Students' critical thinking skills based on the STEAM approach: The issue of waste recycling and ecology

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Article History

Received: 8 June 2025

Revised: 1 August 2025

Accepted: 26 August 2025

Published: 1 September 2025

Keywords

Bioplastic

Critical Thinking Skills

Phenomenological approach

STEAM

Waste Recycling

Abstract

The critical thinking skills of elementary school students are still relatively low, even though these skills are essential for facing the demands of the 21st century and global challenges. The low level of critical thinking skills is a significant problem in the learning process, so an innovative approach is needed to address it. This study aims to analyze the effectiveness of the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach in improving the critical thinking skills of elementary school students. This study was conducted at an elementary school in Ambon City at the 6th grade level that has implemented STEAM learning, involving 20 students as samples. Qualitative methods and a phenomenological approach were chosen to explore the students' experiences, perceptions, and learning processes in depth. Fifteen essay questions based on Facione's (1990) indicators were used to measure students' critical thinking skills, along with semi-structured interviews and documentation of STEAM project results as evidence of implementation. Data analysis was carried out through the stages of data reduction, data presentation, and verification to ensure the validity of the findings. The results showed that the STEAM approach significantly improved critical thinking skills in interpretation, analysis, explanation, inference, and evaluation. However, students still needed further assistance in independently managing the critical thinking process in self-regulation. In conclusion, STEAM-based learning has been proven effective in stimulating critical thinking skills through contextual and collaborative learning models relevant to real-life situations and encouraging student cooperation.

How to cite: Pelamonia, J., Ginting, C., Kempa, E., Tobing, D., & Leasa, M. (2025). Students' critical thinking skills based on the STEAM approach: The issue of waste recycling and ecology. *Journal of Environment and Sustainability Education, 3*(3). 396-413. doi: 10.62672/joease.v3i3.95

1. Introduction

In various industrial sectors such as packaging, construction, transportation, and agriculture, plastic has become an essential element that greatly supports the development of modern life. Since plastic began to be widely used, its global consumption has increased rapidly because of its unique properties, such as durability, affordability, transparency, and light weight. However, the growth in single-use plastic production, which exceeds the world's management capabilities, has made plastic pollution one of today's most pressing environmental challenges. Plastic pollution is most visible in developing countries in Asia and Africa due to urban waste management systems that are often ineffective or non-existent. Plastic is straightforward to shape according to its intended use. Plastic, or polymer, consists of a long chain of monomer units bound together. Polymers can be derived from natural materials, such as cellulose found in plant cell walls and functioning in cell adaptation (Seddiqi et al., 2021). In 2019, plastic use continued to increase, exceeding 368 million tons. Natural materials undergo major processes such as polycondensation and polymerization. Plastic waste that is discarded when exposed to biological, chemical, and environmental elements will break down into microplastics (<5 mm) and nanoplastics (<0.1 micrometers) in large quantities (Yee et al., 2021). Most plastic waste ends up in landfills or in the ocean, causing damage to ecosystems and threatening wildlife (Kehinde et al., 2020). Marine animals such as turtles, whales, and various other species often get entangled in plastic waste or mistake it for food, which can pose serious risks and even death for them (Thushari & Senevirathna, 2020; Rohman et al., 2024). In addition, plastic disposal also releases hazardous chemicals such as lead, phthalates, and cadmium, which can seep into the soil and groundwater, further polluting the environment (Lin et al., 2024). Plastic waste has recently become one of the most critical environmental issues (Kumar et al., 2021). Because plastics are often single-use and do not decompose easily, they can remain in the environment long after disposal. Plastic waste's accumulation negatively impacts nature and reduces the quality of soil, air, and water (Evode et al., 2021). The United Nations Environment Programme (UNEP) states that single-use plastics such as plastic bottles and caps, cigarette butts, plastic shopping bags, straws, stirrers, and food wrappers are a reflection of

doi: 10.62672/joease.v3i3.95

ISSN: 3025-0714

inadequate waste management systems and our attitude towards natural ecosystems (Singh & Biswas, 2023). The chemicals in plastic waste (including dioxins, lead, cadmium, phthalates, etc.) harm human and wildlife health (Verma et al., 2016). Understanding this relationship is also important for designing effective strategies and policy implications. Therefore, awareness and critical thinking among stakeholders are needed in the form of innovative solutions to reduce environmental challenges and global collaboration to manage plastic waste and its consequences for the environment. Recycling waste is one effective way, but it has many important benefits for the ecology because it helps maintain the balance of nature and reduces the adverse effects of excessive and unmanaged waste use and disposal.

The continuous evolution of technology has paved the way for teaching science in exciting and interactive ways that challenge students' reasoning and encourage meaningful learning experiences. Several recent studies show that waste can be recycled into efficient and environmentally friendly building materials (Aciu et al., 2018). Additionally, in Yelwa Village, Nigeria, the first bottle bricks in Africa were built using ecobricks for rural community housing (Edike et al., 2022). Another study reveals that implementing green economy policies is also a solution (Ogunseye et al., 2024). In Nepal, where organic waste accounts for 58–72% of municipal waste streams, significant innovations have been made to valorize resources through composting and biogas initiatives. However, implementation varies from city to city (Bhandari et al., 2025). A study in China evaluated methods such as pyrolysis, photolysis, electrochemical catalysis, and enzymatic processes. In addition, existing technologies for converting plastic waste into carbon materials, valuable chemicals, and fuels were also presented (Qian et al., 2025). Some recent innovations include engineered enzymes for PET Plastic Recycling (Jiang et al., 2025), Catalytic pyrolysis of mixed plastic waste (Cai et al., 2023), Upcycling organic waste into bioplastics (PHA) (Filippou et al., 2025), Organic waste management with biochar & biogas (Sirohi et al., 2024), and AI & Robotics for waste sorting (Wilts et al., 2021). Research shows that science teaching enhanced with technology fosters positive attitudes toward the subject, leading to improved learning outcomes and increased student engagement (Santos et al., 2025). The rapid flow of information and technological advances requires students to have superior competencies to adapt, think reflectively, and compete globally (García-Llamas et al., 2025). In this context, education is no longer solely focused on mastering subject matter. However, higher-order thinking skills, particularly critical thinking, must also be developed as the foundational basis for shaping a generation capable of addressing the complex challenges of the modern era (Kleinig, 2018).

