



STEM-Based Learning Design: Enhancing Students' Scientific and Engineering Literacy through a Green Refrigerant Box in Elementary Schools

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ABSTRACT

Purpose -This study aims to explore how a STEM-based learning design integrated with the engineering design process in enhancing elementary school students' scientific and engineering literacy through the Green Refrigerant Box innovation in elementary schools.

Methodology - A mixed-methods sequential explanatory design was employed. The quantitative phase used a quasi-experimental non-equivalent control group design involving 122 fifth-grade students from four elementary schools. The experimental group received STEM-based learning integrated with the engineering design process, while the control group followed regular instruction without STEM-based learning. Data were collected using scientific and engineering literacy tests and analyzed using N-gain and ANCOVA, with effect sizes reported using partial eta squared (η^2_p). The qualitative phase involved observations, interviews, and documentation, analyzed through thematic analysis to support the quantitative results.

Findings - The experimental group showed higher improvement in scientific literacy (N-gain = 0.63, moderate-high) than the control group (0.36, moderate), with a significant effect ($F = 58.72, p < 0.001, \eta^2_p = 0.33$). Engineering literacy also improved more in the experimental group (0.55, moderate) compared to the control group (0.27, low-moderate), with a significant effect ($F = 46.35, p < 0.001, \eta^2_p = 0.28$). Qualitative findings revealed shifts toward mechanistic reasoning, improved data interpretation, and stronger connections between scientific concepts and real-world contexts, along with more systematic design thinking

Contribution - This study highlights the complementary relationship between scientific and engineering literacy, where science informs design decisions and engineering reinforces conceptual understanding, and offers empirical insights into STEM-based learning in elementary education.

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INTRODUCTION

Scientific literacy and engineering literacy are essential competencies in 21st-century education, playing a crucial role in preparing students to understand scientific phenomena and develop problem-solving skills through scientific and engineering approaches. Scientific literacy is no longer limited to conceptual knowledge; it encompasses critical thinking, data interpretation, and the ability to apply knowledge in real-world contexts (Bybee, 2020; National Academies of Sciences and Medicine, 2021; Tang et al., 2021). At the elementary level, strengthening these literacies serves as a foundational step in equipping students to face global challenges driven by science and technology.

In a global context, these challenges are becoming increasingly complex due to climate change and environmental crises. Primary education provides a strategic space to foster sustainability awareness from an early age through the development of green skills and environmental literacy (UNESCO., 2021). Integrating science, technology, and environmental issues has been shown to promote both scientific understanding and ecological responsibility among students (Anderson & Lee, 2022). Therefore, science education should not only emphasize cognitive outcomes but also cultivate ecological awareness and systems thinking.

However, international studies indicate that students' scientific literacy, particularly at the primary level, remains relatively low and insufficient in fostering higher-order thinking skills. Students often struggle to connect abstract concepts with real-world phenomena and tend to have limited engagement in meaningful scientific inquiry (Ergazaki & Zogza, 2021; Liu et al., 2022; OECD., 2019). This condition suggests that traditional instructional approaches remain dominant and have not fully supported the comprehensive development of literacy competencies.

In response, STEM (Science, Technology, Engineering, and Mathematics) education has emerged as an integrative paradigm that emphasizes interdisciplinary connections and the application of knowledge in authentic contexts. STEM-based learning encourages students to actively engage in inquiry, experimentation, and engineering design as part of solving real-world problems (Honey et al., 2020; Margot & Kettler, 2019; Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, 2021). Previous studies have demonstrated that STEM implementation can significantly enhance scientific literacy, critical thinking, creativity, and problem-solving skills (Anwar et al., 2022; Park et al., 2020; Yacoubian, 2021).

Furthermore, the effectiveness of STEM-based learning is strongly influenced by contextual and experience-based instructional design. Approaches such as project-based learning and the engineering design process have been shown to increase student engagement and strengthen conceptual understanding through authentic learning experiences (English, 2021; Kelley & Knowles, 2016; Moore et al., 2020). Active involvement in hands-on and minds-on activities is essential for connecting scientific concepts with real-world applications, particularly in the context of energy and environmental issues (Hsu et al., 2021; Schnittka, 2020).

Aligned with these developments, the global shift toward green education has encouraged the integration of sustainability issues into STEM-based learning. Approaches such as eco-STEM and green project-based learning have proven effective in enhancing environmental awareness, engineering design skills, and contextual understanding of energy concepts (Carter et al., 2021; Cheng et al., 2022; Wu et al., 2022). However, implementation at the elementary level remains limited, particularly in developing instructional innovations that go beyond conceptual understanding and actively engage students in authentic engineering practices.

Although numerous studies have highlighted the benefits of STEM-based learning in improving scientific literacy, most have focused on general STEM implementation or the use of conventional and digital learning media, with limited integration of sustainability contexts and authentic engineering practices (Cheng et al., 2022; Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, 2021; Wu et al., 2022). Moreover, research at the elementary level remains limited in developing instructional designs that simultaneously integrate scientific and engineering literacy through innovative products that support students' design and experimentation activities. This indicates a gap in the development of contextual, experience-based STEM-based learning designs that transform abstract concepts of energy efficiency and environmentally sustainable technology into tangible and developmentally appropriate engineering experiences for elementary school students.

To address this gap, this study proposes a STEM-based learning design integrated with the Green Refrigerant Box, an innovative hands-on learning product that combines engineering practice and sustainability. The Green Refrigerant Box enables students to manipulate physical materials and engage directly in design and experimentation activities, thereby simplifying complex concepts such as heat transfer, energy efficiency, and environmentally friendly refrigeration into meaningful learning experiences appropriate for elementary school students. Through this integration, students are expected not only to develop conceptual understanding but also to actively participate in engineering processes, thereby supporting the development of both scientific and engineering literacy at the elementary level.

METHODOLOGY

Research Design

This study employed a mixed-methods approach using a sequential explanatory design to obtain a comprehensive understanding of STEM learning integrated with the Green Refrigerant Box. The quantitative phase was conducted first using a quasi-experimental non-equivalent control group design to examine differences in learning outcomes, followed by a qualitative phase aimed at explaining and enriching the quantitative findings. This design was chosen to provide both statistical evidence and in-depth insights into students' learning processes.

