Jurnal Didaktika Pendidikan Dasar
Direktorat Guru Pendidikan Dasar, Kemendikdasmen R.I.

Journal Homepage:
https://ojsdikdas.kemendikdasmen.go.id/index.php/didaktika

Vol. 10, No. 2, July 2026	Copyright © 2026, is licensed under a CC-BY-SA
Pages: 589-622	Publisher: Direktorat Guru Dikdas, Kemendikdasmen R.I.
DOI: https://doi.org/10.67686/didaktika.v10i2.2185	E-ISSN: 2621-6094

STEAMS-Driven Green Innovation to Strengthen Critical Thinking in Elementary Education

Nur Aini Ochtafiya
Sekolah Dasar Muhammadiyah Manyar Gresik, Jawa Timur, Indonesia
Correspondence Email: nurochtafiya42@guru.sd.belajar.id

Article Info

Received: March 15, 2026
Accepted: May 23, 2026
Published: July 30, 2026

Keywords

Critical Thinking;
STEAMS Education;
Design Thinking;
Deep Learning;
Environmental Project-Based Learning.

Abstract

Elementary school students' critical thinking skills remain low, particularly in the aspects of inference, explanation, and self-regulation within the context of 21st-century sustainability-based learning. This condition was found in the education report of SD Muhammadiyah Manyar in 2025. This study aims to improve students' critical thinking skills through the integration of STEAMS, design thinking, and deep learning in the aqua farming green innovation project. This study employed a quasi-experimental design using a one-group pretest–posttest approach involving seventy-nine fourth-grade elementary students. The learning process was implemented based on the stages of design thinking, namely empathize, define, ideate, prototype, test, and reflection, by integrating environmental problem-solving activities. Data was collected through critical thinking tests administered before and after the learning intervention. The results showed a significant improvement in students' critical thinking skills before and after the intervention. The findings indicate that the mean score increased from 66.72 to 88.64. The N-Gain value of 0.63 indicated a moderate level of learning effectiveness. The effect size analysis revealed a large effect (Cohen's d = 2.51), demonstrating a strong practical impact of the intervention on students' critical thinking development. Improvements were observed across all indicators, particularly in inference and self-regulation. Thus, STEAMS-based learning integrated with structured problem-solving processes is effective in strengthening elementary students' critical thinking skills. The novelty of this research lies in the integration of the STEAMS approach, design thinking, deep learning, and the use of digital technology in sustainability-based environmental projects.

P-ISSN: 2580-006X
E-ISSN: 2746-0525

Kata Kunci

Berpikir Kritis;
Pendidikan STEAMS;
Design Thinking;
Pembelajaran Mendalam;
Pembelajaran Berbasis Proyek Lingkungan.

Abstrak

Kemampuan berpikir kritis siswa sekolah dasar masih tergolong rendah, khususnya pada aspek inference, explanation, dan self-regulation dalam konteks pembelajaran abad ke-21 berbasis keberlanjutan. Kondisi ini ditemukan dalam laporan pendidikan SD Muhammadiyah Manyar tahun 2025. Penelitian ini bertujuan untuk meningkatkan kemampuan berpikir kritis siswa melalui pengintegrasian STEAMS, design thinking, dan deep learning dalam proyek inovasi hijau aqua farming. Penelitian ini menggunakan desain kuasi-eksperimen dengan rancangan one-group pretest–posttest yang melibatkan tujuh puluh sembilan siswa kelas IV sekolah dasar. Proses pembelajaran dilaksanakan berdasarkan tahapan design thinking, yaitu empathize, define, ideate, prototype, test, dan reflection, dengan menggabungkan kegiatan pemecahan masalah lingkungan. Data dikumpulkan melalui tes kemampuan berpikir kritis sebelum dan sesudah intervensi pembelajaran. Hasil penelitian menunjukkan adanya peningkatan yang signifikan pada kemampuan berpikir kritis siswa sebelum dan sesudah intervensi pembelajaran. Hasil penelitian menunjukkan adanya peningkatan yang signifikan, dengan rata-rata skor meningkat dari 66,72 menjadi 88,64. Nilai N-Gain sebesar 0,63 menunjukkan tingkat efektivitas pembelajaran pada kategori sedang. Analisis effect size menunjukkan pengaruh yang besar (Cohen's d = 2,51), yang menandakan bahwa intervensi pembelajaran memiliki dampak praktis yang kuat terhadap perkembangan kemampuan berpikir kritis siswa. Peningkatan terjadi pada seluruh indikator berpikir kritis, terutama pada aspek inference dan self-regulation yang menunjukkan perkembangan paling menonjol. Dengan demikian, pembelajaran berbasis STEAMS yang terintegrasi dengan proses pemecahan masalah terstruktur terbukti efektif dalam memperkuat kemampuan berpikir kritis siswa sekolah dasar. Kebaruan penelitian ini terletak pada integrasi pendekatan STEAMS, design thinking, pembelajaran mendalam, dan pemanfaatan teknologi digital dalam proyek lingkungan berbasis keberlanjutan.

A. Introduction

The development of critical thinking skills has become a central focus of 21st-century education, driven by the increasing complexity of global challenges and the growing demand for sustainability-oriented competencies. International frameworks, including those developed by the Organization for Economic Co-operation and Development (OECD), emphasize the importance of equipping students with higher-order thinking skills, such as the ability to analyze information, evaluate evidence, and make well-reasoned decisions in complex situations (Care et al., 2018; Lai, 2011; OECD, 2019; Voogt & Roblin, 2012). However, findings from large-scale international assessments, particularly the Programme for International Student Assessment (PISA), consistently indicate that students' critical thinking and reasoning abilities remain below expected levels, especially in developing countries (OECD, 2019). This concern has become even more pronounced in the context of educational transformation following the COVID-19 pandemic (Zhao & Watterston, 2021). These findings suggest that existing instructional practices have not yet adequately fostered the development of students' higher-order thinking skills (Care et al., 2018; Lai, 2011; OEDC, 2019; Voogt & Roblin, 2012).

However, global assessment data, including the Program for International Student Assessment (PISA), consistently indicates that students' critical thinking and reasoning abilities remain below expected levels, especially in developing countries (OEDC, 2019). This challenge has become increasingly significant in the context of educational transformation in the post-pandemic era (Y. Zhao & Watterston, 2021). These findings suggest that current instructional practices have not yet fully supported the development of students' higher-order thinking skills.

In the Indonesian context, similar challenges are evident. National education reports and empirical studies reveal that elementary school students continue to experience difficulties in critical reasoning, particularly in aspects such as inference, explanation, and self-regulation (SD Muhammadiyah Manyar, 2025; Suryaningsih & Ainun Nisa, 2021). These challenges are also reflected in school-level data. For example, the 2025 Education Report of SD Muhammadiyah Manyar indicates that students' critical reasoning performance has not yet reached the expected level. Preliminary classroom observations further reveal that students experience difficulties in key dimensions of critical reasoning, particularly inference and explanation.