Elementary school students will significantly benefit from developing strong thinking skills essential for success in various industries and areas of life (Kwangmuang et al., 2024). These findings underscore the importance of researching to explore innovative strategies for improving thinking skills in elementary school students. In traditional educational environments, various efforts have been made to develop students' critical thinking skills using various methods and strategies. Although these strategies have shown some success, they may not consistently capture students' full attention or meet their individual academic needs. Critical thinking is an essential skill that involves analyzing, evaluating information, and drawing conclusions based on logical and rational evidence (Ennis, 2015). Since Dewey's work in the 1910s, the definition of critical thinking has proliferated. Surprisingly, we do not have a consensus definition (Hitchcock, 2020). The emphasis on critical thinking skills is based on two main approaches: the cognitive psychology approach and the educational approach (Dunne, 2025). In cognitive psychology, critical thinking is defined through the behaviors and abilities of critically thinking individuals. For example, Halpern (1998) describes critical thinking as 'purposeful, logical, and results-oriented. It is a form of thinking involved in problem solving, drawing inferences, calculating probabilities, and making decisions. Meanwhile, in an educational approach, critical thinking is often identified with the highest level in the information processing taxonomy. The top three levels (namely analysis, evaluation, and creation) of Krathwohl's revised Bloom's taxonomy (2002) are often considered part of critical thinking skills. Analysis involves breaking down ideas or arguments into smaller parts. Evaluation involves judgment based on existing evidence, while creation involves combining various elements to create a new and coherent whole or an original product. The latest consensus in academic studies shows that critical thinking is viewed as a combination of cognitive processes and skills. As a cognitive process, it relates to how individuals analyze, evaluate, interpret, and synthesize information to produce logical understanding or decisions. As a skill, it emphasizes that this ability can be learned, trained, and improved through education, practice, and practical experience. Critical thinking does not stand alone as a function of the brain (cognition) or merely as a technical skill, but rather as an integration of both. The modern consensus in educational and psychological research agrees that the successful mastery of critical thinking depends on cognitive abilities and the mastery of practical skills. Therefore, although the importance of critical thinking skills for students in university has been widely recognized, previous research shows that new students exhibit significant variation in their critical thinking skills (van der Zanden et al., 2020). How about the critical thinking skills of elementary school students? This is a rather interesting topic.

Research shows that although critical thinking skills are critical, students' critical thinking abilities in many countries are still relatively low. A study in Russia revealed that students' critical thinking abilities were deemed inadequate (Shaw et al., 2020). In line with these findings, Liudmila Varenina notes that prospective instructors in Russia tend to have insignificant levels of critical thinking skills (Varenina et al., 2021). In addition, low critical thinking skills were also found among students in Malaysia and the Philippines (Fajari & Chumdari, 2021;

Farillon, 2021). The results of this study are reinforced by the findings of the Trends in International Mathematics and Science Study in 2019, which show that Indonesian students' achievement in solving problems with high cognitive demands is still low (Mullis et al., 2019). A study in China shows that urban elementary school students significantly outperform rural students in overall literacy skills, especially in higher-level tasks. This disparity becomes more pronounced with age, with sixth-grade students in rural areas lagging behind their urban counterparts by at least two academic levels (Yang et al., 2025). This condition reflects elementary school students' weak critical thinking skills (Leasa et al., 2020; Rosyida, 2025). Other factors contributing to students' low critical thinking skills are low interest in learning and learning models that do not guide students to think reflectively and analytically. In addition, the results of studies by Sarwanto et al. (2021) show that the critical thinking skills of elementary school students are still very low and are caused by student factors: (a) students' answers are not systematic; (b) students identify questions incorrectly and only summarize the questions, then immediately use them as answers; (c) misconceptions; (d) students rely more on memory than understanding. Results from several countries, such as Australia, Norway, and England, suggest the importance of including critical thinking skills in the school curriculum (Johnston et al., 2023). Learning that only emphasizes memorization and solving closed questions does not allow students to explore ideas, build arguments, or make decisions independently (Gholam, 2019). Therefore, an innovative learning approach is needed to stimulate interest in learning, actively involve students, and encourage the development of critical thinking skills.

One approach that encourages the strengthening of critical thinking skills is the STEAM (Science, Technology, Engineering, Arts, and Mathematics) approach. This approach integrates five disciplines through contextual and meaningful projects, enabling students to think analytically, creatively, and collaboratively simultaneously (Thornhill-Miller et al., 2023). STEAM-based learning emphasizes applying knowledge to solve real-world problems, encouraging students to understand theory and implement it logically and innovatively (Ellianawati et al., 2025). Implementing the STEAM approach aligns with the critical thinking framework Facione (1990) proposed, which includes six leading indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation. Project-based activities in the STEAM approach provide direct stimulus for students to develop critical thinking processes, including interpreting data, analyzing information, evaluating arguments, and making evidence-based decisions (Henriksen, 2017; Aydın Gürler & Kaplan, 2023). Currently, the application of the STEAM approach at the elementary school level is still limited, even though this approach has great potential in supporting the development of holistic thinking in students. STEAM integrates five disciplines that encourage students to see the world from various perspectives. Through the STEAM approach, students are introduced early on to interconnected cross-disciplinary concepts, enabling them to understand problems comprehensively, evaluate solutions, and make decisions based on various perspectives. It enhances students' critical thinking skills and equips them with broad insights to discover and create new opportunities in the future. With the STEAM approach, students experience improvements in specific skills, such as teamwork, creativity, communication, and self-evaluation (Queiruga-Dios et al., 2021).

STEAM education aims to prepare students for careers in science and technology and individual development through interdisciplinary and dynamic projects. It is known that the application of the STEAM approach can make students more active and improve their affective, psychomotor, and cognitive abilities (Maghfiroh et al., 2023). Student-centered approaches such as Problem-Based Learning, Project-Based Learning, Inquiry-Based Learning, and Cooperative Learning are used in STEAM learning to engage students in real-world problem solving (Bautista, 2021). Since Yakman introduced the acronym 'STEAM' in the early 21st century, this concept has become an important keyword in the world of education, even though the idea is quite complex and controversial (Perignat & Katz-Buonincontro, 2019). Some parties even give STEAM a higher rating, considering it an integrated learning approach (Bedewy & Lavicza, 2023) or a comprehensive education model (Yakman & Lee, 2012). Regardless of the term used, researchers interested in STEAM agree that learning should focus on hands-on projects that enable students to understand, evaluate, and solve daily technological and scientific problems. STEAM also emphasizes solving problems with innovative approaches and ethical responsibility (Belbase et al., 2022). The STEAM movement emerged due to the interaction of various agents using diverse theoretical, epistemological, and practical frameworks (Colucci-Gray et al., 2021). In neoliberal politics and socioeconomics, STEM became known in the United States in the 1980s to compete with other developed countries, such as China. The main objective was to provide students with a more holistic education to ensure national progress (Chen & Buell, 2018). As STEM evolved into STEAM, the agendas and interests of various public and private organizations and industries that viewed the arts as an added value in education and the economy also influenced this movement. The combination of economic interests and practices has made STEAM a significant topic in the world of education, becoming the focus of various academic and training initiatives (such as funding projects, courses, publications, conferences, and social networks), while also placing STEAM at the forefront of educational innovation in the eyes of the public (López-Belmonte et al., 2021). One of the core principles of STEAM education is integrating content and skills from at least two disciplines (Quigley et al., 2017). Studies show that integrating technology in mathematics classrooms with the adoption of STEAM education yields positive results (Haas et al., 2021). For example, Haas et al. 2022) report that using AR technology in outdoor STEAM learning allows students to develop independent learning and connect classroom knowledge with real-life contexts. Therefore, STEAM education is one of the best approaches to improve classroom learning integrated with mathematics and technology. STEAM is an approach that encourages creativity and innovation (Terms, 2016).