The STEM learning intervention was designed based on the engineering design process (EDP) to facilitate active, inquiry-based, and design-oriented learning. Through this approach, students were engaged in solving real-world problems related to energy use and environmental sustainability by developing a Green Refrigerant Box as a contextual engineering product. The learning activities guided students through iterative stages, including problem identification, investigation, idea generation, solution design, prototyping, testing and evaluation, redesign, and communication.

During the implementation, students worked collaboratively to explore issues related to energy consumption, environmental impact, and sustainable technology. They designed and constructed a prototype of the Green Refrigerant Box using accessible and environmentally friendly materials, tested its performance in maintaining temperature stability, and evaluated its effectiveness in preserving perishable items. The iterative nature of the EDP enabled students to refine their designs based on evidence and feedback, thereby fostering both conceptual understanding and engineering thinking.

The detailed stages of the engineering design process and corresponding student activities implemented in this study are presented in Table 1.

Table 1. Implementation of the Engineering Design Process in STEM Learning

Stage	Activities
Problem Identification	<ol style="list-style-type: none"> 1) Discuss the increasing demand for energy due to population growth and human needs. 2) Identify that electricity generation in Indonesia is still dominated by fossil fuels. 3) Analyze the environmental impacts of fossil fuel use, including carbon emissions, greenhouse effects, and climate change. 4) Emphasize the importance of energy-saving behaviors and the use of environmentally friendly technologies.
Problem Investigation	<ol style="list-style-type: none"> 1) Discuss commonly used technologies that rely on electrical energy in daily life. 2) Examine the positive and negative impacts of these technologies, such as refrigerators producing CFC gases that contribute to ozone depletion. 3) Explore concepts of energy-efficient and environmentally friendly technologies. 4) Gather information from various sources on sustainable solutions, particularly related to the Green Refrigerant Box.
Idea Generation	<ol style="list-style-type: none"> 1) Generate and record possible solution ideas based on gathered information. 2) Analyze and discuss the required materials and tools for designing a prototype, considering energy efficiency, environmental sustainability, aesthetics, and functionality.

Stage	Activities
Solution Design	<ol style="list-style-type: none"> 1) Develop a detailed plan and timeline for constructing the Green Refrigerant Box. 2) Create design sketches, including the names and functions of each component. 3) Assign a creative name to the product. 4) Select appropriate materials and tools. 5) Determine the size and quantity of materials needed.
Prototyping	<ol style="list-style-type: none"> 1) Prepare the required tools and materials. 2) Assemble components according to the planned design. 3) Construct the Green Refrigerant Box and test its functionality by storing fruits and vegetables while measuring temperature using a thermometer.
Testing and Evaluation	<ol style="list-style-type: none"> 1) Measure and record the temperature of the box and room over three days (morning, afternoon, evening). 2) Analyze temperature stability and changes over time. 3) Evaluate product performance by comparing the freshness of stored items with those kept at room temperature. 4) Receive feedback from the teacher and peers for improvement.
Redesign	<ol style="list-style-type: none"> 1) Revise and improve the prototype based on evaluation results and feedback. 2) Optimize product performance through further testing.
Communication	<ol style="list-style-type: none"> 1) Students present their Green Refrigerant Box in groups, with teacher guidance through structured questions, including: <ol style="list-style-type: none"> a) What is the title of your modified product? b) What materials and tools were used, and why were they selected? c) What modifications were made during the design process? d) How was the product constructed? e) How does the product work? f) How effective is the product (e.g., temperature achieved, duration of temperature stability)? g) How long can the product maintain the freshness of fruits and vegetables? h) What challenges were encountered and how were they addressed? i) What values or lessons were gained from the activity? 2) The teacher provides feedback on the presentations and facilitates discussion to evaluate whether the product requires further improvement. 3) Students participate in a product exhibition to share their work, receive feedback from a wider audience, and communicate their ideas and findings.

Participant

The study was conducted in four elementary schools in Madiun, Indonesia, selected through cluster purposive sampling based on school readiness for STEM implementation, curriculum consistency, and contextual representation. Two schools were assigned to the experimental group and two to the control group. Each school contributed one fifth-grade class, resulting in a total of 122 students aged 10–11 years. The experimental group participated in STEM learning based on the engineering design process using the Green Refrigerant Box, while the control group followed regular instruction aligned with the existing curriculum without STEM integration. Both groups received equivalent learning content, duration, and difficulty levels to minimize treatment bias.

Data Collection

Data were collected in two sequential phases aligned with the mixed-methods design. In the quantitative phase, pretest and posttest assessments were administered to measure students' scientific and engineering literacy before and after the intervention. The implementation was conducted over several instructional sessions, during which the experimental group engaged in STEM learning based on the engineering design process using the Green Refrigerant Box, while the control group followed regular instruction without STEM integration.

To ensure consistency, both groups received equivalent learning content, instructional time, and difficulty levels. The pretest was administered prior to the intervention to establish baseline equivalence, while the posttest was conducted after the completion of the learning activities to measure learning gains. In the qualitative phase, data were collected through classroom observations, semi-structured interviews, and documentation. Observations were conducted throughout the implementation to capture students' engagement and participation in each stage of the engineering design process. Semi-structured interviews were conducted with twelve students purposively selected from the experimental group, with three students from each participating school representing high, medium, and low levels of achievement, to explore their learning experiences, reasoning processes, and perceptions of STEM learning. Documentation, including field notes, photographs, and students' artifacts, was used to support and triangulate the findings.

Instrument

Scientific literacy was measured based on internationally recognized frameworks, including the ability to explain scientific phenomena, evaluate and design investigations, and interpret data and evidence (Bybee, 2020; OECD, 2023; Tang et al., 2021). Engineering literacy was assessed according to the stages of the engineering design process, including problem identification, solution design, implementation, and evaluation (English, 2021; Moore et al., 2020).

The quantitative instrument consisted of 35 items combining reasoned multiple-choice and open-ended questions, designed contextually around heat transfer and energy efficiency concepts. In addition, a product assessment rubric (scale 1–4) was used to evaluate the Green Refrigerant Box based on design quality, functionality, application of scientific concepts, and environmental sustainability.