At the same time, the school environment presents authentic sustainability-related challenges that can serve as meaningful learning contexts. Organic waste generated from students' daily dining activities remains inadequately managed, while the available backyard area has not been fully utilized as an educational resource. Although these conditions provide valuable opportunities for contextual and project-based learning, they have not yet been systematically integrated into instructional practices aimed at fostering students' critical thinking skills.

Taken together, these findings underscore the need for instructional innovations that actively engage students in learning while systematically developing their reasoning abilities from an early age. More specifically, they highlight the importance of instructional practices that explicitly promote reflective and critical thinking processes

P-ISSN: 2580-006X
E-ISSN: 2746-0525

(Brookfield, 2013).

Various instructional approaches have been implemented to enhance students' critical thinking skills, including inquiry-based learning, problem-based learning, and project-based learning (Saefudin, & Berdiati, 2026). These approaches are widely recognized for their effectiveness in promoting meaningful, student-centered learning experiences (Barron & Darling-Hammond, 2008; Thomas, 2000). Previous studies have demonstrated that these approaches can increase student engagement and improve conceptual understanding (Hmelo-Silver, 2004; Krajcik & Blumenfeld, 2006). However, their effectiveness in fostering structured critical thinking remains inconsistent. Previous studies suggest that these approaches often lack explicit scaffolding to support students in engaging in systematic reasoning processes, including analysis, evaluation, and reflective thinking (Abrami et al., 2015; Li, 2016). Moreover, students are rarely encouraged to generate questions and critically evaluate evidence (Chin & Osborne, 2008). As a result, students may actively participate in learning activities without demonstrating substantial improvements in higher-order critical reasoning skills.

In response to these limitations, interdisciplinary approaches such as STEAM (Science, Technology, Engineering, Arts, and Mathematics) have gained increasing attention as promising alternatives. STEAM learning integrates multiple disciplines to create meaningful and contextual learning experiences that foster creativity, collaboration, and problem-solving skills (Herro & Quigley, 2017; Takeuchi et al., 2020; Yakman & Lee, 2012). This interdisciplinary approach aligns with the growing emphasis on STEM/ STEAM education as a framework for connecting knowledge across disciplines and addressing complex real-world challenges (Moore et al., 2014; Sanders, 2008; Widyawati, 2025). Empirical studies have demonstrated that STEAM-based learning can enhance students' engagement, creativity, and innovative thinking (Henriksen et al., 2017; Liao, 2016; Pangestuti, & Masbur, 2025).

However, the potential of STEAM to promote critical thinking largely depends on how learning experiences are designed and facilitated. Without explicit instructional guidance and appropriate scaffolding, STEAM activities may place greater emphasis on product creation than on the development of systematic reasoning processes, such as analysis, evaluation, and reflection (Margot & Kettler, 2019; Thibaut et al., 2018). Critical thinking is also defined as a disciplined process of actively and skillfully conceptualizing, applying, analyzing, and evaluating information to guide belief and action (Elder & Paul, 2020).

Therefore, there is a need to integrate STEAM-based learning with structured pedagogical frameworks that explicitly support students' thinking processes. One promising approach is Design Thinking, which provides a systematic problem-solving framework through the stages of empathize, define, ideate, prototype, and test. These stages guide students in identifying problems, analyzing relevant information, generating ideas, and developing logical solutions (Brown, 2008; Liedtka, 2018; Razzouk & Shute, 2012). In educational settings, Design Thinking has also been shown to foster both creative and analytical problem-solving skills (Henriksen, 2013). Complementing this approach, Deep Learning emphasizes meaningful engagement, reflection, and knowledge construction through authentic learning experiences (Fullan et al., 2017). By encouraging students to connect prior knowledge with real-world contexts, Deep Learning promotes deeper understanding and sustained cognitive engagement. The integration of STEAM, Design Thinking, and Deep Learning therefore offers a comprehensive framework for fostering students' critical thinking skills through authentic, reflective, and problem-oriented learning experiences.

Furthermore, environmental project-based learning provides authentic learning contexts that enable students to engage in real-world problem-solving while fostering sustainability awareness. Through meaningful interactions with environmental issues, students are encouraged to apply knowledge across disciplines, evaluate alternative solutions, and make informed decisions. Previous studies have demonstrated that environmental STEAM projects can enhance students' critical thinking and creativity by promoting contextual, collaborative, and inquiry-oriented learning experiences (Hasanah, 2014). Despite the growing body of research on STEAM, Design Thinking, and project-based learning, important gaps remain in the literature. First, previous studies have largely examined these approaches independently rather than integrating them into a comprehensive instructional framework capable of supporting students' higher-order thinking processes (Margot & Kettler, 2019; Thibaut et al., 2018). Second, many STEAM implementations prioritize creativity, innovation, and product-oriented outcomes, while providing limited support for the systematic development of critical thinking skills across key dimensions such as interpretation, analysis, evaluation, inference, explanation, and self-regulation. Third, empirical evidence regarding the integration of STEAM, Design

P-ISSN: 2580-006X
E-ISSN: 2746-0525

Thinking, and Deep Learning within environmental and sustainability-oriented learning contexts at the elementary school level remains limited.

Taken together, these gaps indicate the need for a more structured and integrative learning model that explicitly supports the development of students' critical reasoning skills. Such an approach is particularly important in preparing students with essential 21st-century competencies, including critical thinking, collaboration, and problem-solving (Trilling & Fadel, 2009).

This study contributes to the existing literature by examining the effectiveness of an integrated STEAMS, Design Thinking, and Deep Learning framework implemented within an environmental project-based learning context. Specifically, the study investigates the Aqua Farming Green Innovation Project as a learning intervention designed to enhance elementary students' critical thinking skills.

Against this backdrop, an important question arises regarding the extent to which the integration of STEAMS, Design Thinking, and Deep Learning can improve students' critical thinking across key dimensions, including interpretation, analysis, evaluation, inference, explanation, and self-regulation.

Therefore, this study aims to evaluate the effectiveness of the integrated STEAMS–Design Thinking–Deep Learning framework in improving elementary students' critical thinking skills. Its effectiveness is assessed through changes in pre-test and post-test scores, normalized gain (N-gain), and effect size.

B. Method

A quasi-experimental one-group pretest–posttest design was employed to evaluate the effectiveness of an integrated STEAMS-based learning model in improving students' critical thinking skills. The design facilitated the assessment of changes in students' cognitive performance by comparing pre-intervention and post-intervention measures of critical thinking (Creswell & Creswell, 2017). The independent variable in this study was an integrated STEAMS-based learning model grounded in the principles of Design Thinking and Deep Learning, implemented through the Aqua Farming Green Innovation Project. The dependent variable was students' critical thinking skills, assessed across six dimensions: interpretation, analysis, evaluation, inference, explanation, and self-regulation.