Previous researchers have also shown that STEAM effectively improves students' critical thinking skills (Nurhikmayati et al., 2024). The STEAM approach combines various disciplines, requiring students to understand the interrelationships between different concepts and apply their knowledge to solve problems. Students are encouraged to think deeply, analyze data, and evaluate ideas by integrating various disciplines. This process requires critical thinking skills to understand the context of the problem thoroughly, analyze, evaluate, and find the right solution. Well-integrated learning allows students to learn through more relevant and engaging experiences, and encourages the use of higher-order critical thinking skills (Stohlmann et al., 2012). Thus, the STEM/STEAM approach could improve students' critical thinking skills. One important element of critical thinking is the ability to apply learning in new contexts. Students involved in transdisciplinary STEAM learning can explain these applications more complexly, reflecting a higher level of critical thinking. They apply this learning both inside and outside the school environment and use it to improve the results of their products and projects. Another element of critical thinking is the ability to solve problems. Students who participate in transdisciplinary STEAM learning demonstrate a much higher level of complexity in applying problem-solving strategies in their projects. They use various strategies, such as experimentation, careful observation, collaboration, and perseverance, to help solve problems (Wilson et al., 2021).

Research by Ntemngwa & Oliver (2018) shows that applying a robotics-based STEAM approach at the secondary school level can increase student engagement in asking critical questions, evaluating solutions, and making logic-based decisions. Although this research focused on the secondary school level, the results provide valuable insights into the potential of the STEAM approach in improving the critical thinking skills of elementary school students. Student engagement in the STEAM approach encourages the development of their reflective and metacognitive abilities and increases student activity in asking critical questions, evaluating solutions, and making logic-based decisions (Chappell et al., 2025). Similar research was also revealed by Meepat et al. (2024), which showed that the STEAM approach can strengthen elementary school students' conceptual understanding and analytical skills through cross-disciplinary learning. In addition, STEAM education learning packages can be valuable tools for improving science education at the elementary school level. Thus, the STEAM approach is relevant for improving academic abilities and for shaping creative, innovative, and adaptive mindsets in response to changing times. Based on the above explanation, there is little information about the STEAM approach in elementary school learning. Therefore, this study is important to examine more specifically how the STEAM approach can be effectively implemented in elementary school learning. The aim is to improve students' critical thinking skills, particularly regarding the indicators of critical thinking skills proposed by Facione. This study aims to analyze the effectiveness of the STEAM approach in improving students' critical thinking skills.

2. Method

This study uses a qualitative method with a phenomenological approach designed to explore students' experiences in undergoing the STEAM-based learning process in depth. The study focuses on how these experiences significantly shape and influence students' critical thinking skills. The qualitative method was chosen because of its ability to understand the meaning and process of phenomena holistically in a natural context or real situation, without manipulating existing variables, thus enabling researchers to obtain a comprehensive and in-depth understanding of the subjective experiences of students (Willig, 2008; Lim, 2024). The phenomenological approach used then reinforces this focus by allowing researchers to delve into students' subjective experiences through in-depth interviews and reflection techniques, which are highly relevant and appropriate in the context of STEAM-based learning, where interaction, innovation, and creativity are the center of attention (Ediyanto et al., 2023).

The research was conducted at an elementary school in Ambon City at the sixth grade level, involving 20 students who actively participated in an essay test specifically designed to measure their critical thinking skills based on six indicators taken from Facione's theory (1990), which includes six leading indicators, namely interpretation, analysis, evaluation, inference, explanation, and self-regulation. Before the 6 essay test questions were given to the students, they were validated by two experts, namely an expert in science education and an expert in basic education. In addition, several students were purposively selected for in-depth interviews to explore in detail their personal experiences and perceptions of the STEAM learning process they participated in. It was done because some students were not focused and were shy to be interviewed when faced with the research team or teachers who were asked to assist in data collection. Therefore, the classroom teacher had prepared several students to be interviewed. In qualitative research with a phenomenological approach, the main objective is not to generalize to a broad population, but to deeply understand participants' experiences, meanings, and perspectives on a phenomenon. A sample size of 20 people in phenomenology is viewed from the perspective of depth of information, not statistical representation. The richness of data is more important than the number of respondents. In phenomenology, 20 people can even be considered a large number, because usually only 5-25 participants can provide depth of data. Ritchie & Lewis (2003) suggest that studies using individual interviews should conduct no more than 50 interviews so that researchers can manage the complexity of the analytical task. Samples in qualitative research tend to be small to support the depth of caseoriented analysis that is fundamental to the research method (Sandelowski, 1996). In addition, qualitative samples are purposive, selected based on their ability to provide rich and relevant information about the phenomenon being investigated. As a result, purposive sampling is very different from probability sampling used in quantitative research, which selects cases that are rich in information (Vasileiou et al., 2018). The primary purpose of these interviews was to obtain rich qualitative data on how students understand, experience, and respond to the STEAM approach in their daily learning activities. Data collection was carried out using three complementary main techniques, namely essay tests as a quantitative measurement tool that had been validated by two science learning experts at the elementary school level, semi-structured interviews to explore in-depth qualitative information from informants, and documentation that included student project results, photos of learning activities, and worksheets that they used as evaluation materials.