Qualitative instruments included observation sheets, interview guidelines, and documentation records. Instrument validity was established using Aiken's *V* with expert judgment, while reliability was tested using Cronbach's Alpha (≥ 0.70), indicating acceptable internal consistency.

Data Analysis

Quantitative data were analyzed using normalized gain (N-gain) and Analysis of Covariance (ANCOVA). N-gain was calculated to determine the extent of students' improvement in scientific and engineering literacy between pretest and posttest scores. The results were interpreted using standard gain categories (low, moderate, and high). ANCOVA was conducted to examine differences between the experimental and control groups while controlling for pretest scores. Prior to analysis, assumptions of normality and homogeneity were tested. Effect size was calculated using partial eta squared (η^2_p) to determine the magnitude of the intervention effect. Qualitative data were analyzed using thematic analysis following Braun and Clarke's framework, including data familiarization, initial coding, theme development, review, and definition. An inductive approach was applied to identify patterns emerging from students' experiences (Braun & Clarke, 2006).

Integration of quantitative and qualitative data was conducted at the interpretation stage using an explanation-building strategy, linking statistical results with qualitative insights. Data trustworthiness was ensured through credibility, dependability, and confirmability, supported by triangulation, member checking, and consistent documentation procedures.

FINDINGS

The findings of this study were derived from both quantitative and qualitative analyses to provide a comprehensive understanding of the impact of STEM learning based on the engineering design process on students' scientific and engineering literacy. Quantitative data were used to examine differences in learning outcomes between the experimental and control groups, while qualitative data offered deeper insights into students' thinking processes, engagement, and classroom dynamics during the implementation.

The presentation of the findings begins with the quantitative results, followed by the qualitative findings, and concludes with the integration of both data sets to provide a more holistic interpretation of the phenomenon under investigation.

Quantitative Data

Tabel 2. Comparison of Scientific Literacy and Engineering Literacy Scores

Variable	Group	Pretest (Mean ± SD)	Posttest (Mean ± SD)	N-Gain	Category
Literasi Sains	Experimental	53.94 ± 6.85	82.81 ± 5.92	0.63	Moderate-High
	Control	53.49 ± 6.70	70.03 ± 6.45	0.36	Moderate
Engineering Literacy	Experimental	60.12 ± 7.10	82.28 ± 5.75	0.55	Moderate
	Control	59.85 ± 6.95	70.59 ± 6.20	0.27	Low-Moderate

Based on Table 2, both groups demonstrated relatively comparable initial abilities in both scientific literacy and engineering literacy, as indicated by similar pretest scores. Following the intervention, improvements were observed in both variables across the two groups; however, the experimental group exhibited a more substantial increase compared to the control group.

In terms of scientific literacy, the experimental group improved from 53.94 to 82.81, with an N-gain of 0.63, categorized as moderate-high. In contrast, the control group showed a smaller increase from 53.49 to 70.03, with an N-gain of 0.36 (moderate). A similar pattern was observed in engineering literacy, where the experimental group increased from 60.12 to 82.28, achieving an N-gain of 0.55 (moderate), while the control group improved from 59.85 to 70.59, with an N-gain of 0.27 (low-moderate).

Tabel 3. The Result of ANCOVA Scientific and Engineering Literacy

Variable	Source	df	F	Sig. (p)	Partial η^2	Interpretation
Science Literacy	Pretest (Covariate)	1	32.45	0.000	0.21	Large
	Group (Exp vs Control)	1	58.72	0.000	0.33	Large
Engineering Literacy	Pretest (Covariate)	1	28.10	0.000	0.19	Moderate-Large
	Group (Exp vs Control)	1	46.35	0.000	0.28	Large

Based on Table 3, the ANCOVA results indicate that pretest scores, treated as a covariate, had a significant effect on both scientific literacy and engineering literacy outcomes. For scientific literacy, the covariate effect was significant ($F = 32.45$, $p < 0.001$) with a partial η^2 of 0.21, indicating a large effect size. Similarly, in engineering literacy, the pretest also showed a significant influence ($F = 28.10$, $p < 0.001$) with a partial η^2 of 0.19, which falls within the moderate-large effect category.

Furthermore, the group factor (experimental vs. control) demonstrated a significant effect on both variables. In scientific literacy, the group effect was significant ($F = 58.72$, $p < 0.001$) with a large effect size (partial $\eta^2 = 0.33$). Likewise, for engineering literacy, a significant group effect was observed ($F = 46.35$, $p < 0.001$), with a partial η^2 of 0.28, also indicating a large effect.

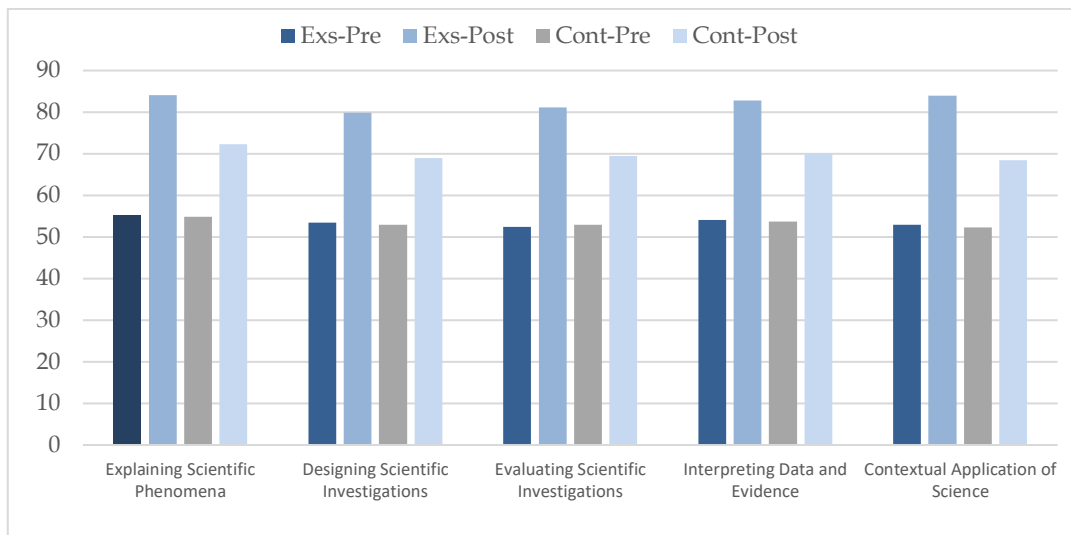


Figure 1. Comparison of Scientific Literacy Aspect Scores

Based on Figure 1, all aspects of scientific literacy showed improvement in both groups, with more pronounced gains observed in the experimental group. In the aspect of explaining scientific phenomena, the experimental group increased from 55.21 to 84.12, while the control group improved from 54.87 to 72.35. For designing scientific investigations, scores in the experimental group rose from 53.44 to 79.80, compared to an increase from 52.98 to 68.90 in the control group.

