in waste-to-energy projects acted as a powerful stimulus for students, allowing them to explore and address the practical aspects of waste management and renewable energy. Research supports that direct engagement in project-based learning fosters scientific attitudes and problem-solving skills, as students experience firsthand the process of applying knowledge to solve environmental challenges (Debrah et al., 2021; Gök & Boncukçu, 2023; Kalungwizi et al., 2020; Lewinsohn et al., 2014; Satriawan et al., 2024). Moreover, previous studies have shown that project-based activities can enhance students' understanding of core concepts, making learning experiences more relevant and impactful (Genc, 2015; Perrault & Albert, 2018; Satriawan et al.,

2024).Through the Waste-to-Energy project, students not only learned about waste as a resource but also developed an increased curiosity and a proactive attitude toward tackling environmental problems. This heightened curiosity often leads to a deeper interest in sustainable practices, as students seek to understand and mitigate the environmental issues they encounter (Astuti et al., 2019; Utami et al., 2020; Yli-Panula et al., 2022). Project-based learning thus becomes a meaningful educational experience, allowing students to engage with real-world problems and reinforcing their understanding of environmental concepts and their applications in daily life.

Experience-Based Awareness

In addition to conceptual awareness, this research also examined awareness indicators tied to students' personal experiences, as shown in Figure 2. This figure illustrates an increase in awareness across groups, though the statistical test of mean differences yielded a p-value of 0.041, which is greater than the significance level α = 0.025. This result suggests that, although there was an observable increase, the Waste-to-Energy project did not significantly impact students' experience-based awareness.