The research procedure involved exploring students' experiences in STEAM-based learning and its impact on their critical thinking skills. The research process began with a preparation stage that included identifying the focus of the research, which was to gain an in-depth understanding of how students experience and respond to STEAM learning and how it shapes their critical thinking skills. At this stage, research instruments were also developed, consisting of essay tests based on Facione's critical thinking indicators, semi-structured interview guidelines used to explore students' subjective experiences, and documentation preparation such as photos of activities and student project results. These instruments were then validated by science learning experts at the elementary school level to ensure their validity and reliability. After the preparations were complete, the data collection stage was carried out at the school. A total of 40 students were selected as participants to take the essay test to measure their critical thinking skills. In addition, two students were purposively selected for in-depth interviews to understand their perceptions and personal experiences of STEAM learning. The interview process was semi-structured to ensure that the data collected was rich and in-depth. In addition, documentation in the form of student project results, photos of learning activities, and worksheets was also collected as supporting data sources to reinforce the research findings. The collected data were then analyzed using the Miles & Huberman (1994) data analysis model. The analysis process began with data reduction, in which the data obtained from the essay tests, interviews, and documentation were selected and sorted based on Facione's six indicators of critical thinking. After that, the data were presented as descriptive narratives, tables, and relevant interview excerpts to clarify the picture of students' experiences and critical thinking skills. In the final stage, conclusions were drawn through a verification process using data triangulation and member checking techniques to ensure the accuracy, credibility, and validity of the research results. With this procedure, the research not only explores the students' experiences in depth but also maintains the integrity and validity of the data, so that the research results can be accounted for scientifically and practically. This procedure provides clear step-by-step guidance for researchers conducting research with a qualitative and phenomenological approach in the context of STEAM learning.

Subsequently, data analysis was conducted using the model developed by Miles & Huberman (1994), which comprises three essential stages. The first stage was data reduction, where the collected data were organized and categorized based on Facione's critical thinking indicators to maintain analytical focus. The next stage was data display, presented in the form of descriptive narratives, tables, and relevant interview excerpts to reinforce the interpretation of findings. The final stage involves drawing conclusions accompanied by a verification process through data triangulation and member checking. These are key steps to ensure the credibility, validity, and reliability of the data obtained in this study. Thus, this research provides an in-depth portrayal of students' experiences and the development of critical thinking in STEAM-based learning and upholds methodological integrity, ensuring that the findings are scientifically and practically accountable.

3. Results and Discussion

3.1. Result

Based on the analysis's results, detailed qualitative responses from students were obtained for the critical thinking skills indicators of interpretation, analysis, evaluation, inference, explanation, and self-regulation.

3.1.1. Interpretation

Interpretation is understanding and giving meaning to information, whether in text, images, symbols, or observed events. In this context, students were asked to interpret an image of a river filled with plastic waste and relate it to the impact on the environment and living things. The students' responses to the interpretation questions provided can be seen in Table 1.

Table 1. Interpretation Skill Test Results

Question	Observe the image of a river filled with plastic waste. In your opinion, what are the impacts of the habit of littering plastic waste on the environment and living things?	
Respondent	Answer	Answer Category

S1	People often dispose of trash improperly, clogging waterways and causing flooding. When it rains, plastic waste accumulates and increases in quantity.	Interpretation very accurate
S2	The environment becomes dirty and neglected due to the large amount of trash scattered in the river, causing discomfort to nearby residents.	Interpretation very accurate
S3	There is no fresh air because the river is full of trash.	Interpretation Accurate

Explanation:

S1 and S2 demonstrate highly accurate interpretation skills by logically linking visual information to environmental issues. In contrast, S3 only mentions one impact without explaining the cause and effect, so it is categorized as "accurate" but not in-depth. To reinforce this statement, interviews were also conducted to assess the students' interpretation skills. The results of the interviews on the interpretation skills of informants S1 and S3 are presented in the following transcript:

T : *How did you feel while working on the questions? Were the questions easy to understand?*
S : ▪ *I found the questions easy to understand and easy to answer (S1)*
▪ *Ma'am, I feel happy and a little nervous, but the questions are easy to understand (S3)*
T : *What do you think of when you see the picture of the river?*
S : *In that question, I see a river that has been polluted, and the river is filled with trash (S1)*
I see that the river is dirty and polluted with much trash, Ma'am (S3)
T : *In your opinion, what impact will this issue have?*
S : ▪ *As the picture shows, if there is a lot of trash in the river, it can cause flooding (S1).*
▪ *The impact is that living creatures will find it challenging to adapt to a dirty environment, and there will be no fresh air because the river is full of trash (S3)*

The interview supports the idea that students can recognize the main message from the image and relate it to environmental issues. It demonstrates good visual context reading skills, as expected in the STEAM-based learning approach.

3.1.2. Analysis

Analysis is the ability to identify relationships between ideas or information, break down problems into parts, and assess the relevance of evidence. Students were asked to analyze the types of waste that can be recycled and explain the process. The students' responses to the analysis questions provided can be seen in Table 2.

Table 2. Analysis Ability Test Results

Question	Among the following types of waste: paper, plastic, cans, and food scraps, categorize which can be recycled and explain how the recycling process works. Provide your reasoning.	
Respondent	Answer	Answer Category
S4	Bottles, paper, and food scraps can be recycled. Bottles and paper can be recycled in factories, while food scraps can be turned into fertilizer for plants.	The analysis is very accurate.
S8	Paper, plastic, cans, and food waste can be recycled; some are recycled into crafts and fertilizer for plants.	The analysis is very accurate.
S7	Plastic and cans are turned into valuable items.	The analysis is accurate.

Explanation:

S4 and S8 are not only able to classify types of waste, but also explain the process and its purpose, reflecting systematic understanding and logical relevance in critical thinking, which shows that students with high critical thinking skills can build fundamental skills and draw logical conclusions in the context of learning about recycling and environmental issues. S7 has the correct idea but is still too general without explaining "how" and "why." To strengthen this statement, interviews were also conducted to assess students' analytical abilities as follows:

T : *Can you distinguish between recyclable and non-recyclable waste?*
S : ▪ *Yes, I can, Ma'am (S8)*
▪ *Yes, I can tell the difference, Ma'am (S7)*
T : *From the picture, what kinds of trash can be recycled?*
S : *The recyclable items are plastic bottles and food waste (S8).*

What can be recycled are plastic and cans (S7).

T : *How do you know that the waste is recyclable? Can you give an example?*

S :
- *Plastic bottles can be recycled by factories, and food scraps can be recycled and turned into fertilizer (S8).*
- *It can be turned into crafts such as ecobricks, because we were taught by our teacher (S7)*

The interviews show that students associate the concept of recycling with their previous learning experiences about the importance of social context in critical thinking.

3.1.3. Evaluation

Evaluation is the ability to assess arguments or statements based on logic and evidence, and to make decisions. In the question, students were asked to assess the statement that recycling is a waste of time and to provide reasons and examples to support their opinion. The students' responses to the evaluation questions provided can be seen in Table 3.