The research procedure consisted of three phases: pretest, intervention, and posttest. During the pretest phase, students' baseline critical thinking skills were measured. The intervention phase involved the implementation of the integrated STEAMS-based learning model through the Design Thinking stages of empathize, define, ideate, prototype, test, and reflection within the Aqua Farming Green Innovation Project. Following the intervention, a posttest was administered to evaluate changes in students' critical thinking skills. The overall research procedure is presented in Figure 1.

Figure 1. Research Procedure (a quasi-experimental design a one-group pretest–posttest)

The research took place at SD Muhammadiyah Manyar, Gresik, Indonesia, during the first semester of the 2025/2026 academic year. The study population comprised all fourth-grade students, with seventy-nine students involved as participants. A total sampling technique was employed, in which all members of the population were included due to the small population size and to ensure comprehensive data representation (Sugiyono, 2017).

Data collection was conducted using a critical thinking test instrument designed based on six indicators: interpretation, analysis, evaluation, inference, explanation, and self-regulation (Facione, 2011). The instrument was administered in the form of pre-test and post-test to measure students' improvement. The validity of the instrument was established through expert judgment. The results indicated that the instrument was appropriate and met the established validity criteria.

Data analysis was conducted using both descriptive and inferential statistical techniques. Descriptive statistics were used to present the distribution of students' pre-test and post-test scores, including mean and standard deviation. To examine the effectiveness of the intervention, several inferential analyses were performed. First, a normality test

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E-ISSN: 2746-0525

using the Kolmogorov-Smirnov (sample more than > 50) was conducted to determine whether the data were normally distributed. If the significance value (p-value) is greater than 0.05, the data are normally distributed. If the significance value (p-value) is less than 0.05, the data are not normally distributed (Field, 2024; Ghasemi & Zahediasl, 2012; Shapiro & Wilk, 1965).

Figure 2. Kolmogorov – Smirnov Test for Normality

A paired sample t-test was applied to analyze whether there was a statistically significant difference between pre-test and post-test scores based on the normality results. The decision was based on the significance value (p-value), where p < 0.05 indicates a statistically significant difference between the two sets of scores (Hake, 1998).

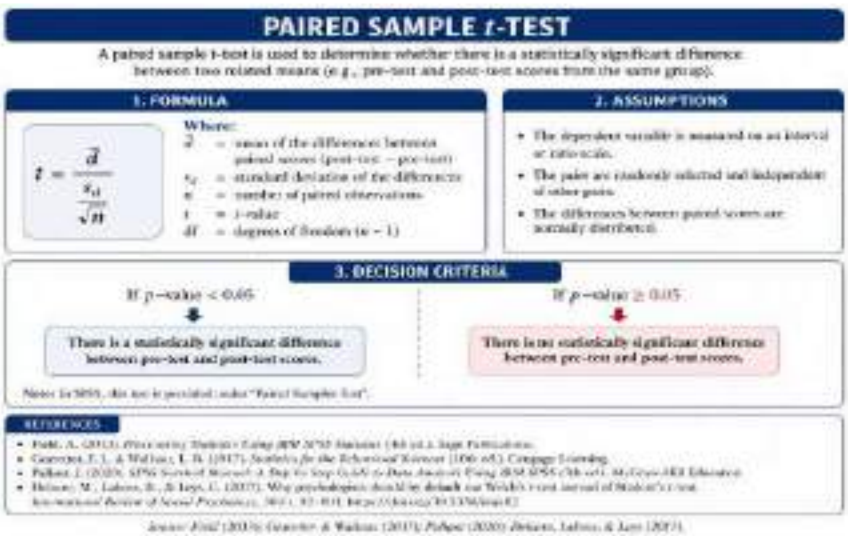

Figure 3. Paired Sampe T-Test

Effect size was calculated using Cohen’s d to assess the magnitude of the intervention effect and to provide a more comprehensive interpretation of the findings. For paired-sample data, Cohen’s d was computed by dividing the mean difference between pretest and posttest scores by the standard deviation of the difference scores. The effect size was interpreted as small ($d < 0.50$), medium ($0.50 \le d < 0.80$), and large ($d \ge 0.80$). In addition, an analysis of each critical thinking dimension—interpretation, analysis, evaluation, inference, explanation, and self-regulation—was conducted to determine which aspects demonstrated the greatest improvement following the intervention. (Cohen, 2013).

Figure 4. Effect Size using Cohen’s d

The magnitude of students’ improvement was calculated using the normalized gain (N-Gain) formula proposed (Hake, 1998):

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Figure 5. Normalized Gain (N-Gain)

The N-gain value represents the proportion of the maximum possible improvement achieved by the students following the intervention. The resulting N-gain scores were classified into three categories: low ($g < 0.30$), moderate ($0.30 \leq g < 0.70$), and high ($g \geq 0.70$).

To provide a clearer conceptual foundation, this study integrates STEAMS, Design Thinking, and Deep Learning into a unified learning framework aimed at fostering students' critical thinking skills. This integration emphasizes interdisciplinary learning, structured problem-solving processes, and meaningful student engagement within sustainability-oriented contexts (Fullan & Quinn, 2020; Razzouk & Shute, 2012; Yakman & Lee, 2012). Prior to data collection, permission was obtained from the school, and informed consent was secured from participants. All data were treated confidentially, and participants' identities were kept anonymous throughout the study. The conceptual framework of this study is illustrated in Figure 6.

Figure 6. Research Implementation Procedure

As shown in Figure 6, STEAMS serves as an interdisciplinary foundation that integrates science, technology, engineering, arts, mathematics, and social context in solving real-world problems (Takeuchi et al., 2020; Yakman & Lee, 2012). This framework is strengthened by the Design Thinking process, which guides students through systematic stages of empathizing, defining problems, generating ideas, developing prototypes, and testing solution (Brown, 2008; Liedtka, 2018; Razzouk & Shute, 2012). Furthermore, Deep Learning principles emphasize authentic engagement, reflective thinking, and knowledge construction, ensuring that students actively participate in meaningful learning experiences (Fullan & Quinn, 2020). The integration of these three approaches is expected to support the development of higher-order thinking skills, particularly critical thinking, within environmental and sustainability-based learning contexts.

The research implementation was systematically organized into six stages. The first

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stage involved preparation through pre-test and learning orientation. The second stage focused on problem identification and analysis, where students explored environmental issues and developed initial understanding. The third stage involved idea generation (ideation), encouraging students to propose creative and eco-friendly solutions.

The fourth stage consisted of prototype development, in which students designed and constructed the Aqua Farming system as a practical solution. The fifth stage involved testing and implementation, allowing students to evaluate the effectiveness of their prototypes through real-world application. Finally, the sixth stage focused on reflection and discussion, where students analyzed their learning processes and outcomes, thereby strengthening their critical thinking and self-regulation skills (Zimmerman, 2002).