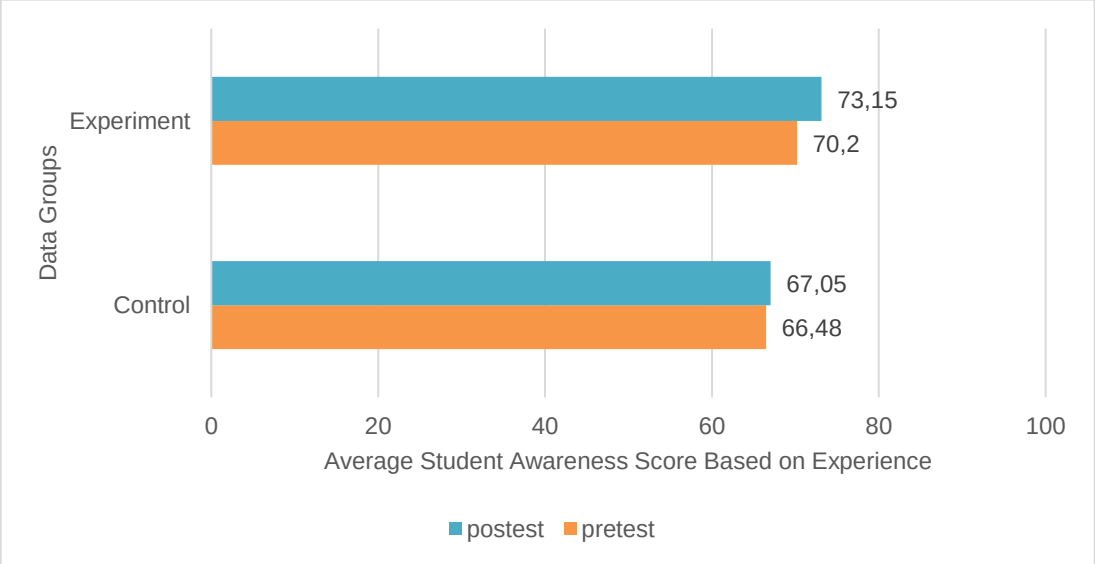

Figure 2. Average student awareness score based on experience

The findings indicate that a lack of prior experience with waste-to-energy concepts may contribute to these results. Interviews with students revealed that many were unfamiliar with using waste as an energy source, as they traditionally view waste as material for crafts or compost. This lack of familiarity with waste-to-energy processes highlights an important area for future emphasis, as students showed limited understanding of how waste could be transformed into renewable energy. Research has shown that without foundational knowledge, individuals are less likely to develop a strong awareness or motivation to engage in new, sustainable practices (Curdt-Christiansen, 2020; Goralnik & Nelson, 2017).
Experience-based awareness in this context refers to students' understanding of environmental pollution over time and its impacts on resource availability and sustainability (Sen et al., 2021). Since managing waste as an energy source is a relatively novel concept for these students, their experiential awareness remains low. Direct involvement is essential in creating meaningful learning experiences, as it allows students to engage firsthand with environmental issues, fostering awareness and scientific attitudes (Debrah et al., 2021; Goralnik & Nelson, 2017; Kosta et al., 2022). To effectively increase experience-based awareness, it is important for future learning activities to incorporate more practical, hands-on experiences that familiarize students with renewable energy processes. Providing students with direct involvement in the energy transformation process can help bridge this knowledge gap, enabling them to gain practical skills and insights that contribute to long-term environmental stewardship.

Students' Involvement

In addition to experience-based awareness, this study found a significant increase in students' awareness of involvement in addressing environmental issues. This aspect of awareness—students' desire to actively participate—includes the frequency of their contributions in discussions, attentiveness, and eagerness to engage directly in problem-solving efforts (Sen et al., 2021). As shown in Figure 3, the average score for students' willingness to get involved improved notably post-intervention, supported by a statistical test result of p-value (0.023) < α (0.025). This demonstrates that the Waste-to-Energy project

had a meaningful impact on students' engagement and motivation to participate. This is particularly relevant given that waste management remains a critical issue in Indonesia. Prior studies suggest that fostering students' involvement can enhance their capacity to manage waste, seek out information, and actively address environmental challenges (Altıntaş et al., 2024; Debrah et al., 2021; Sen et al., 2021; Utami et al., 2020). During project-based learning, students participated in discussions, generated ideas, and collaborated on projects to tackle waste issues by turning them into sustainable energy sources. This hands-on approach not only heightened their engagement but also encouraged the development of scientific attitudes essential for addressing environmental problems.

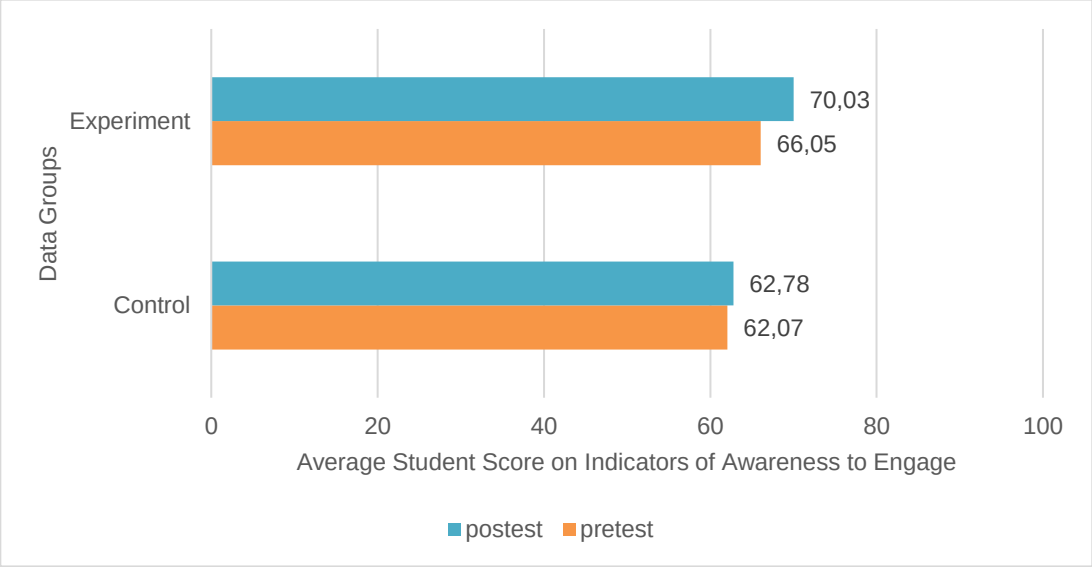

Figure 3. Average student score on indicators of awareness to engage

The project served as an effective stimulus for increasing student involvement by making the learning process interactive and directly relevant to real-world challenges. Focusing on student engagement in waste management efforts is a vital step toward cultivating an environmentally conscious generation. As they are directly involved in understanding and implementing waste-to-energy solutions, students are more likely to internalize these practices and maintain a commitment to sustainable behaviors (Dagadu et al., 2024; Mofid-Nakhaee et al., 2020). This emphasis on active involvement underscores the role of students as future human resources who can contribute to environmental sustainability. Encouraging them to take part in managing waste responsibly ensures that they develop the necessary skills and awareness to positively impact the environment. Utilizing waste as a resource can reduce environmental pollution, turning a potential problem into an opportunity for sustainable development.