A similar pattern was evident in evaluating scientific investigations, where the experimental group improved from 52.45 to 81.10, while the control group increased from 52.98 to 69.52. In terms of interpreting data and evidence, the experimental group showed a rise from 54.12 to 82.78, whereas the control group improved from 53.76 to 70.12. The highest gain in the experimental group was observed in the contextual application of science, with scores increasing from 52.98 to 83.90, while the control group showed a more modest improvement from 52.33 to 68.45. Overall, the experimental group demonstrated greater and more consistent improvements across all aspects compared to the control group.

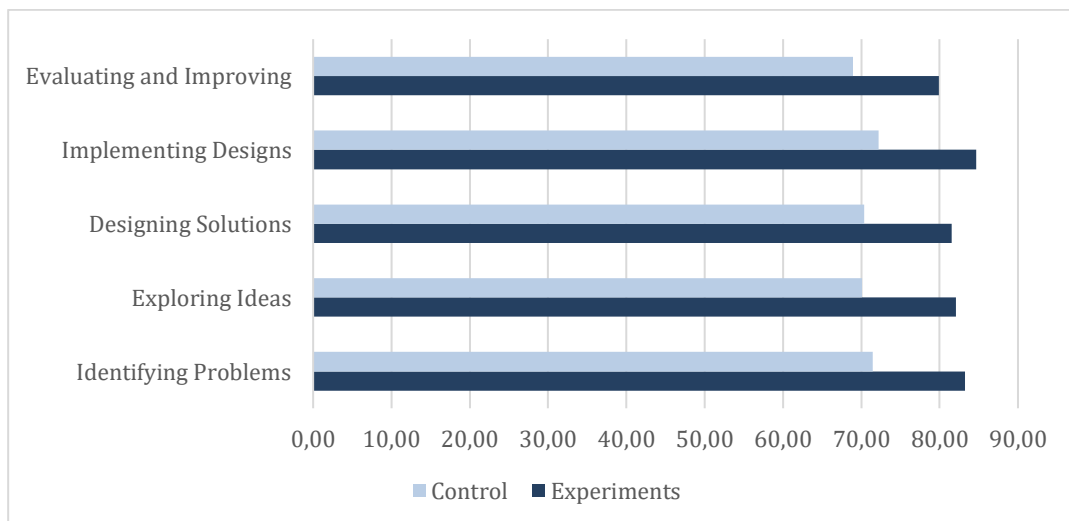


Figure 2. Comparison of Engineering Literacy Aspect Scores

Based on Figure 2, engineering literacy scores across each stage of the engineering design process indicate that the experimental group consistently outperformed the control group at all stages. In the problem identification stage, the experimental group achieved a score of 83.21, compared to 71.44 in the control group. During idea exploration, the experimental group scored 82.10, exceeding the control group's score of 70.10.

A similar trend was observed in the solution design stage, where the experimental group reached 81.56, while the control group obtained 70.33. The highest performance in the experimental group was recorded in

the design implementation stage, with a score of 84.67, compared to 72.18 in the control group. In the evaluation and improvement stage, the experimental group achieved a score of 79.88, whereas the control group scored 68.90. Overall, these findings demonstrate that the experimental group consistently achieved higher performance across all stages of the engineering design process compared to the control group.

Qualitative Data

The qualitative analysis revealed that STEM learning based on the engineering design process fostered the comprehensive development of students' scientific literacy. Students not only demonstrated improved conceptual understanding but also showed enhanced abilities in designing investigations, interpreting data, and connecting scientific concepts to real-world contexts. This development was reflected in a shift from descriptive responses toward more mechanistic reasoning, an increased ability to use evidence in drawing conclusions, and the emergence of awareness in applying scientific concepts to solve simple problems. More detailed findings on these aspects are presented in Table 4.

Table 4. Thematic Analysis of Students' Scientific Literacy Development

Theme	Sub-theme	Behavioral Indicators	Specific Findings
Mechanistic Understanding of Scientific Phenomena	Causal Explanation	Linking heat concepts to phenomena	Students moved from descriptive statements to causal explanations by linking material properties to heat transfer and temperature stability. One student stated, <i>"It's not just cold, but because the material can prevent heat from escaping, the temperature stays stable."</i>
	Concept Elaboration	Explaining processes in a structured manner	Students provided more structured explanations of heat transfer processes, indicating deeper conceptual understanding. One student explained, <i>"At first, heat comes from outside, then slowly enters, but it is held back by the material."</i>
	Misconception Revision	Correcting initial understanding	Initial assumptions that thicker materials were always better were revised after experimentation. Students recognized that insulating properties were more important than thickness. One student stated, <i>"What matters is not the thickness, but whether the material can prevent heat transfer."</i>
	Consistency of Reasoning	Applying concepts consistently	Students applied heat transfer concepts consistently across different design situations, demonstrating more stable and integrated understanding. One student noted, <i>"The principle is the same – heat transfers, but it can be slowed down."</i>
	Concept Generalization	Connecting to other contexts	Students transferred insulation concepts to everyday contexts such as thermos flasks and food containers, reflecting knowledge transfer. One student stated, <i>"It's like a thermos – it keeps the heat from escaping."</i>
Scientific Investigation Skills	Variable Identification	Identifying independent, dependent, and control variables	Students gradually learned to distinguish independent, dependent, and control variables, recognizing that fair comparisons require consistent conditions. One student stated, <i>"The material is what we change, but the time must be the same so it's fair."</i>
	Formulating Research Objectives	Stating clear experimental goals	Students progressed from general goals to more specific experimental purposes focused on identifying the most effective insulating material.