Table 3. Evaluation Ability Test Results

Question	Would you agree if your friend said that recycling is a waste of time? Explain your reasoning with examples!	
Respondent	Answer	Answer Category
S12	Recycling activities are not a waste of time. For example, if we engage in recycling activities, we can reduce plastic waste in our environment. Therefore, I disagree that recycling activities are a waste of time.	The evaluation is very accurate.
S5	No, because recycling activities can be used to make crafts that can be sold, for example, coconut shells can be turned into bowls.	The evaluation is very accurate.
S9	No, because we can pollute the environment. Therefore, we must recycle to clean up the environment. For example, plastic bottles can be turned into chairs.	The evaluation is very accurate.

Explanation:

All students in this table reject the notion that recycling is useless. They support their arguments with concrete examples, such as crafts made from trash and environmental benefits, which demonstrate an understanding of the practical value of recycling. It reflects good evaluative thinking.

T : *Do you think recycling trash is a waste of time?*

S :
- *No, Ma'am (S12)*
- *No, Ma'am (S5)*

T : *Give reasons why you think recycling is not a waste of time!*

S :
- *Because if we recycle, we can reduce plastic waste in our environment (S12).*
- *Because recycling waste can generate income, for example, by making crafts and then selling them (S5)*

The interview results showed that students were able to evaluate and convey their arguments or ideas about the questions they had worked on.

3.1.4. Inference

Inference is the ability to draw conclusions based on evidence and logical reasoning. Students must calculate the number of bottles recycled in one year and conclude its impact on the environment. The students' responses to the inference questions provided can be seen in Table 4.

Table 4. Inference Ability Test Results

Question	If one family recycles 10 plastic bottles every week, how many bottles are recycled in a year? What is the positive impact on the environment?	
	Answer	Answer Category
S4	They recycle 520 bottles each year, and the impact is that it reduces plastic bottle waste.	The inference is very accurate.
S9	10 plastic bottles x 1 year equals 52 weeks, resulting in 520 bottles per year and a clean environment free of plastic waste.	The inference is very accurate.
S10	There are 520 bottles recycled each year, and the environment is clean.	The inference is very accurate.

Explanation

Students S4 and S9 can draw meaningful conclusions by connecting the number of bottles recycled with the environmental impact, demonstrating scientific reasoning based on real-world experience. Meanwhile, S10, although understanding the numbers, cannot yet explain the specific impact. It reflects the need for reflective learning that encourages students to develop cause-and-effect thinking.

T : *How do you calculate how many bottles in a year if one family recycles 10 plastic bottles each week? (S9)*

S :
- *So, I multiply it. Since there are 52 weeks in one year, I multiply it by 10 to get 520 bottles per year.*
- *So, there are 52 weeks in a year, then I multiply that by 10 bottles. The result is 520 bottles per year (S1)*

T : *What do you think is the impact of that activity?*

S :
- *It can reduce plastic bottle waste, Ma'am (S9)*
- *The impact is that the environment can become clean (S10)*

3.1.5. Explanation

Explanation is the ability to communicate the results of one's thinking clearly, and the process undertaken, including explaining the reasons, procedures, and teamwork. Students are asked to explain the steps in a recycled product manufacturing project. The students' responses to the explanation questions provided can be seen in Table 5.

Table 5. The test results of the Explanation ability

Questions	Explain the steps you and your group took to design and complete your project. What tools did you use, and how did you and your group work together to create it?	
Informant	Answer	Answer Category
S1	We prepared rice paper, guava tree branches, wire, and sand or stone pots. The steps were: we folded the paper and shaped it repeatedly until we had many pieces, tied them to the branches, and secured them in place. Then, we covered the branches with rice paper and glued it down.	The explanation is very accurate.
S12	Making flowers from rice paper requires a glue gun, wire, and scissors. The steps are to fold the rice paper into one piece and attach each piece with a wire to form the stem.	The explanation is very accurate.
S8	The steps are to crumple the paper, then glue it together to form a house.	The explanation is accurate.

Explanation:

S1 and S12 demonstrate metacognitive abilities and structured planning in STEAM projects, which support the development of critical and collaborative thinking skills. Conversely, S8 still needs improvement in scientific communication, as systematic explanations reflect a deep understanding of STEAM learning.

T : *Have you ever created a product with your friends?*

S :
- *Yes, we made flowers from rice paper (S12).*
- *Yes, Ma'am, we made flower pots from plastic bottles (S1)*

T : *How did you make that? How did you work together as a team?*

S :
- *To make it, we cut and folded the paper to form leaves, then attached them to wooden branches and stuck them into flowerpots filled with small stones. We divided the tasks within the group to prepare the materials (S12).*
- *First, we cut the bottle, painted it, and decorated it. We also worked together as a group (S1).*

From the interviews, it was found that the students could already explain. They were able to describe the process of making the products they had made and showed an understanding of the importance of teamwork.

3.1.6. Self-regulation

Self-regulation is the ability to reflect on and evaluate one's thinking process, acknowledge weaknesses, and plan for improvement. Students were asked about the difficulties they experienced and how they overcame them. The students' responses to the self-regulation questions provided can be seen in Table 6.

Table 6. Self-regulation Ability Test Results

Question	What difficulties did you encounter while working on this project? How did you overcome them? What would you like to improve if you were to do it again?	
Informant	Answer	Answer Category

Question	What difficulties did you encounter while working on this project? How did you overcome them? What would you like to improve if you were to do it again?	
S6	I had difficulty folding the paper into a triangle.	Self-reflection skills are not yet accurate.
S8	Difficulty in organizing; if repeated, I want to check the organization.	Self-reflection skills are accurate.
S11	I experience many difficulties with my learning methods.	Self-reflection skills are accurate.

Explanation:

Self-regulation is the weakest aspect of critical thinking. Students tend to only mention difficulties without identifying concrete solutions.

T : *What did you learn from your experience of making that product?*

S :
- *I can work with a team and understand that waste can be recycled and have a positive impact (S8)*
- *Recycling unused waste and turning it into items that can be reused (S6)*

T : *any difficulties? What would you like to improve if the activity were repeated?*

S :
- *Difficulty in folding; if repeated, I would like to improve my folding technique (S8)*
- *I had difficulty folding the paper into a triangle (S6)*

These results indicate that students cannot adequately reflect on the process and results of their activities. However, some students showed an open attitude and a desire to improve.