Adaptive Awareness

Another key indicator explored in this study is students' awareness to adapt. This concept involves students' understanding of environmental pollution, adaptation techniques, and policy responses, as well as their ability to adjust behaviors accordingly (Sen et al., 2021). The data on students' adaptive awareness, shown in Figure 4, reflects positive changes following the intervention. Statistical analysis reveals a significant difference, with a p-value of 0.024, which is less than the α level of 0.025. This suggests that the Waste-to-Energy project positively impacted students' adaptability in terms of environmental response. Through the Waste-to-Energy project, students engaged in STEM-based learning that encouraged direct involvement and practical application, beginning with observation and discussion phases to foster problem-solving (Castilla, 2024; Kartini et al., 2021; Priemer et al., 2020) Such hands-on engagement allowed students to adapt to new learning environments and apply adaptive techniques in addressing real-world issues. Rather than limiting waste utilization to crafts or compost, students learned to explore its potential as a renewable energy source. This shift in focus aligns with prior studies showing that involving students in project-based activities fosters adaptive behaviors in waste management and environmental problem-solving.

This adaptive awareness is essential for developing resilience and proactive behavior toward environmental issues. Studies suggest that collaborative projects help students build adaptation skills, as direct involvement in such activities facilitates behavioral changes that support sustainable habits (Labog, 2017; Nolt & Leviton, 2022). Adaptation also influences students' willingness to form new, environmentally conscious habits, preparing them to contribute to waste management solutions on a broader scale. The findings align with research showing that when students are introduced to

environmental adaptation practices early on, they develop a sustained interest and a proactive attitude toward environmental care (Dewi et al., 2019). While students are generally open to adapting to new habits, significant shifts in awareness often require continuous exposure to experiential learning methods. This emphasizes the importance of project-based learning as a valuable tool in cultivating an adaptable mindset that extends beyond the classroom, fostering a generation that can respond thoughtfully and sustainably to environmental challenges.

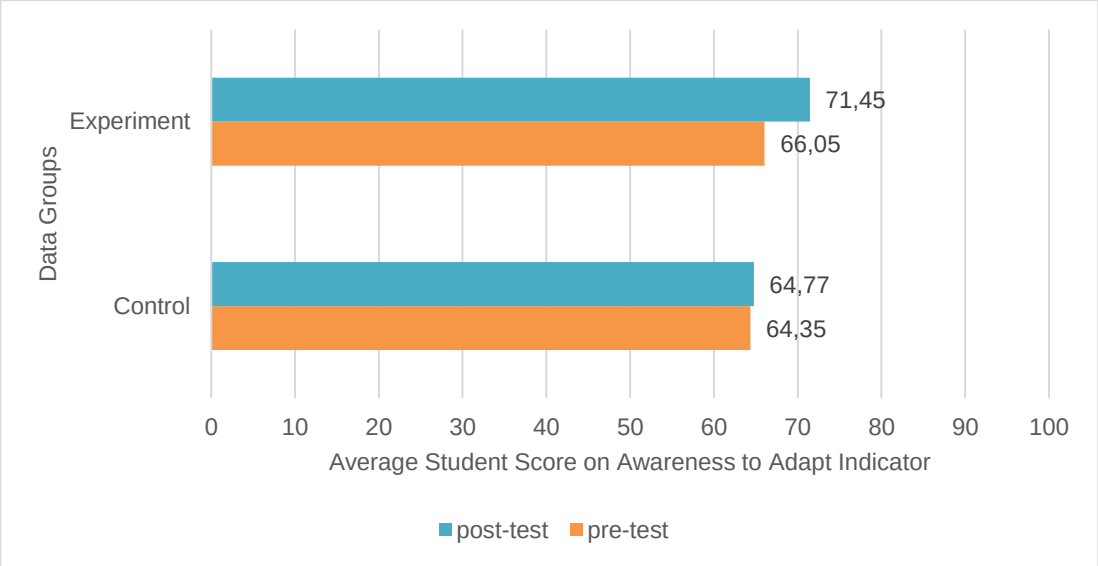

Figure 4. Average student score on awareness to adapt indicator

Student Action

The Waste-to-Energy project learning results regarding students' actions to utilize waste as an eco-friendly energy source are presented in Table 3. The T-test analysis revealed that the p-value (0.201) exceeded the significance level (α = 0.05), indicating no statistically significant effect of the intervention on students' actions to actively apply waste-to-energy concepts. This result suggests that while students participated in the learning activities, their actions regarding waste utilization as a sustainable energy source did not notably increase, as the data show little to no overall improvement in active application.