Overall, this structured procedure integrates interdisciplinary STEAMS components, systematic problem-solving through Design Thinking, and meaningful engagement through Deep Learning principles.

C. Results and Discussion

1. Results

a. Implementation of the STEAMS Aqua Farming Learning Innovation

The integrated STEAMS-based learning model was implemented through the Aqua Farming Green Innovation Project using the Design Thinking framework, which comprised six stages: empathize, define, ideate, prototype, test, and reflection. The learning process was designed to engage students in addressing authentic environmental challenges through interdisciplinary, inquiry-based, and sustainability-oriented learning activities.

During the empathize stage, students conducted environmental observations in the school garden and investigated organic waste generated by the school lunch catering system. They also viewed educational videos illustrating waste management practices in developed countries and discussed their environmental implications. These activities encouraged students to interpret real-world environmental information, identify relevant issues, and connect new observations with their prior knowledge.

In the define stage, students analyzed the data collected during the observation process and formulated environmental problem statements. Through collaborative discussions, they identified two primary issues: the underutilization of the school garden and the ineffective management of organic food waste. Students then examined the potential of transforming food waste into liquid organic fertilizer and utilizing the garden as a resource for sustainable food production. This stage required students to analyze evidence, evaluate existing conditions, and formulate reasoned conclusions regarding possible solutions.

 *Observation in the school backyard.*	 *Interview with the gardener.*	 *Interview with school chef*
 *Discussion to find out the problems*	 *Watching movie about waste management system.*	 *Define the problem*

Figure 7. Environmental Observation and Problem Identification

Figure 7 illustrates the empathize and define stages of the learning process, during which students explored environmental conditions and identified sustainability-related issues within the school context. During the observation phase, students examined the school backyard and collected information through direct interactions with stakeholders, including interviews with the school gardener and kitchen staff. These activities enabled students to gather authentic data and develop a deeper understanding of real-world environmental challenges, particularly those related to organic waste management.

To broaden their perspectives and deepen their understanding of environmental issues, students also participated in group discussions and viewed educational videos on waste management practices. Through these learning experiences, students collaboratively interpreted information, analyzed evidence, identified key environmental problems, and formulated problem statements grounded in observational data.

Within the STEAMS framework, the Science component was reflected in ecological observations and the exploration of environmental systems, while Technology was incorporated through the use of digital learning media. Social and sustainability dimensions were developed through communication and collaboration with members of

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E-ISSN: 2746-0525

the school community. Collectively, these activities supported the development of students' critical thinking skills, particularly in the dimensions of interpretation and analysis.

The next phase was the ideate stage, during which students collaboratively generated and evaluated potential solutions to the identified environmental problems. Through group discussions, three primary ideas emerged: converting food waste into liquid organic fertilizer, developing a fish cultivation system, and establishing a vegetable garden. These ideas were subsequently integrated into the Aqua Farming Green Innovation Project, which combines aquaculture and plant cultivation within a sustainable environmental system.

The prototype design stage involved students developing visual representations of the proposed Aqua Farming and liquid compost systems. Students created both hand-drawn posters and digital posters using the Canva application. During this process, they explained the scientific principles underlying their designs, communicated their ideas to peers, and justified their design decisions using evidence gathered during the previous stages. These activities encouraged students to articulate explanations, evaluate alternative solutions, and refine their reasoning.

Students were further supported by agricultural practitioners who introduced aquaponic systems and sustainable farming practices. Based on the consultation and subsequent group discussions, students selected catfish as the primary aquaculture species, chose vegetables such as bok choy and cucumbers for cultivation, and designed a liquid compost system using recycled water containers and organic waste materials. This process required students to evaluate the feasibility of different alternatives and make informed decisions based on environmental and practical considerations.

During the prototype construction stage, students built the Aqua Farming system using tarpaulin ponds, PVC pipes, water pumps, and planting media. They also constructed liquid compost systems using recycled gallon containers filled with organic waste, dry leaves, rice-washing water, and microbial solutions. Through these hands-on activities, students observed the interactions among fish, plants, water, and nutrients within the ecosystem. These observations enabled them to infer cause-and-effect relationships, evaluate system performance, and develop a deeper understanding of environmental sustainability.

  *Ideation*	  *Desing the prototype in paper and Canva*	 *Guess teacher from Dinas Pertanian Kabupaten Gresik talk shows about aquaponic.*
 *Develop an Aqua Farming framework*	 *Nursery the plant*	 *Composing liquid composter*

Figure 8. Design and Prototype Development of the Aqua Farming System

Figure 8 illustrates the ideate and prototype stages of the learning process, during which students collaboratively generated ideas and developed initial designs for the Aqua Farming system. During the ideation phase, students explored potential solutions to environmental challenges and translated their ideas into visual representations through both hand-drawn sketches and digital designs using Canva. The learning process was further enriched through a guest session with an agricultural expert from the local agricultural office, who introduced aquaponic concepts and sustainable farming practices. This experience enabled students to refine their ideas, evaluate alternative solutions, and

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strengthen their understanding through authentic, real-world perspectives.

During the prototype stage, students developed the Aqua Farming framework, conducted plant nursery activities, and designed a liquid composting system. These activities demonstrated the integration of multiple STEAMS components. Engineering was reflected in the planning and design of the Aqua Farming and composting systems, Mathematics in measurement, estimation, and proportional reasoning, and Arts in the visual communication of ideas. Science was incorporated through the exploration of plant growth, nutrient cycles, and ecological interactions, while Technology was utilized through digital design tools and learning resources. Collectively, these interdisciplinary experiences supported students in applying knowledge across domains, evaluating design alternatives, and developing creative solutions to environmental problems.

The final phase involved project presentation, testing, and reflection. Students presented their projects through a "window shopping" exhibition format, during which groups shared their findings, exchanged ideas, and received feedback from peers. Reflection activities were facilitated through interactive digital platforms, encouraging students to evaluate both their learning processes and project outcomes. These activities promoted self-regulation, reflective thinking, and evidence-based evaluation, which are essential dimensions of critical thinking. Overall, the implementation of the Aqua Farming Green Innovation Project transformed the classroom into an inquiry-driven learning environment in which students actively constructed knowledge through observation, experimentation, collaboration, presentation, and reflection.

 *Aqua Farming maintenance*	 *Liquid composter maintenance*	 *Sharing and discussing result*
		

Presentation	*Windows shopping*	*Students make an experience story through Gemini AI*
  *Aqua Farming and liquid compester.*	 *Video of implementation.*	  *Gemini AI story book.*

Figure 9. Implementation and Testing of the Aqua Farming System

Figure 9 illustrates the testing and reflection stages of the Aqua Farming Green Innovation Project. During the testing phase, students actively maintained the Aqua Farming and liquid composting systems, observed plant growth, monitored water quality, and evaluated overall system performance. Through these experiences, students analyzed cause-and-effect relationships within ecological systems and assessed the effectiveness of the solutions they had developed.