3.2. Discussion

3.2.1. Interpretation Ability Test

There are differences in the interpretation abilities of three students (S1, S2, and S3) in logically and deeply relating visual information related to environmental issues. S1 and S2 showed excellent and accurate interpretation abilities. They can connect various information from images or visual data with environmental issues in a coherent and detailed manner. Their answers not only mention the impact but also clearly explain the cause and effect, for example, how water pollution affects marine life. It indicates a broad understanding and critical thinking skills in processing visual information. In contrast, S3, although the answer was accurate, only mentioned one impact without clarifying the underlying cause-and-effect relationship. These answers show good accuracy, but the depth and breadth of interpretation are still lacking. S3 was unable to relate all visual elements to the environmental situation. To reinforce the assessment results from the written answers, interviews were conducted with each student. Therefore, interviews are essential. It aims to explore the students' verbal understanding in linking visual information with environmental issues and to ensure that accurate and in-depth thinking is also reflected verbally. The interview results reinforce that S1 and S2 have consistent and in-depth interpretation skills, while S3 needs guidance to develop cause-and-effect analysis skills and broaden their knowledge of environmental issues. An important conclusion from this case is the significant difference in the depth of interpretation among the three students and the importance of mentoring students whose interpretations are still superficial to develop more comprehensive analytical skills. The interview approach as a method of assessment reinforcement has also proven effective in revealing the students' thought processes behind their written answers.

The results show that students' ability to analyze local waste recycling helps stimulate their critical thinking. This finding aligns with previous studies stating that linking the learning context to everyday situations can improve students' understanding of the concepts taught (Martawijaya et al., 2023). Several influencing factors include cultural aspects, as young children are very adept at imitating and adopting community habits. Schools often conduct environmental clean-ups on Fridays or at certain times. This situation shapes students' habits and allows them to distinguish between actual knowledge. Although environmental protection awareness is relatively high, it rarely manifests in concrete actions (Zhang et al., 2019). Recent research shows that watching YouTube on mobile phones has made students accustomed to disposing of trash in its proper place. This habit also shapes their knowledge, especially for those in Generation Z and Alpha, who are tech-savvy and more digitally literate. Therefore, using game applications with the black box method on Android phones can provide proper education for early childhood (Gayatri, 2023). Waste sorting games are considered child-friendly and effective as an educational medium based on Android technology [20]. In addition, the application of gamification and game-based learning in elementary school students has been proven to help overcome problems related to waste management (Magista et al., 2018). Other games, such as Trash Hero, can provide effective learning for elementary school children, especially regarding how to sort waste, recycle waste, and manage different types of waste (Oktaviani et al., 2022). Other recent findings show that (STEAM) can be an alternative solution for developing waste management literacy among school children (Syahmani et al., 2021).

Children need to be equipped with a proper understanding of health from an early age. This is an opportunity for the environment, especially parents, teachers, and schools, to provide broad educational influence to shape positive behavior in children (Siegel et al., 2017). The development of preschoolers' mindsets and learning processes can be done through play activities. Educational games are an effective medium for improving children's understanding and health awareness. Through play activities with educational toys, children can be accustomed to, trained in, and instilled with character education values (Lagu et al., 2025).

The STEAM approach provides students with the opportunity to develop critical thinking skills through the integration of various disciplines. Many Indonesian researchers have also developed learning models and media. Other countries focus more on computer-based activities, developing community programs, and identifying participants' perceptions of critical thinking. These differences give each country its own characteristics in improving and identifying the critical thinking skills of its people. These differences in practices and interventions can also provide alternatives for researchers in their studies on critical thinking through the STEM/STEAM approach (Nurhikmayati et al., 2024). Regarding the distribution of the authors' countries and the research period, the findings show that over the past five years, only five countries have been interested in conducting studies on critical thinking skills through the STEM/STEAM approach in mathematics education. Of the five countries, Indonesia ranks first in the number of studies conducted. Indonesian researchers' interest in developing critical thinking skills through STEM/STEAM is based on the low mathematics achievement of Indonesian students in the PISA survey (Suherman et al., 2022). The PISA results serve as an important reference for educators in Indonesia in improving the quality of students' mathematical abilities, one of which is by applying the STEM/STEAM approach. Research also shows that STEM-based learning can improve students' critical thinking skills (Suherman et al., 2021). Through the STEM approach, students obtain new information from observations, encouraging them to analyze and develop critical thinking (Borrego & Henderson, 2014). Other countries, such as the United States, Taiwan, Saudi Arabia, Turkey, and Malaysia, contributed little to this research. The low contribution from various countries indicates the need to increase the diversity of countries in studies on critical thinking through STEM/STEAM. Even the United States, as a pioneer of the STEM approach, has made only a small contribution to research on critical thinking skills through STEM/STEAM. US researchers focus on robotic coding activities in mathematics learning. These robotic coding activities have transferability, providing access to STEM learning and opportunities for students to develop mathematical reasoning and critical thinking skills that can be applied in the context of programming (Kim, 2012).

3.2.2. Analysis Ability Test

This case illustrates the differences in critical thinking abilities among several students (S4, S7, and S8) in understanding and managing environmental issues related to waste classification, the recycling process, and the waste management objectives. S4 and S8 demonstrated excellent and systematic abilities in logically and deeply connecting various concepts and aspects of learning. They were not only able to identify and classify types of waste accurately, but also explain the waste management process involving the stages of recycling and the objectives of such management, which include positive impacts on the environment and society. This ability reflects strong critical thinking skills, where students can build understanding gradually and connect relevant information logically. They also demonstrated the ability to draw appropriate conclusions based on that understanding. It shows that students with high critical thinking skills understand basic concepts and can apply them in real-world contexts, such as environmental management. In contrast, S7 had the correct idea about the importance of waste management and recycling, but their explanation was still very general and lacked depth. S7 had not yet been able to explain in detail how the recycling process is carried out and why it is important for the environment. This lack of in-depth explanation shows that S7 still needs to be encouraged to develop more critical analysis skills, especially regarding cause and effect and the relevance of the waste management process. From this case, developing critical thinking skills is significant in learning about environmental issues. Students with high critical thinking skills can systematically build basic skills, connect information, and draw logical conclusions. In contrast, students who have not reached this level need further guidance to understand and explain concepts in a more in-depth and applicable manner. Strengthening learning that focuses on developing critical thinking skills will support students' comprehensive understanding. From the case in this analysis stage, students could analyze accurately. In theory, according to Piaget, sixth-grade students are at the concrete operational stage towards formal operational. Several scientific studies from Carey (2000); Metz (2004); Vosniadou (2019) explain that at this stage, they begin to: 1) Be able to connect simple abstract concepts with real experiences; 2) Be able to perform more complex cause-and-effect reasoning than lower grades; 3) Be familiar with simple scientific thinking strategies (e.g., observing, comparing, drawing conclusions); 4) Be able to analyze scientific cases with teacher guidance and relevant context, such as everyday natural phenomena or simple experiments. Thus, the ability of sixth-grade students to analyze scientific concepts is not only due to their age and cognitive development, but also because of an education that provides opportunities for exploration, inquiry, and problem-based learning.