Table 3. The result of independent samples t - test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Posttest score	Equal variances assumed	.242	.626	1.300	42	.201	3.077	2.367	-1.700	7.853
	Equal variances not assumed			1.300	41.045	.201	3.077	2.367	-1.703	7.856

In the initial stages, students engaged in observation and were encouraged to identify and address environmental challenges. However, despite this stimulus, many students did not take initiative in applying these concepts independently and needed more structured guidance. Action-taking often involves sequential stages, including recognizing a problem, identifying solutions, and then implementing actions (Karim et al., 2022). Without sufficient knowledge and familiarity with waste-to-energy processes, students hesitated to go beyond theoretical understanding to hands-on application. During follow-up interviews, students commonly expressed a preference for familiar and straightforward waste management methods, such as composting. One student shared:

"*I tend to utilize vegetable waste for compost because it doesn't require complicated tools.*"

This response illustrates a limited understanding of how to convert waste into energy, showing that students defaulted to simpler solutions due to limited practical knowledge of biogas and waste-based energy production. These findings align with prior research, suggesting that students' actions are often contingent on their baseline knowledge and education level (Michael et al., 2024; Moody-Marshall, 2023; Srisathan et al., 2024). Furthermore, practical, action-oriented behaviors often require group dynamics

or peer influence to spur individual efforts. Common waste management actions that students are more likely to engage in—such as sorting waste and basic cleanup—are familiar practices that don't require specialized tools or knowledge. However, in this study, the more advanced application of waste-to-energy concepts, like biogas production, remained a challenge due to insufficient background knowledge and prior experience. To address these gaps, future initiatives could benefit from a more gradual and supported approach to introduce students to the technical and practical aspects of waste-to-energy conversion. Hands-on workshops or guided experiments focused specifically on biogas production or other renewable technologies could make these applications more approachable. Direct exposure to the entire waste-to-energy process may empower students with the confidence and skills to undertake these eco-friendly practices in real life, thereby translating environmental awareness into meaningful, sustainable actions.

Past and Present Actions

In addition to assessing general indicators of students' actions, the study specifically evaluated students' past and present engagement with waste-to-energy practices. This indicator, adapted from the framework of Hadjichambis and Paraskeva-Hadjichambi (2020), offered insights into whether students' habits and knowledge influenced their current waste management actions. As shown in Figure 5, students' average scores for past and present actions in waste utilization increased slightly post-intervention. However, T-test results revealed no statistically significant difference between pre-and post-intervention actions, with a p-value of 0.347 exceeding the significance level (α = 0.025). This suggests that the intervention did not substantially alter students' historical or habitual actions in utilizing waste for energy.