Students also participated in collaborative discussions to share findings, evaluate outcomes, and propose potential improvements. The learning process was further enriched through project presentations, including a "window shopping" session in which students communicated their project outcomes and received feedback from peers. These experiences strengthened students' abilities to explain their reasoning, evaluate evidence, and justify conclusions, thereby supporting the development of critical thinking skills.

During the reflection stage, students documented their learning experiences by creating digital storytelling products using artificial intelligence tools, such as Gemini AI. These outputs were subsequently presented in the form of digital storybooks and project implementation videos. This stage demonstrated the integration of STEAMS components in multiple ways: Science through the observation and analysis of ecological processes;

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E-ISSN: 2746-0525

Technology through the use of digital tools and AI-assisted storytelling; Engineering through system refinement and improvement; Mathematics through monitoring, measurement, and data interpretation; Arts through creative communication and visual presentation; and Sustainability through students' ongoing engagement with environmental problem-solving and responsible resource management.

Collectively, the testing and reflection stages promoted higher-order thinking by encouraging students to evaluate outcomes, communicate evidence-based explanations, and reflect on their learning processes. These experiences particularly supported the development of evaluation, explanation, and self-regulation skills. Overall, the implementation of the STEAMS Aqua Farming Green Innovation Project created an inquiry-driven learning environment that engaged students in observation, experimentation, collaboration, communication, and reflection, thereby fostering meaningful learning and strengthening their critical thinking skills.

b. Improvement of Students' Critical Thinking Skills

The objective of this study was to evaluate the effectiveness of the integrated STEAMS-based learning model in improving students' critical thinking skills. Critical thinking was assessed using pretest and posttest instruments covering six dimensions: interpretation, analysis, evaluation, inference, explanation, and self-regulation. The results revealed a significant improvement in students' critical thinking performance following participation in the Aqua Farming Green Innovation Project.

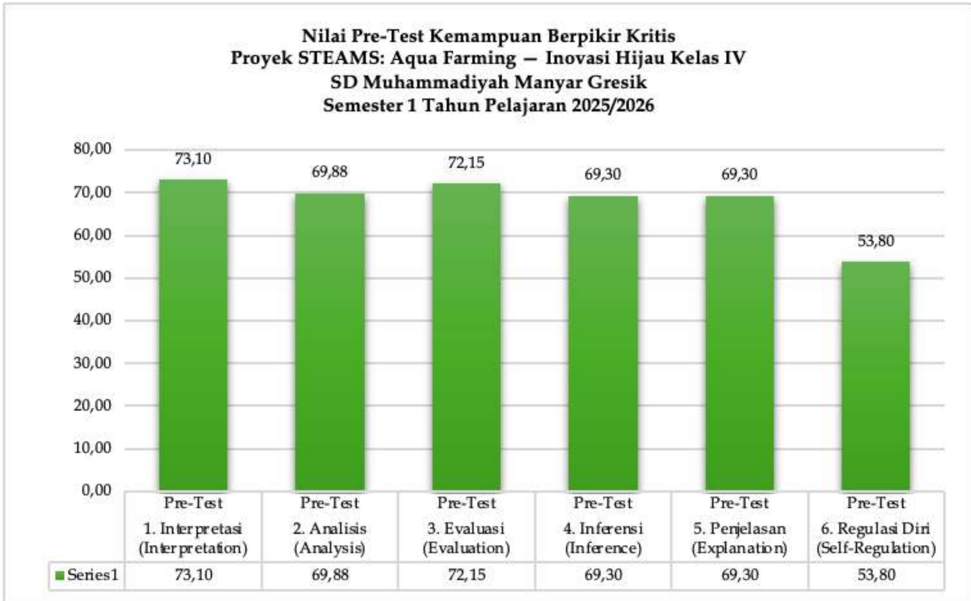

Figure 10. Pre-Test Performance in Critical Thinking Skills

The pretest results indicated that students' initial critical thinking skills were at a moderate level across all measured dimensions. The overall mean score was 66.72, suggesting that students had not yet fully developed higher-order thinking skills prior to the intervention.

At the dimensional level, the highest mean score was observed for interpretation (73.10), followed by evaluation (72.15). Analysis (69.88), inference (69.30), and explanation (69.30) demonstrated comparable levels of performance, indicating that students possessed a basic capacity to process and interpret information but had not yet developed more advanced reasoning skills. In contrast, self-regulation recorded the lowest mean score (53.80), suggesting limitations in students' ability to monitor, evaluate, and reflect upon their own thinking processes.

Overall, these findings indicate that while students were generally able to understand and respond to information, their capacity to critically evaluate evidence, draw well-reasoned conclusions, and regulate their thinking remained underdeveloped. This baseline profile highlights the need for instructional approaches that promote deeper cognitive engagement, reflective thinking, and structured problem-solving experiences to support the development of critical thinking skills. Therefore, an instructional intervention is needed to improve students' critical thinking skills through meaningful and structured

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learning experiences.

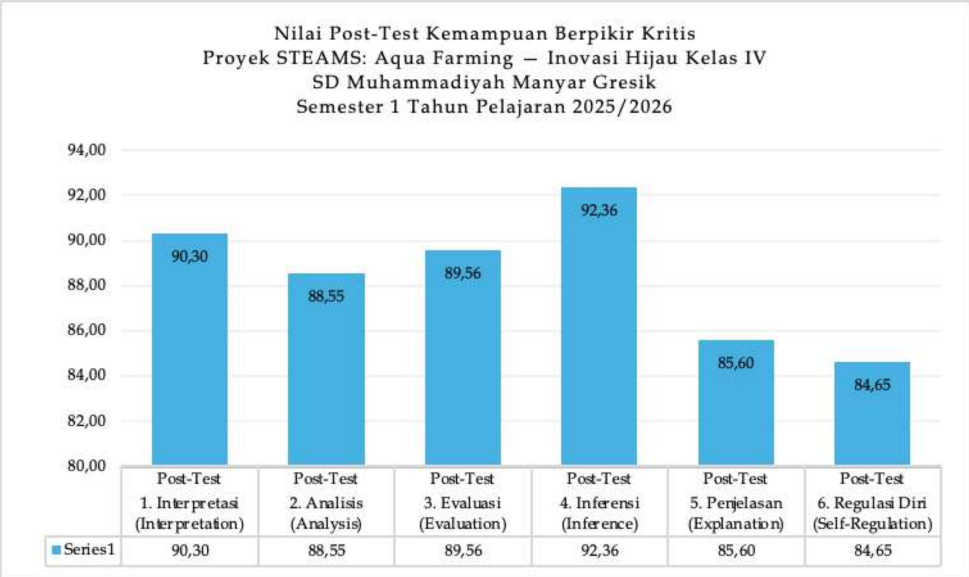

Figure 11. Post-Test Performance in Critical Thinking Skills

The posttest results indicated a substantial improvement in students' critical thinking skills following the implementation of the integrated STEAMS-based learning model. The overall mean score increased to 88.64, suggesting a marked enhancement in students' critical thinking performance after the intervention.