Teachers or educators can use these findings to guide students who still need to improve their analytical skills and make them capable of playing critical thinking role models in the learning process (Wartono et al., 2018). S4 and S8 are examples of students with superior critical thinking skills who can manage information systematically and draw logical and relevant conclusions regarding environmental issues. These results align with the findings of Pertiwi et al. (2024), which show that 78.67% fall into the critical category. It means that students can find creative and innovative ideas and solutions to problems presented in learning, and detect arguments or ideas. In addition, this also shows that students can formulate problems through observation and can design temporary answers to problems given during the learning process in class. Despite having the right ideas, S7 needs more focused development to improve in-depth analysis skills, explain processes, and understand the objectives of waste management. A learning approach that emphasizes strengthening critical thinking skills will be very beneficial in developing a comprehensive and applicable understanding among students. Teachers and educators can use these findings to identify additional guidance needs for students who lack depth and make S4 and S8 models or examples in learning. It is in line with the findings of Hariaji & Sinaga (2024) that critical thinking skills are important for students to succeed academically and in their future careers. These skills involve thinking logically, evaluating arguments, and making decisions. Critical thinking is a systematic process that provides opportunities for students to formulate and evaluate their beliefs and opinions. In addition, the study results show that STEAM projects and increased learning motivation increase students' critical thinking skills. This study highlights the potential of project-based learning in STEAM classrooms to address the learning motivation gap in this area. However, further research is needed in this area as current research on this topic is limited.

3.2.3. Evaluation Ability Test

This case shows that all students listed in Table 3 rejected the negative assumption that recycling is useless. They supported their arguments by citing concrete examples, such as making handicrafts from recycled waste and the various environmental benefits of recycling. This approach reflects a deep understanding of the practical value and usefulness of recycling, not just theory or assumptions. These students demonstrate good evaluative thinking skills by providing real and applicable examples, namely the ability to assess and provide logical reasons for an issue based on relevant evidence and examples. It shows that students are aware of the importance of recycling in the context of the environment and can relate this activity to its tangible positive impacts. Concrete examples also strengthen their arguments, making their rejection of negative assumptions rational and fact-based. Overall, the students' attitudes and explanations reflect a successful learning process in developing critical and evaluative thinking skills, which are crucial in understanding environmental issues and encouraging positive actions towards environmental sustainability.

In addition, the arguments of S12, S5, and S9 show that all three demonstrate very accurate evaluation because they reject the statement and provide logical justification. Other reasons are supported by concrete examples, which align with the thinking abilities at the end of elementary school (concrete operational to formal), and there is evidence of environmental awareness and understanding of the socio-economic functions of science. This finding is consistent with several previous studies showing that elementary school students can understand scientific concepts when provided with real-life contexts relevant to their daily lives, such as environmental issues. The students' responses in this case provide clear evidence of this. (Vosniadou, 2019). For example, Metz (2004) found that late elementary school children can use evaluative reasoning and even construct arguments that include cause and effect, especially in scientific contexts close to their daily experiences. It is evident in how students provide real examples (plastic bottle → chair, coconut shell → bowl). Carey (2000) also emphasizes that late elementary school age is an important stage for conceptual change, where students begin to be able to reject false ideas with science-based reasoning. This case demonstrates such a conceptual change: students do not accept the claim that "recycling is a waste of time," but reject it with scientific and social arguments. This case proves that sixth-grade elementary school students can conduct accurate scientific evaluations by providing logical reasons and concrete examples. It aligns with previous research findings stating that late elementary school-aged children can connect scientific concepts with environmental, economic, and social issues to understand, analyze, and evaluate science-based statements.

3.2.4. Inference Ability Test

Scientific reasoning based on real-life experiences by S4 and S9 students demonstrates strong and concrete scientific reasoning skills. They can connect the number of plastic bottles recycled with positive environmental impacts. For example, they explain how reducing the number of plastic bottles sent to landfills can reduce soil and water pollution and conserve the natural resources needed to produce new bottles. This ability shows that S4 and S9 students do not just memorize numbers but are also able to make logical connections between quantitative data and real ecological impacts based on direct experience. Thus, they can engage in scientific reasoning that involves observation, analysis of cause-and-effect relationships, and reflection on the real consequences of recycling activities. Unlike S4 and S9, S10 demonstrated limited understanding, as the student could comprehend numerical data related to the number of recycled bottles but was not yet able to explain specifically how such data affects the environment. S10's explanations are still general and lack depth in linking the data to ecological changes or the practical benefits of recycling. It indicates that S10 needs more reflective learning to develop critical and analytical thinking skills, particularly in clearly identifying cause-and-effect relationships. Learning that focuses on reflection on data and environmental context will help improve the understanding of S10 and other similar students. With learning that emphasizes reflection and scientific reasoning, students will be able to understand data critically and see its ecological impact clearly, so that their understanding of environmental issues becomes more comprehensive and applicable. In line with previous research on accuracy in problem solving, efforts to improve students' critical thinking skills using STEM-based E-modules in the classroom learning process have proven effective in improving student evaluation. The resulting electronic modules, which are based on STEM learning with a problem-based approach, can be accessed via smartphones to strengthen students' critical thinking skills in evaluation aspects. When giving presentations, students learn to formulate ideas and provide clear explanations. In addition, in group presentations, students are expected to be able to explore more deeply and develop innovations and ideas creatively and uniquely (Kartimi et al., 2021; Yustina et al., 2022).

3.2.5. Explanation Ability Test

S1 and S2 students demonstrated good metacognitive abilities, namely awareness and control over their thinking processes, while carrying out STEAM projects. They were able to plan project steps in a structured manner, reflecting a deep understanding of the stages that must be passed to achieve learning objectives. This planning ability supports the development of critical thinking skills and strengthens collaborative skills, as structured planning allows for effective coordination and division of tasks among team members. It is important in multidisciplinary STEAM projects that require collaboration between various fields. In contrast, S8 students showed a need to strengthen their scientific communication skills. Despite their knowledge, S8 students' ability to deliver systematic and structured explanations still needs to be further honed to reflect a deep understanding of STEAM material and learning processes. Good scientific communication skills are key to conveying ideas, observations, and analyses clearly and logically to others, including in team discussions or project presentations. Therefore, improving these skills will greatly support mastery of the material and success in STEAM activities. It can be achieved by providing opportunities and guidance for students to develop metacognitive skills, such as reflection on the learning process and systematic planning (Ananda et al., 2023). Through structured planning, collaborative work can be strengthened so that STEAM projects can run effectively and efficiently. Scientific communication skills can be developed, especially for students who need more support, so that they can convey ideas and results systematically and logically. These findings align with using learning strategies that emphasize critical thinking, collaboration, and communication as an integral part of STEAM projects in science learning (Rohman et al., 2024). With the right learning approach, students can optimally develop critical thinking, collaborative, and communicative skills that are very important in STEAM and 21st-century learning.