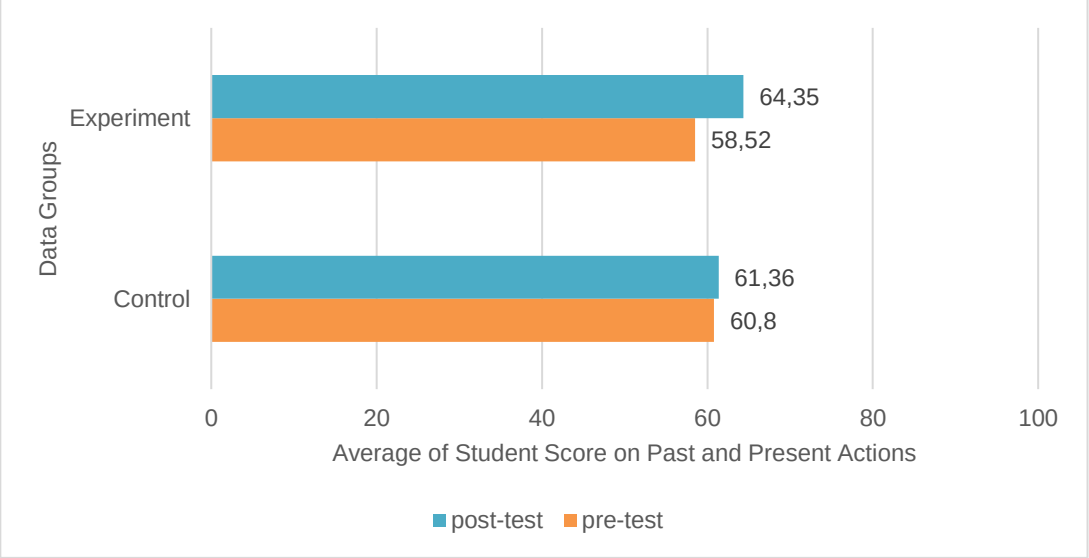

Figure 5. Average of score on past and present actions

Student interviews provided valuable context, indicating that most students were familiar with waste management for compost or crafts but had a limited understanding of waste-to-energy applications. This aligns with findings that waste-to-energy concepts are generally underexplored in Indonesian education, where students commonly associate waste reuse with traditional applications rather than renewable energy generation (Irsyad et al., 2018). This limited scope of awareness and experience may have contributed to the minimal change observed in their actual waste management actions.Previous studies support this observation, indicating that while students often engage in basic recycling activities like composting, they rarely encounter educational opportunities to develop waste-to-energy solutions (Castilla, 2024; Fitriati et al., 2021; Vicario et al., 2024). These findings highlight a gap in educational content and practical training that limits students' ability to innovate in waste utilization.

Addressing this gap may require not only introducing waste-to-energy concepts earlier but also providing hands-on learning opportunities that allow students to experiment with energy generation from waste. Such activities could encourage students to move beyond traditional waste uses, equipping them with skills to manage waste sustainably. By bridging this knowledge-action gap, educational institutions can support the development of eco-conscious practices that align with the broader environmental goals of sustainable waste management and energy generation.

Competency Achievement

Student competency achievement, defined as the practical skills required to implement and utilize waste as an environmentally friendly energy source, was assessed as an action indicator in this study. Adapted

from the framework of Hadjichambis and Paraskeva-Hadjichambi (2020), the results are summarized in Figure 6. Contrary to expectations, the average score for competency achievement decreased in the experimental group, and statistical analysis revealed no significant effect, with a p-value of 0.499 exceeding the threshold (α = 0.025). These findings suggest a gap in students' abilities to apply waste-to-energy concepts practically. Previous research supports this, highlighting that student often focus on waste management practices such as composting rather than innovative applications like energy production (Suharno & Tanjung, 2021). This limited focus may result from insufficient exposure to practical training or technical knowledge regarding biogas and other energy conversion processes. As noted in interviews conducted during the study, many students were unfamiliar with the tools, techniques, and processes required to generate energy from waste, further indicating a lack of foundational knowledge.