At the dimensional level, all critical thinking dimensions demonstrated notable improvement. The highest mean score was observed for inference (92.36), followed by interpretation (90.30) and evaluation (89.56), indicating that students were increasingly able to draw logical conclusions, interpret information accurately, and evaluate evidence effectively. The analysis dimension also showed a substantial increase to 88.55, reflecting an improved ability to examine, organize, and interpret information systematically.

The explanation (85.60) and self-regulation (84.65) dimensions likewise demonstrated considerable improvement, although their mean scores remained slightly lower than those of the other dimensions. This finding suggests that, while students became more capable of articulating their reasoning and reflecting on their thinking processes, these metacognitive aspects of critical thinking may require continued development through sustained learning experiences.

Overall, the posttest findings indicate that the integrated STEAMS-based learning model effectively supported the development of students' critical thinking skills across all measured dimensions, with particularly strong gains observed in inference, interpretation, and analysis.

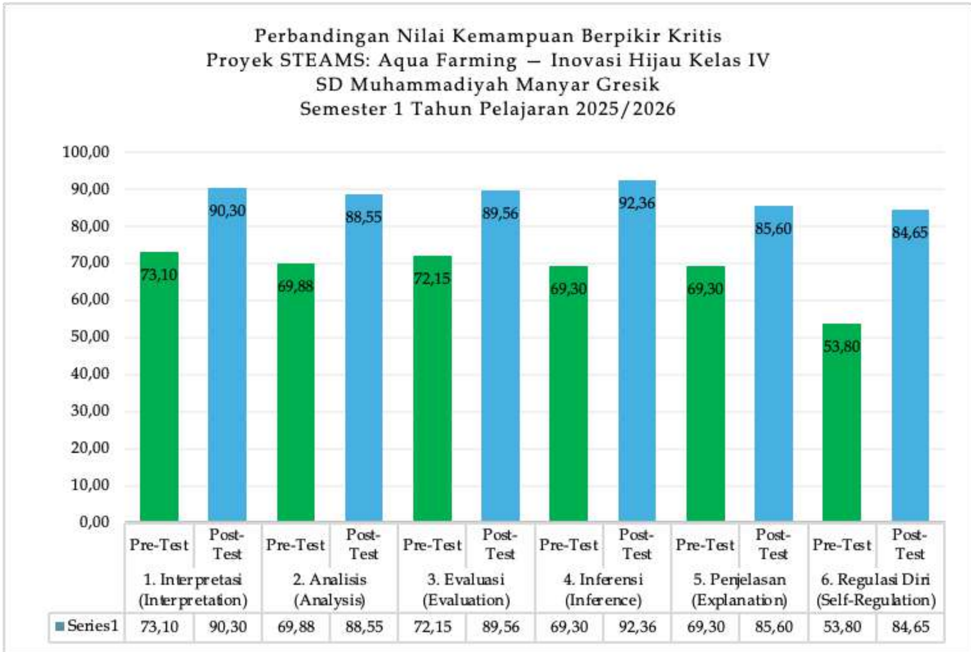

Figure 12. Improvement of Students' Critical Thinking Scores Before and After Learning Implementation

Table 1. Mean Score of Pre-Test and Post-Test

Assessment	Mean Score
Pre-test	66.72
Post-test	88.64
Score Increase	21.92
Percentage Increase	32.85%

Source: Author's Data Analysis, 2026

Table 2. Comparison of Pre-Test and Post-Test Scores of Critical Thinking Skills

Indicator	Pre-Test	Post-Test	Gain
Interpretation	73.10	90.30	17.20
Analysis	69.88	88.55	18.67
Evaluation	72.15	89.56	17.41
Inference	69.30	92.36	23.06
Explanation	69.30	85.60	16.30
Self-Regulation	53.80	84.65	30.85

Source: Author's Data Analysis, 2026

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E-ISSN: 2746-0525

A comparison of pretest and posttest scores across all critical thinking dimensions revealed consistent and substantial improvement following the implementation of the integrated STEAMS-based learning model. All six dimensions—interpretation, analysis, evaluation, inference, explanation, and self-regulation—showed positive gains, indicating that the intervention contributed to the enhancement of students' higher-order thinking skills.

Among the dimensions, the greatest improvement was observed in self-regulation, with a gain of 30.85 points, suggesting a marked increase in students' ability to monitor, evaluate, and reflect upon their own thinking processes. This was followed by inference (23.06), indicating substantial progress in students' ability to draw logical conclusions based on available evidence.

Analysis (18.67), evaluation (17.41), and interpretation (17.20) also demonstrated considerable gains, reflecting improvements in students' ability to examine information, assess arguments, and construct meaning from evidence. Although explanation recorded the smallest gain (16.30), the increase nevertheless indicates meaningful progress in students' ability to communicate and justify their reasoning.

Overall, these findings suggest that the integrated STEAMS-based learning model supported not only the development of cognitive aspects of critical thinking but also metacognitive dimensions, particularly self-regulation and reflective thinking.

Table 3. Test of Normality

Tests of Normality						
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pretest	.089	79	.188	.971	79	.065
Posttest	.093	79	.088	.980	79	.244

a. Lilliefors Significance Correction

The normality of the data was assessed using the Kolmogorov–Smirnov test. The results indicated that the significance values for both the pretest (p = .188) and posttest (p = .088) exceeded the threshold of .05. Therefore, the assumption of normality was satisfied, indicating that both datasets were normally distributed.

Based on these results, a paired-samples t-test was performed to examine whether a significant difference existed between the pretest and posttest scores. The analysis revealed a statistically significant difference between the two measurements ($p < .05$), indicating that students' critical thinking performance improved significantly following the implementation of the integrated STEAMS-based learning model.

Table 4. Paired Sample Test

Paired Samples Test									
		Paired Differences							
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Pretest - Posttest	-20.91772	8.34384	.93876	-22.78664	-19.04880	-22.282	78	.000

A paired sample t-test was conducted to examine the difference between pre-test and post-test scores. The results revealed a statistically significant difference ($t (78) = -22.282$, $p < 0.05$). The mean difference was -20.92, indicating that the post-test scores were significantly higher than the pre-test scores. Furthermore, the 95% confidence interval [-22.79, -19.05] did not include zero, confirming the significance of the difference. These findings indicate that the implemented learning model had a significant effect on improving students' critical thinking skills.

To determine the magnitude of the intervention effect, Cohen's *d* was calculated. Based on the paired samples t-test output:

1. Mean difference (Pretest − Posttest) = -20.91772
2. Standard deviation of the differences = 8.34384

Since this is a pretest–posttest design, Cohen's d is calculated using:

$$d = \frac{\text{Mean Difference}}{\text{Standard Deviation of Differences}}$$

Step-by-step calculation

d = <u>20.917728.34384</u>

8.3438420.91772

d ≈ 2.506 ≈ 2.51

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d = 2.51 indicates a large effect size, meaning the intervention had a strong practical impact on students' outcomes. The effect size was calculated using Cohen's d based on the mean difference and standard deviation of the paired differences. The result showed a large effect (d = 2.51), indicating that the intervention had a strong practical impact on students' learning outcomes beyond statistical significance.