3.2.6. Self-Regulation Ability Test

From the three informants (S6, S8, and S11), there were differences in the quality of self-reflection: S6 had difficulty folding the paper into a triangle. However, his reflection was categorized as inaccurate because his answers tended only to mention the difficulty without a clear strategy for improvement. In addition, S8 stated that they had difficulty arranging the paper, but were able to mention that if they repeated the task, they would improve their arrangement. It shows an accurate reflection, as they were able to link the problem with a solution for future improvement. S11 experienced many difficulties in learning but was not specific in explaining the nature of the difficulties and how to overcome them. Their answers are pretty accurate because there is an awareness of the difficulties, but the improvement strategies are still unclear. From this, students' self-regulation abilities vary. Some have only recognized the problem, some can already plan solutions, and some are still vague in their reflections. Students tend only to convey or mention the difficulties they experience during the learning process or while working on assignments, without being able to go further to identify tangible and measurable solutions. This shows that even though students are aware of obstacles, they do not yet have sufficient skills or motivation to reflect deeply on the causes of problems and seek alternative solutions independently. This situation can negatively affect the learning process. Without effective self-regulation, students' difficulties will persist and hinder the development of critical thinking and other essential metacognitive skills. To address this challenge, teachers need to provide systematic support and guidance. Such support enables students to recognize obstacles, design concrete solutions, and reflect on their learning progress. Cultivating metacognitive awareness is also essential, as it encourages students to solve problems and strengthen their capacity for reflection and self-evaluation. In addition, explicit self-management strategies can be introduced, such as training students to develop action plans when facing difficulties, assess the effectiveness of attempted solutions, and make necessary adjustments. These efforts will be more effective when implemented within a supportive classroom environment that promotes experimentation, accepts mistakes as part of the learning process, and fosters collaborative problem-solving. Thus, improving self-regulation skills will significantly help students manage the learning process independently and critically and increase the overall effectiveness of learning (Tan et al., 2021).

Low self-regulation is due to several specific reasons based on the findings. Zimmerman (2002) emphasizes that self-regulation is a determining factor in learning success, especially in complex tasks. Low reflective ability means students cannot optimize the learning cycle (planning, implementation, reflection). Dignath & Büttner (2008) show that many students struggle to develop self-regulation independently without explicit instructional support. It explains why the results in the data are low, as students are not yet accustomed to internalizing reflective strategies. Efklides (2009) explains that metacognitive awareness does not arise automatically but develops through practice and guidance. If learning does not provide explicit space for reflection, students tend to only mention problems without thinking about solutions. Suan (2023) adds that students often focus on the result (project product) rather than the thinking process. It causes the reflective aspect to be neglected. Therefore, STEAM emphasizes integrating creativity, problem-solving, and collaboration in learning design. However, if self-regulation is low, students will struggle to manage an open and complex learning process. Chang & Lee (2022) emphasize that project-based or STEAM learning needs to be complemented with metacognitive scaffolding, for example, through learning journals, self-questioning prompts, or structured reflection. Lai & Hwang (2016) also found that reflection-based interventions in science learning improve students' self-regulation skills and learning outcomes.

4. Conclusion

Based on the study's results, the STEAM approach has a very positive effect on improving the critical thinking skills of elementary school students. This approach broadens students' perspectives in understanding a problem and encourages them to explore various solutions with a more systematic, creative, and collaborative approach. The most notable improvement was seen in the indicators of interpretation, analysis, explanation, inference, and evaluation, which showed that students could understand problems more deeply, critically analyze information, provide coherent explanations, and convey opinions and conclusions with clear logic and a structured manner. It proves that STEAM-based learning can stimulate higher-order thinking, as students are directly involved in learning experiences emphasizing interdisciplinary connections and applying concepts in real-world contexts. Through collaborative projects, students are trained to work together in groups and learn to express ideas, respect others' opinions, and develop innovative solutions that can be applied to everyday situations. However, this study also found that the results are still not optimal in terms of self-regulation. Students still need intensive guidance to become more skilled at managing their time, monitoring their learning progress, and conducting independent evaluation and improvement. These metacognitive skills are important so that the critical thinking skills acquired do not stop at the level of task completion but can also develop into a habit of continuous reflective thinking. Thus, the STEAM approach effectively improves students' critical thinking skills through active, collaborative, and contextual learning processes. However, efforts to strengthen self-regulation and metacognitive awareness are still needed so that students can develop into independent learners who are critical and able to manage and direct their learning process continuously.

There are several important recommendations for further development. First, strengthening the aspect of self-regulation is essential. Students need more intensive guidance to develop this skill. Guidance programs can take the form of special classes or individual consultation sessions that focus on metacognitive techniques, such as reflection and self-assessment. It will help students manage their learning process more effectively. Furthermore, the integration of STEAM in learning must be carried out more deeply. Students should be involved in collaborative projects that combine various disciplines. Contextual learning experiences relevant to everyday life will help them see the practical applications of the concepts they learn. It is also important to provide training for teachers. Specially designed workshops and training will help teachers understand and apply the STEAM approach effectively. In addition, forming a community of practice for teachers can be a forum for sharing experiences and strategies in implementing STEAM and supporting the development of students' critical thinking. In terms of evaluation and assessment, project-based assessment methods should be applied. It will allow a more holistic evaluation of students' critical thinking and self-regulation skills. In addition, students must be encouraged to reflect regularly on their learning process to identify areas for improvement. Finally, further research is highly recommended to explore the impact of STEAM integration on students' self-regulation and character development. Developing learning models that integrate STEAM with a focus on strengthening self-regulation must also be tested for effectiveness in various educational contexts. Overall, the STEAM approach has been proven effective in improving students' critical thinking skills. However, special attention to the aspect of self-regulation is significant. By implementing these recommendations, it is hoped that students will be able to think critically and manage their learning process better, which will support their overall development.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

Funding

No funding support was received.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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