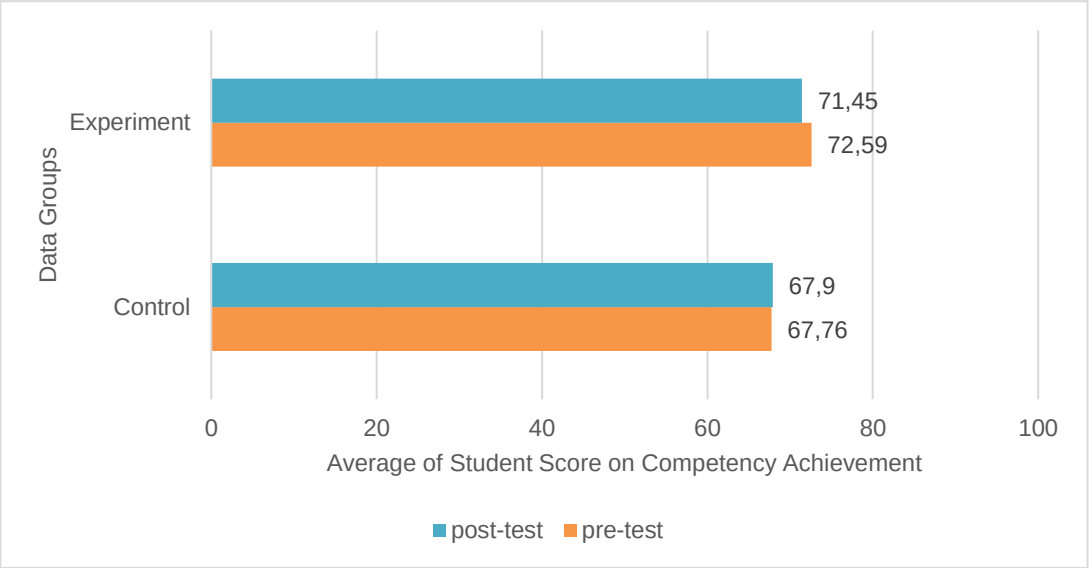

Figure 6. Average of student score on competency achievement

Enhancing student skills in waste-to-energy utilization requires creative, student-centered approaches that emphasize both theoretical understanding and hands-on practice. Research has shown that project-based learning, when effectively structured, can foster creativity, critical thinking, and problem-solving skills essential for addressing complex environmental challenges (Debrah et al., 2021; Kosta et al., 2022; Prayogo et al., 2024). However, to be effective in waste-to-energy contexts, students must first build a robust knowledge base regarding biogas production, energy conversion mechanisms, and the broader implications of renewable energy solutions. To address the decline in competency scores observed in this study, future interventions should include scaffolded learning experiences that combine step-by-step technical training with real-world applications. For instance, introducing small-scale experiments to demonstrate energy generation from waste could help bridge the gap between theory and practice. Additionally, collaborative projects that require students to design and test prototypes for energy conversion could provide the experiential learning opportunities necessary to build confidence and competence in this area.

Future Actions

Students' future actions, a critical indicator of their ability and willingness to utilize waste as an environmentally friendly energy source, were assessed based on the framework developed by Hadjichambis and Paraskeva-Hadjichambi (2020). These actions reflect students' potential to address environmental challenges proactively and act as agents of change. The results of this study, as shown in Figure 7, indicate a positive change and an increase in the average scores for future actions. However, statistical T-test testing revealed no significant effect, with a p-value of 0.205 exceeding the threshold (α = 0.025). This lack of statistical significance suggests that the intervention did not sufficiently impact students' intentions or readiness to undertake future actions related to waste-to-energy initiatives. One possible explanation for this outcome is the students' limited knowledge and familiarity with environmentally friendly energy sources. Prior studies have reported that students often have a low baseline understanding of renewable energy technologies, including biogas production. Without adequate foundational knowledge, students may struggle to envision or commit to future actions in this domain (Castilla, 2024; Debrah et al., 2021; Hidayah et al., 2021; Michael et al., 2024).

Another contributing factor may be the technical challenges encountered during the project. For instance, issues with digester functionality, such as leaks and inefficiencies in biogas production, likely

discouraged students from perceiving biogas as a viable energy source. This aligns with findings that practical setbacks can influence students' confidence and willingness to adopt sustainable practices (Runhaar et al., 2019). Despite their efforts, students may view the process as overly complex or impractical, reducing their interest in further exploring or applying these concepts.