To further measure learning effectiveness, the normalized gain (N-Gain) analysis was conducted. The results are presented in Table 3. The mean N-Gain score was 0.63, which falls within the moderate category. This indicates that the learning intervention produced a meaningful improvement in students' critical thinking abilities. The increase in scores suggests that interdisciplinary learning combined with structured problem-solving processes effectively supports higher-order thinking development.

To further measure learning effectiveness, the normalized gain (N-Gain) analysis was conducted.

Table 5. Normalized Gain Analysis of Students' Critical Thinking Skills

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Ngain	79	.17	1.00	.6272	.16864
Valid N (listwise)	79				

Source: Author's Data Analysis, 2026

The N-gain value of 0.63 falls within the moderate category, indicating that the intervention resulted in a meaningful improvement in students' critical thinking skills. This finding suggests that interdisciplinary learning experiences combined with structured problem-solving processes can support the development of higher-order thinking skills in elementary school settings.

Overall, the results indicate that the integrated STEAMS-based learning model contributed positively to the development of students' critical thinking skills across all measured dimensions. This interpretation is supported by multiple lines of evidence, including the moderate N-gain score, the paired-samples t-test demonstrating a statistically significant difference between pretest and posttest scores ($p < .05$), and the large effect size. Collectively, these findings suggest that the observed improvement was not only statistically significant but also educationally meaningful.

2. Discussion

a. Improvement of students' critical thinking skills through STEAMS integration

The findings of this study demonstrate that the integration of STEAMS, Design Thinking, and Deep Learning within the Aqua Farming Green Innovation Project significantly improved elementary students' critical thinking skills. Quantitative results showed that the mean score increased from 66.72 on the pretest to 88.64 on the posttest, representing an improvement of 21.92 points (32.85%), with an N-gain score of 0.63, which falls within the moderate category. These findings suggest that the instructional innovation effectively supported the development of higher-order thinking skills among elementary students.

The observed improvements across the dimensions of interpretation, analysis, evaluation, inference, explanation, and self-regulation indicate that students not only acquired conceptual knowledge but also developed more structured reasoning processes. Notably, the greatest gain was observed in self-regulation, suggesting that students became more capable of monitoring, evaluating, and reflecting on their own thinking. This finding is particularly important because self-regulation is a key component of critical thinking and metacognitive development, enabling learners to manage and refine their cognitive processes during problem-solving and decision-making (Zimmerman, 2002). These findings are consistent with the critical thinking framework proposed by Facione, which conceptualizes critical thinking as a set of interconnected cognitive skills, including interpretation, analysis, evaluation, inference, explanation, and self-regulation (2015). The observed improvements across these dimensions suggest that students developed not only stronger reasoning abilities but also greater capacity to monitor and regulate their own thinking processes. This interpretation is further supported by research emphasizing that critical thinking involves the active evaluation of evidence, logical reasoning, and reflective judgment in problem-solving contexts (Facione, 2011; Halpern, 2013).

The findings of this study also align with Ennis's (2011), who describes it as reflective and reasonable thinking focused on deciding what to believe or do (Ennis, 2011). conception of critical thinking as reflective and reasonable thinking directed toward deciding what to believe or how to act. Through the STEAMS Aqua Farming Green Innovation Project, students were actively engaged in authentic problem-solving experiences that required them to observe environmental conditions, analyze waste management challenges, design aquaponic systems, and evaluate the effectiveness of their proposed

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E-ISSN: 2746-0525

solutions. These learning experiences provided meaningful opportunities for students to apply reasoning skills in real-world contexts, thereby fostering the development of critical thinking through evidence-based inquiry, decision-making, and reflection.

From a constructivist perspective, the observed improvement in students' critical thinking skills can be explained by Bruner's discovery learning theory, which posits that knowledge is actively constructed through engagement with meaningful problems and direct experiences (Myers, 2021). In the Aqua Farming Green Innovation Project, students constructed knowledge through observation, experimentation, collaborative discussion, and reflective evaluation. These learning experiences enabled them to connect theoretical concepts with authentic environmental challenges, thereby fostering deeper understanding and more sophisticated reasoning processes.

The findings also align with principles of reflective learning, which emphasize that learners construct meaning by critically examining their experiences and reflecting on the outcomes of their actions (Brookfield, 2013). Through continuous reflection during the Design Thinking process, students were encouraged to evaluate their decisions, reconsider alternative solutions, and refine their understanding. Such experiences likely contributed to the development of both critical thinking and self-regulation skills observed in this study.

Furthermore, interdisciplinary learning through STEAMS has been widely recognized as an effective approach for fostering higher-order thinking skills. According to Yakman and Lee (2019), STEAMS integration allows students to connect scientific reasoning with technological creativity, engineering design, artistic expression, mathematical analysis, and social context. Such interdisciplinary engagement helps students develop deeper conceptual understanding and enhances their ability to analyze complex problems (Moore et al., 2014).

The magnitude of the intervention effect was examined using Cohen's d. The analysis revealed a large effect size ($d = 2.51$), indicating that the integrated STEAMS learning model had a substantial practical impact on students' critical thinking development. According to Cohen's (1988) criteria, this value exceeds the threshold for a large effect, suggesting that the improvement observed in students' scores is not only statistically significant but also educationally meaningful.

The moderate N-gain score obtained in this study suggests that, although the learning intervention substantially improved students' critical thinking skills, the development of higher-order thinking remains a gradual process that requires continuous instructional support and sustained learning experiences. Critical thinking is a complex cognitive competency that develops progressively through repeated opportunities for inquiry, reflection, and problem-solving.

This finding is consistent with previous studies reporting that project-based and interdisciplinary learning approaches contribute to meaningful, yet incremental, improvements in higher-order thinking skills (Margot & Kettler, 2019; Thibaut et al., 2018). While the N-gain score indicates a moderate level of improvement, the very large effect size ($d = 2.51$) suggests that the intervention had a substantial educational impact on students' critical thinking performance. Taken together, these findings indicate that the integrated STEAMS-based learning model not only facilitated measurable learning gains but also produced a practically significant improvement in students' critical thinking skills.