Theme	Sub-theme	Behavioral Indicators	Specific Findings
			One student explained, <i>"The goal is not just to make it cold, but to find out which material can best maintain the temperature."</i>
	Procedure Planning	Organizing systematic steps	Experimental procedures became more systematic and sequential, enabling students to conduct investigations more effectively. One student stated, <i>"First we prepare the materials, then put them in, and then measure the temperature."</i>
	Variable Control	Maintaining consistent experimental conditions	Students showed increasing awareness that all conditions should remain constant except the manipulated variable to ensure valid comparisons. One student noted, <i>"Everything should be the same except the material, so the results can be compared."</i>
	Prediction	Making evidence-based predictions	Students began making predictions based on prior assumptions and comparing them with actual results, reflecting hypothesis-oriented thinking. One student stated, <i>"I thought this material would be the best because it is the thickest."</i>
	Design Comparison	Testing alternative solutions	Students tested multiple materials and design alternatives rather than relying on a single solution, demonstrating comparative reasoning. One student stated, <i>"We tried two different materials to see which one is more effective."</i>
	Design Argumentation	Justifying design choices	Students increasingly justified their design decisions by linking material choices to functional performance. One student explained, <i>"We chose this because the material can hold heat longer."</i>
	Repetition of Experiments	Conducting repeated trials	Some groups repeated experiments to verify consistency, indicating an emerging understanding of data reliability. One student stated, <i>"We repeated it to make sure the results were the same."</i>
Scientific Investigation Skills	Variable Identification	Identifying independent, dependent, and control variables	Students developed the ability to distinguish independent, dependent, and control variables, recognizing that consistent conditions are necessary for valid comparisons. One student stated, <i>"The independent variable is the type of material, but time and position must be the same so the results can be compared."</i>
	Formulating Research Objectives	Stating clear and operational goals	Students progressed from general aims to specific and operational objectives focused on comparing the effectiveness of different materials. One student explained, <i>"The purpose of this experiment is to compare the effectiveness of different materials in maintaining temperature."</i>
	Procedure Planning	Organizing systematic and replicable steps	Experimental steps became more logical, sequential, and replicable, reflecting improved investigation design skills. One student stated, <i>"The steps must be in order, starting from preparing materials, applying treatment, and then measuring."</i>
	Variable Control	Maintaining consistent	Students increasingly understood the importance of maintaining constant conditions to avoid bias and ensure experimental validity. One student

Theme	Sub-theme	Behavioral Indicators	Specific Findings
		experimental conditions	noted, <i>"All conditions must be the same except the tested variable so the results are valid."</i>
	Prediction	Making informed predictions	Students made informed predictions based on prior knowledge and compared them with actual results, promoting reflective scientific thinking. One student stated, <i>"I predicted this material would be the most effective because it has better insulating properties."</i>
	Design Comparison	Testing multiple alternative solutions	Students tested multiple material combinations and alternative designs, demonstrating comparative and evaluative reasoning. One student stated, <i>"We tried several material combinations to find which one works best."</i>
	Design Argumentation	Justifying procedural and design choices	Students justified their procedural and design choices using scientific concepts such as insulation and heat transfer. One student explained, <i>"We chose this material because it has better insulation, so it can slow down heat transfer."</i>
	Repetition of Experiments	Conducting repeated trials for reliability	Some groups repeated trials to verify consistency and reliability, indicating an emerging understanding of scientific reliability. One student stated, <i>"We repeated the experiment to make sure the results were consistent and not just by chance."</i>
Interpreting Data and Scientific Evidence	Data Reading Skills	Identifying information from tables, graphs, or observations	Students in the experimental group progressed from simply reading numerical values to identifying patterns and trends in tables, graphs, and observations. One student stated, <i>"The graph keeps increasing, which means the temperature rises in each trial."</i>
	Data Relationship Analysis	Linking two or more variables based on data	Students began linking variables and explaining cause-effect relationships based on data, such as connecting temperature changes with melting rates. One student explained, <i>"If the temperature increases, the ice melts faster, so they are related."</i>
	Evidence-Based Conclusion	Drawing conclusions based on data	Students demonstrated improved ability to draw conclusions supported by empirical data rather than assumptions. One student stated, <i>"From this data, it means that higher temperatures make the changes happen faster."</i>
	Data Accuracy Evaluation	Assessing validity of data	Students showed emerging awareness of potential measurement errors and factors affecting data validity. One student noted, <i>"The numbers might be different because the tool is not accurate or we measured it incorrectly."</i>
	Use of Evidence in Argumentation	Using data to support arguments	Students increasingly used data as the basis for selecting and defending their decisions. One student stated, <i>"I chose this because the data shows the highest result."</i>

Theme	Sub-theme	Behavioral Indicators	Specific Findings
Application of Science in Real-Life Contexts	Connecting Concepts to Daily Life	Relating scientific concepts to everyday phenomena	Students demonstrated an increasing ability to relate scientific concepts to everyday phenomena, such as refrigerators and insulated containers, indicating meaningful contextual understanding. One student stated, <i>"This is like a refrigerator at home – it uses the same principle to keep things cold."</i>
	Applying Concepts in Problem-Solving	Using science concepts to solve simple problems	Students applied scientific concepts to propose practical solutions to contextual problems, showing that conceptual understanding was used functionally rather than memorized. One student explained, <i>"If we want it to be colder, we can add a material that absorbs heat faster."</i>
	Awareness of the Value of Science	Understanding the importance of science in daily life	Students developed a stronger appreciation of science as useful knowledge for daily life rather than merely a school subject. One student stated, <i>"Science is actually useful in daily life, not just in the classroom."</i>
	Concept Adaptation	Applying concepts in new contexts	Students began transferring their understanding to new situations and adapting concepts to unfamiliar contexts. One student noted, <i>"If this is used in another place, the method might be the same but the materials could be different."</i>
	Science-Based Decision Making	Using scientific reasoning in decision-making	Students increasingly used scientific evidence and experimental results to justify their decisions. One student explained, <i>"I chose this because the experiment showed it was the most effective."</i>

The qualitative analysis revealed that students' engineering literacy developed progressively through the stages of the engineering design process. This development was evident in their ability to identify problems in more contextual ways, generate and evaluate alternative solutions, and design and implement science-based prototypes. In addition, students began to demonstrate the ability to conduct data-driven testing, evaluate design weaknesses, and make iterative improvements. The process was also accompanied by increasing reflective thinking regarding both outcomes and learning processes. More detailed findings on the development of engineering literacy are presented in Table 5.