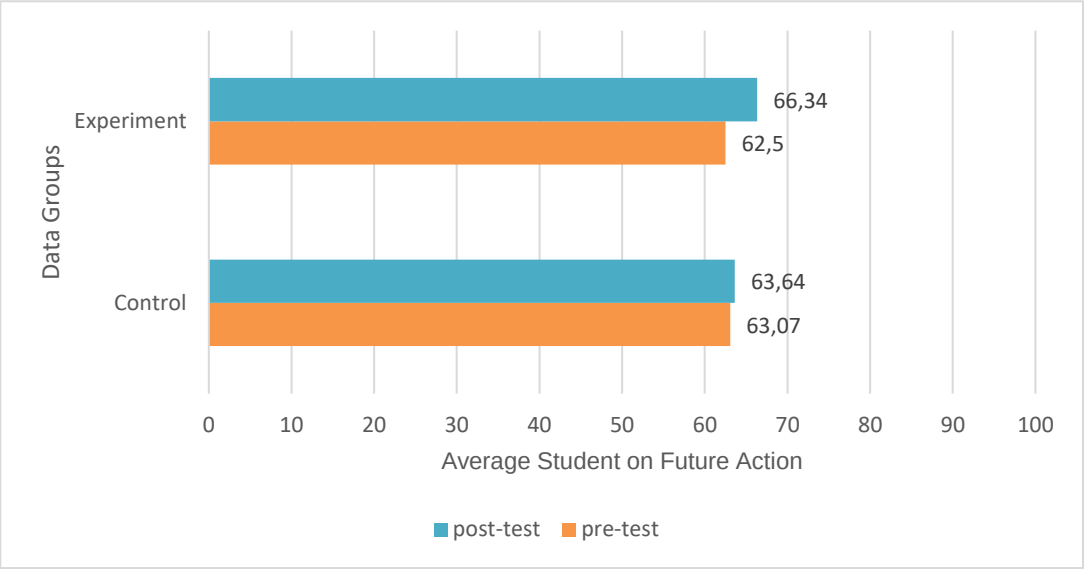

Figure 7. Average of student score on future action

To foster a stronger commitment to future actions, educators should integrate more robust scaffolding and support throughout the learning process. For instance, providing detailed demonstrations, troubleshooting guidance, and success stories of effective biogas utilization can help students grasp its feasibility and importance more clearly. Additionally, creating opportunities for students to engage with professionals in the field or visit operational waste-to-energy facilities could inspire greater enthusiasm and provide practical insights into the potential of these technologies. Future research and interventions should also explore ways to increase students' ownership of waste-to-energy projects. By enabling them to design and refine prototypes with fewer technical barriers, educators can enhance their problem-solving skills and boost their confidence. Empowering students with knowledge, skills, and motivation is essential for them to become change agents. This empowerment is crucial for cultivating sustainable practices and effectively addressing environmental challenges.

The findings of this research highlight various aspects of students' awareness and actions in utilizing waste as an environmentally friendly energy source through the waste-to-energy project-based learning approach. For students' awareness, significant improvements were observed in conceptual awareness (p-value 0.015 < α 0.025) and awareness to get involved (p-value 0.023 < α 0.025), emphasizing the positive influence of direct student participation in STEM-based project learning. These findings align with prior research showing that hands-on and problem-solving activities enhance students' understanding and engagement in addressing environmental issues. However, awareness based on students' experiences (p-value 0.041 > α 0.025) showed limited improvement, likely due to their lack of prior exposure to utilizing waste as an energy source. Similarly, while awareness to adapt improved significantly (p-value 0.024 < α 0.025), the novelty of the concept and limited familiarity with waste-to-energy processes posed challenges for students. In terms of students' actions, the results were mixed. While the waste-to-energy project prompted some behavioral changes, actions related to past and present activities (p-value 0.347 > α 0.025), competency achievement (p-value 0.499 > α 0.025), and future actions (p-value 0.205 > α 0.025) showed no significant effects. These findings suggest that while students demonstrated an initial interest, technical difficulties, such as digester leaks during biogas production, and a lack of knowledge about environmentally friendly energy sources limited their practical engagement and confidence. Prior research corroborates these challenges, linking action-taking to adequate knowledge, hands-on success, and effective support systems. Overall, these findings underscore the need for more structured guidance, improved technical support, and exposure to successful applications to maximize the impact of project-based learning in fostering students' awareness and actions toward environmental sustainability.

Conclusion

Learning through waste-to-energy projects demonstrates a positive impact on students' awareness of utilizing waste as an environmentally friendly energy source. Significant improvements were observed in indicators such as conceptual awareness, awareness to get involved, and awareness to adapt, highlighting the effectiveness of STEM-based project learning in fostering environmental awareness ($p = 0.009 < \alpha = 0.05$). However, the results indicate that while there was a noticeable increase in students' action scores, these changes were not statistically significant ($p = 0.201 > \alpha = 0.05$). It suggests that although the learning approach successfully enhanced students' understanding and willingness to engage, it fell short of translating this awareness into concrete, impactful actions. The challenges faced, such as students' limited knowledge about biogas production and technical difficulties during project execution, underscore the need for enhanced support, practical exposure, and structured guidance. Future implementations should focus on bridging these gaps by providing more comprehensive technical training, real-world examples of waste-to-energy applications, and opportunities for students to succeed in hands-on activities. It would ensure that the learning process not only fosters awareness but also empowers students to take meaningful actions in addressing environmental sustainability.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author Contributions

R. Solihat, B. Y. Haqiqi, and **A. Widodo:** methodology, **B. Y. Haqiqi and R. Solihat:** analysis; **B. Y. Haqiqi** and **R. Solihat:** writing original draft preparation, and **B. Y. Haqiqi, R. Solihat,** and **A. Widodo:** review and editing.

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