The results of inferential analysis indicated a statistically significant improvement in students' critical thinking skills ($p < 0.001$). In addition, the N-Gain score of 0.63 suggests a moderate level of learning improvement, indicating a meaningful but gradual development of students' abilities. More importantly, the effect size analysis revealed a large effect ($d = 2.51$), demonstrating that the STEAMS-based learning intervention had a strong practical impact on students' critical thinking development. These findings confirm that the improvement is not only statistically significant, but also educationally substantial. Therefore, the findings confirm that the integration of STEAMS learning with structured problem-solving processes can serve as an effective strategy to strengthen critical thinking in elementary education.

b. The role of design thinking and deep learning in supporting critical reasoning

The findings of this study also underscore the important role of Design Thinking and Deep Learning principles in facilitating students' critical thinking development. The learning process was structured around the Design Thinking phases of empathize, define, ideate, prototype, test, and reflection, providing students with a systematic framework for analyzing environmental challenges and developing innovative solutions.

The empathize and define phases enabled students to investigate environmental conditions within the school context and identify issues related to organic waste management and the underutilization of available land. Through observation, data collection, and problem identification, students developed their interpretation and analysis

P-ISSN: 2580-006X
E-ISSN: 2746-0525

skills by examining information and recognizing key issues that required intervention.

The ideate and prototype phases encouraged students to generate, evaluate, and refine potential solutions through the design of the Aqua Farming system. During these phases, students engaged in inference and evaluation processes as they compared alternative ideas, justified design decisions, and anticipated the potential effectiveness of their proposed solutions.

Finally, the test and reflection phases provided opportunities for students to assess the performance of their prototypes and critically reflect on their learning experiences. These activities supported the development of explanation and self-regulation skills by encouraging students to articulate their reasoning, evaluate outcomes, and monitor their own understanding. Collectively, these findings suggest that the structured problem-solving processes embedded within Design Thinking contributed substantially to the improvement of students' critical thinking skills.

This structured thinking process aligns with the theoretical perspective of Design Thinking as a problem-solving framework that promotes creativity, analytical reasoning, and iterative learning (Razzouk & Shute, 2012). Design Thinking encourages learners to move beyond passive knowledge acquisition and engage in active inquiry and experimentation. The implementation of Deep Learning principles facilitated meaningful learning experiences by encouraging students to explore concepts deeply, connect ideas across disciplines, and reflect on their learning outcomes. According to Fullan, Quinn, and McEachen (2018), deep learning occurs when students develop competencies such as critical thinking, creativity, collaboration, communication, and character through authentic learning tasks (Fullan & Quinn, 2020).

The integration of Design Thinking and Deep Learning in this study therefore provided a structured cognitive pathway that supported students' critical reasoning development. Rather than focusing solely on knowledge transmission, the learning process emphasized inquiry, experimentation, and reflective thinking. These findings support previous research indicating that project-based and design-oriented learning environments can significantly enhance higher-order thinking skills in STEM and STEAM education (Henriksen et al., 2016; F. Zhao & Schuchardt, 2021).

c. Limitations and future research

Despite its contributions, this study has several limitations that should be acknowledged. First, the research was conducted within a single elementary school setting, which may limit the generalizability of the findings to other educational contexts with different student characteristics, institutional conditions, or learning environments. Consequently, caution should be exercised when interpreting and extending the findings beyond the context of this study.

Second, the study focused primarily on the development of students' critical thinking skills. Although the integrated STEAMS-based learning model was designed to support a range of 21st-century competencies, other important outcomes, such as creativity, collaboration, communication, and digital literacy, were not quantitatively assessed. As a result, the broader educational impact of the intervention remains to be fully explored.

Future research is therefore recommended to examine the implementation of this instructional model across diverse educational settings and larger participant populations. Further studies could also investigate its effectiveness in fostering multiple 21st-century competencies and explore the long-term sustainability of learning outcomes. Such research would provide a more comprehensive understanding of the potential of integrated STEAMS, Design Thinking, and Deep Learning approaches in elementary education.

D. Conclusion

This study examined the effectiveness of an integrated STEAMS-based learning model combined with Design Thinking and Deep Learning in enhancing elementary students' critical thinking skills through the Aqua Farming Green Innovation Project. The findings revealed significant improvements in students' critical thinking performance, as evidenced by higher posttest scores, a moderate N-gain score, and a very large effect size. Improvements were observed across all dimensions of critical thinking, including interpretation, analysis, evaluation, inference, explanation, and self-regulation, with particularly strong gains in self-regulation and inference.

These findings suggest that integrating STEAMS, Design Thinking, and Deep Learning within a contextual environmental project provides an effective framework for fostering both cognitive and metacognitive aspects of critical thinking. By engaging students in authentic problem-solving, interdisciplinary inquiry, collaboration, and reflection, the learning model created meaningful opportunities for the development

P-ISSN: 2580-006X
E-ISSN: 2746-0525

of higher-order thinking skills in elementary education.

Future research is encouraged to investigate the long-term effects of this instructional approach, examine its applicability across diverse educational contexts, and explore its impact on other 21st-century competencies. Overall, the study highlights the potential of integrated STEAMS learning as a meaningful, contextual, and sustainability-oriented approach to strengthening critical thinking skills among elementary school students.

Policy Recommendations

Based on the findings of this study, several practical recommendations can be proposed. First, elementary school teachers are encouraged to implement STEAMS-based project learning integrated with structured problem-solving processes, as the results indicate significant improvements in students' critical thinking performance. Particular attention should be given to learning activities that foster inference and self-regulation, as these dimensions demonstrated the greatest gains following the intervention.

Second, schools are encouraged to create learning environments that support contextual, interdisciplinary, and sustainability-oriented learning experiences. Environmental projects and community-based initiatives can provide authentic opportunities for students to engage with real-world challenges while applying knowledge across multiple disciplines.

Third, educational policymakers and curriculum developers should consider incorporating STEAMS, Design Thinking, and Deep Learning principles into curriculum frameworks, teacher professional development programs, and instructional guidelines. Such support may facilitate more consistent implementation of innovative pedagogical practices that promote higher-order thinking and meaningful learning.

Future research should examine the long-term effects of integrated STEAMS-based learning, explore its implementation across diverse educational settings and subject areas, and employ more rigorous experimental designs to strengthen causal interpretations. In addition, future studies may investigate the influence of this approach on other key 21st-century competencies, including creativity, collaboration, communication, and digital literacy.

Overall, the findings highlight the potential of integrating STEAMS, Design Thinking, and Deep Learning as a comprehensive pedagogical framework for promoting meaningful, contextual, and sustainability-oriented learning. By engaging students in authentic inquiry, interdisciplinary problem-solving, and reflective practice, this approach can contribute to the development of critical thinking and other essential competencies required for navigating the complex challenges of the twenty-first century.

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Attachment

1. Student Activity Project STEAMS Sekolah Ramah Iklim

Link: https://teacherfiya.my.canva.site/steams-aqua-farming
2. Modul Pembelajaran Mendalam STEAMS Sekolah Ramah Iklim

Link:https://drive.google.com/file/d/1rnsBSpi8EdssmssC-s3spDGv1g8tMDsG/view?usp=sharing
3. Innovation STEAMS Implementation Video

Link: https://youtu.be/oNmLqPT98wg?si=uFG0C8uw2iyq-3mi