Table 5. Thematic Summary of Engineering Literacy

Main Theme	Sub-theme	Behavioral Indicators	Specific Findings
Problem Framing	Understanding user needs	Defining the purpose of the tool	Students showed development in defining more specific objectives. The goal was no longer simply <i>"to make it cold,"</i> but to maintain temperature stability over a certain period. One student stated, <i>"The goal is not just to make it cold, but to keep the temperature stable for longer."</i>
	Contextual problem analysis	Relating to real-world conditions	Students began to consider contextual factors such as environment and practical use, indicating more contextualized problem understanding. One student stated, <i>"If it is used outdoors, the temperature will definitely be more affected."</i>

Main Theme	Sub-theme	Behavioral Indicators	Specific Findings
	Problem limitation	Defining design constraints	Students considered constraints such as materials, size, and time, reflecting awareness of realistic engineering conditions. One student stated, <i>"The materials are limited, so we have to choose the most effective ones."</i>
Ideation & Solution Exploration	Generating alternatives	Producing multiple ideas	Students generated more than one design alternative before selecting a final solution, indicating divergent thinking skills. One student stated, <i>"We created several design options before deciding on the best one."</i>
	Material exploration	Testing different materials	Students explored different materials to examine their properties and effectiveness in heat resistance. One student stated, <i>"We tried different materials to see which one can withstand heat better."</i>
	Idea justification	Providing reasons for choices	Design selection began to be supported by functional reasoning related to material properties. One student stated, <i>"We chose this because it can retain heat longer."</i>
Concept-Based Design Development	Design visualization	Creating sketches	Students created preliminary sketches before implementation, showing more structured planning. One student stated, <i>"We drew it first so we could understand the structure."</i>
	Science concept integration	Linking design with heat transfer	Students connected design decisions with heat transfer concepts, showing application of scientific knowledge. One student stated, <i>"The material was chosen because it can reduce heat transfer."</i>
	Basic technical specification	Determining size and structure	Students began specifying dimensions and structural arrangements more systematically, indicating improved design precision. One student stated, <i>"The size was adjusted so it fits and remains effective."</i>
Implementation and Testing	Product construction	Building the prototype	Students worked collaboratively in constructing the product according to the design plan, demonstrating teamwork skills. One student stated, <i>"We divided the tasks so the process would be faster."</i>
	Performance testing	Measuring results	Students measured and compared performance outcomes across different designs, reflecting data-based evaluation. One student stated, <i>"We measured the temperature to see which design is most effective."</i>
	Documentation	Recording experimental data	Students began systematically recording results for comparison and evaluation purposes. One student stated, <i>"We recorded the results so we could compare them later."</i>
Iterative Evaluation and Reflection	Weakness identification	Detecting design limitations	Students were able to identify weaknesses in their designs based on test results. One student stated, <i>"This part was not sealed well, so heat still entered."</i>
	Result comparison	Comparing design performance	Students compared multiple designs to determine effectiveness, showing evaluative thinking skills. One student stated, <i>"The second design was better because the temperature was more stable."</i>

Main Theme	Sub-theme	Behavioral Indicators	Specific Findings
	Design iteration	Making improvements	Students revised and improved their designs based on evaluation results, reflecting iterative engineering thinking. One student stated, <i>"We improved it again to make the result better."</i>
	Process reflection	Evaluating learning process	Students reflected not only on outcomes but also on their working process, indicating emerging metacognitive skills. One student stated, <i>"We realized our initial steps were not right, so the result was not optimal."</i>

The integration of quantitative and qualitative data indicates that the improvement in both scientific literacy and engineering literacy is not only reflected in achievement scores but is also strengthened by changes in students' thinking processes and engagement during learning. The quantitative findings, which show higher gains in the experimental group, are consistent with the qualitative results that reveal the development of students' abilities to explain phenomena mechanistically, design investigations, interpret data, and apply scientific concepts in real-world contexts. In addition, the improvement in engineering literacy is supported by students' active engagement across all stages of the engineering design process, from problem identification to design evaluation and refinement. Overall, both data sets complement each other and provide a more comprehensive understanding of the effectiveness of STEM learning. A detailed integration of the quantitative and qualitative findings is presented in Table 6.

Table 6. Integration of Quantitative and Qualitative Data

Variable	Quantitative Findings	Qualitative Findings (Thematic Synthesis)	Meta-Interpretation (Integration)
Scientific Literacy	The experimental group showed higher improvement (N-gain = 0.63; moderate-high category) compared to the control group (0.36; moderate). ANCOVA results indicated a significant effect of group ($F = 58.72$; $p < 0.001$; $\eta^2 = 0.33$, large effect).	Students experienced a shift from descriptive understanding to mechanistic explanations, demonstrating the ability to interpret data and use evidence in drawing conclusions. They also began linking concepts to real-life contexts and showing basic evaluative reasoning. Quotations such as <i>"heat does not transfer quickly, so the temperature stays stable"</i> and <i>"from this data, higher temperature leads to faster changes"</i> reflect the development of scientific reasoning.	The significant quantitative improvement aligns with changes in the quality of scientific thinking. The learning process not only increased scores but also facilitated a transformation from knowing → reasoning → applying, which represents the core of scientific literacy development.
Engineering Literacy	The experimental group showed higher improvement (N-gain = 0.55; moderate) compared to the control group (0.27; low-moderate). ANCOVA results indicated a significant effect of group ($F = 46.35$; $p < 0.001$; $\eta^2 = 0.28$, large effect).	Students demonstrated development across all stages of the engineering design process, from problem identification and idea generation to concept-based design, evaluation, and iteration. There was a clear shift from trial-and-error approaches to more reasoning-based design decisions. Quotations such as <i>"we tried several designs to find the most effective one"</i> and <i>"after testing, we</i>	The quantitative gains reflect the development of engineering skills that are qualitatively evident in design thinking and iterative improvement. The learning experience enabled students not only to produce a product but also to understand engineering as a systematic and reflective process.

		<i>improved it again</i> " indicate iterative and comparative thinking processes.	
Integration of Scientific & Engineering Literacy	Both variables showed significant improvement with large effect sizes, particularly in the experimental group.	Qualitative findings indicate a strong interconnection between both literacies: scientific understanding served as a foundation for design decision-making, while engineering activities strengthened conceptual understanding through hands-on experience.	The integration reveals a synergistic relationship : scientific literacy enhances the quality of engineering design, while engineering practice deepens scientific understanding. Thus, STEM/EDP-based learning effectively develops both cognitive and practical competencies simultaneously.

DISCUSSION

Transformation of Scientific Literacy: From Descriptive to Mechanistic Understanding

The findings indicate that students' scientific literacy in the experimental group improved significantly, not only in quantitative measures but also in qualitative dimensions. This improvement was consistently observed across three main assessed aspects: explaining scientific phenomena, interpreting data and evidence, and applying science in real-life contexts. Quantitatively, the N-gain scores in the moderate-to-high category indicate the effectiveness of the instructional intervention. However, the qualitative findings provide deeper insight, revealing a transformation in students' thinking from descriptive responses toward mechanistic reasoning.

In the aspect of explaining scientific phenomena, students demonstrated a shift from merely describing observed outcomes to explaining the underlying cause-and-effect processes, particularly related to heat transfer mechanisms. This shift reflects the development of causal reasoning, which in contemporary science education literature is considered a key indicator of advanced conceptual understanding. Recent frameworks of scientific literacy emphasize that the ability to explain phenomena mechanistically distinguishes superficial understanding from deep conceptual comprehension (Duschl, 2019; OECD., 2019). Furthermore, recent studies show that STEM-based instruction significantly enhances students' ability to construct mechanism-based scientific explanations compared to traditional approaches (Cao et al., 2025).

Regarding the interpretation of data and scientific evidence, students progressed from simply reading data to identifying patterns, connecting variables, and drawing evidence-based conclusions. This transformation reflects the emergence of evidence-based reasoning, defined as the ability to use data as the foundation for scientific arguments. Recent research confirms that such competencies develop optimally when students are actively engaged in authentic and reflective data analysis activities (Halawa et al., 2024). Thus, the integration of experimental and design-based learning activities plays a crucial role in fostering meaningful scientific practices.

Furthermore, in the aspect of applying science in real-life contexts, students began to transfer learned concepts into everyday situations. This ability indicates that learning has progressed beyond conceptual understanding to a functional level. Current literature positions transfer ability as the highest level of scientific literacy, as it reflects flexible knowledge application across contexts (Li et al., 2020). In addition, context-based STEM learning has been shown to improve students' ability to make science-based decisions in real-world situations (English, 2020).

Theoretically, this transformation from descriptive to mechanistic understanding can be explained through constructivist learning theory and the framework of science practices. Within this perspective, knowledge is constructed through active engagement with phenomena and reflection on experiences. Activities such as experimentation, design, and evaluation enable students to reconstruct prior understanding,

including the revision of misconceptions. Recent studies indicate that engagement in science practices significantly contributes to the development of scientific reasoning and deeper conceptual understanding (National Academies of Sciences and Medicine, 2022).

However, the findings also indicate that the transition toward mechanistic reasoning is not yet evenly distributed among all students. Some students remain in a transitional phase, particularly in developing systematic evidence-based arguments. This suggests that scientific literacy develops gradually and requires sustained pedagogical support. Previous studies also emphasize that without adequate scaffolding, students tend to revert to intuitive reasoning patterns even after exposure to STEM-based instruction (Schwarz et al., 2021)

From a research gap perspective, most prior studies have primarily focused on quantitative improvements in learning outcomes without deeply exploring changes in students' reasoning quality. In addition, studies integrating quantitative and qualitative data to explain epistemic transformation in scientific literacy remain limited, particularly in the context of engineering design-based learning. This study addresses this gap by demonstrating that improvements in scientific literacy scores are accompanied by shifts in students' ways of thinking, from knowing to reasoning and applying.

Therefore, the main contribution of this study lies in strengthening evidence that STEM-based learning not only enhances academic achievement but also promotes epistemological transformation in scientific understanding. This transformation is characterized by the ability to explain phenomena mechanistically, use evidence in reasoning, and transfer concepts to real-life contexts. It further confirms that scientific literacy is a multidimensional competence encompassing conceptual, procedural, and applied dimensions in an integrated manner.

Enhancing Engineering Literacy: From Trial-and-Error to Design Thinking

The findings indicate that engineering literacy in the experimental group improved significantly, with a moderate gain and a large effect size. However, the most substantial insight is not merely reflected in the quantitative improvement, but in the qualitative transformation of students' thinking processes. The qualitative data reveal a clear shift from a trial-and-error approach toward more systematic, structured, and conceptually grounded design thinking.

This transformation is evident in the problem framing stage, where students no longer interpreted problems in a simplistic manner (e.g., "making it colder"), but instead began to articulate functional needs and design constraints more explicitly. For example, one student explained, "The goal is not just to make it cold, but to keep the temperature stable for longer," indicating a shift from a general objective toward a more precise and measurable engineering goal. This reflects the development of *problem scoping*, an essential early stage in the engineering design process that strongly influences the quality of the resulting solution. Recent literature emphasizes that precise problem definition is a prerequisite for producing effective and innovative designs (Cunningham & Kelly, 2017; Van Breukelen et al., 2020).

In the ideation and solution exploration phase, students began generating multiple design alternatives and providing justifications for their choices. This development was reflected in students' ability to propose several possible solutions before selecting the most effective one, as illustrated by one student's statement, "We created several design options before deciding on the best one." This shift indicates the simultaneous development of divergent and evaluative thinking. In engineering education, the ability to generate and compare alternative solutions is a key indicator of design thinking (Razzouk & Shute, 2012). Recent studies further confirm that STEM-based learning encourages learners to move beyond single-solution thinking and develop cognitive flexibility in exploring multiple possibilities (Cheng & al., 2023).

In the concept-based design development stage, students demonstrated improved integration of scientific concepts into their designs. As one student stated, "The material was chosen because it can reduce heat transfer," demonstrating that design decisions were increasingly grounded in scientific understanding rather than intuition alone. Material selection and structural decisions were no longer intuitive but increasingly informed by an understanding of material properties, particularly thermal insulation and heat transfer. This

reflects a strong connection between scientific literacy and engineering literacy. Recent research highlights that integrating scientific concepts into design processes is essential for developing *informed design*, where decisions are grounded in scientific knowledge rather than experience alone (Crismond & Adams, 2012; Kelley & Knowles, 2016).

During the implementation and testing phase, students not only constructed prototypes but also began conducting systematic performance evaluations and measurements. This was evident when students reported, “We measured the temperature to see which design is most effective,” indicating that testing activities were increasingly based on empirical evidence rather than subjective impressions. This indicates engagement in authentic engineering practices, where testing is an integral part of solution development. Empirical studies show that involvement in testing and evaluation activities enhances critical thinking skills and strengthens understanding of the relationship between design and outcomes (Fan & Yu, 2017; Hsu et al., 2018).

The most evident transformation toward design thinking appears in the iterative evaluation and reflection stage. Students demonstrated the ability to identify design weaknesses and revise their prototypes based on testing results. For instance, one student noted, “We improved it again to make the result better,” reflecting an emerging understanding that effective engineering requires repeated refinement and evidence-based revision. This iterative process represents a core characteristic of the engineering design cycle, distinguishing it from linear problem-solving approaches. Recent studies confirm that iterative cycles—comprising design, testing, and refinement—play a crucial role in developing complex problem-solving abilities and reflective thinking (English, 2020; Lottero-Perdue & al., 2021).

Theoretically, the shift from trial-and-error to design thinking can be explained through the frameworks of *informed design* and *engineering habits of mind*. Within this perspective, learners do not engage in random experimentation but instead base their decisions on knowledge, data, and reflection. This aligns with the view that engineering literacy encompasses systematic, creative, and evidence-based thinking (Engineering, 2020)

However, the findings also indicate that this transition is not yet fully optimized across all students. Some still rely on intuitive approaches, particularly in the early design stages. This may be attributed to students’ limited prior understanding of heat transfer and energy efficiency, their difficulties in connecting scientific concepts with engineering design decisions, and their limited experience with iterative design and reflective evaluation processes. This suggests that developing engineering literacy requires time and sustained pedagogical support, especially through scaffolding during design and evaluation phases. Previous studies similarly emphasize that without adequate guidance, students may revert to trial-and-error strategies even after being introduced to structured engineering design frameworks (Purzer et al., 2015).

From a research gap perspective, most prior studies have focused on product outcomes or general skill improvements without deeply examining the cognitive shift from trial-and-error to design thinking. Moreover, studies integrating quantitative and qualitative approaches to explain engineering literacy development remain limited, particularly in STEM-based learning contexts at primary and secondary education levels. This study addresses this gap by demonstrating that improvements in engineering literacy scores are accompanied by qualitative changes across five interconnected themes: problem framing, ideation and solution exploration, concept-based design development, implementation and testing, and iterative evaluation and reflection.

Therefore, the findings confirm that STEM-based learning integrating the engineering design process is effective in developing engineering literacy in a comprehensive manner. The transformation from trial-and-error to design thinking demonstrates that students are not only capable of producing solutions but also of understanding the underlying processes. This provides an important foundation for developing 21st-century competencies, particularly critical thinking, creativity, and problem-solving skills.

Integration of Scientific Literacy and Engineering Literacy

The findings of this study indicate that scientific literacy and engineering literacy develop in a synergistic manner rather than as two separate constructs. Quantitatively, both variables showed significant improvements with large effect sizes in the experimental group, indicating the effectiveness of STEM-based learning in fostering multidimensional competencies. These findings are consistent with meta-analytic

evidence showing that STEM integration has a significant impact on enhancing cognitive skills and higher-order thinking abilities (Cao et al., 2025; Li et al., 2020). Moreover, integrated STEM instruction has been found to be more effective than disciplinary approaches in improving scientific literacy and problem-solving skills (English, 2020; Zuza et al., 2024).

From a qualitative perspective, scientific concept understanding served as a foundation for design decision-making. Students no longer relied solely on intuition but increasingly used scientific concepts as a basis for selecting solutions. This reflects the development of *informed design*, in which conceptual knowledge is explicitly applied within engineering processes (Crismond & Adams, 2012; Kelley & Knowles, 2016). This finding is also supported by studies demonstrating that the integration of science into design processes improves solution quality and deepens conceptual understanding (Fan & Yu, 2017; Hsu et al., 2021).

Conversely, the engineering design process itself contributed to strengthening scientific understanding through direct experience. The stages of design, testing, and evaluation encouraged students to reflect on the relationship between scientific concepts and observed outcomes. This process reinforces evidence-based reasoning and experiential learning within STEM contexts (English, 2020; Halawa et al., 2024). Furthermore, engagement in design practices has been shown to enhance conceptual understanding as students learn through meaningful iterative cycles (Lottero-Perdue & al., 2021; National Academies of Sciences and Medicine, 2022).

From the perspective of scientific literacy, this integration strengthened students' abilities to explain phenomena, interpret data, and apply concepts. Students were required to understand underlying mechanisms in order to produce effective solutions, thereby fostering the development of causal reasoning (Duschl, 2019; Schwarz et al., 2021). In addition, the use of data in design evaluation enhanced analytical skills and evidence-based argumentation (Li et al., 2020; OECD., 2019). This demonstrates that engineering activities can serve as an effective context for developing authentic scientific practices.

From the perspective of engineering literacy, scientific understanding enabled students to produce more rational and evidence-based designs. This indicates that design quality is not solely dependent on creativity but also on the depth of underlying scientific knowledge. This aligns with the concept of *informed design*, which emphasizes the integration of scientific knowledge into engineering processes (Crismond & Adams, 2012; Kelley & Knowles, 2016). Furthermore, research shows that STEM integration enhances complex problem-solving abilities and improves the quality of generated designs (Hsu et al., 2018; Van Breukelen et al., 2020).

More broadly, the integration of scientific and engineering literacy reflects the development of STEM epistemic practices, namely the ability to integrate conceptual, procedural, and applied knowledge simultaneously. In this context, students not only understand concepts but are also able to apply them within systematic and reflective design processes (Cunningham & Kelly, 2017; National Academies of Sciences and Medicine, 2022). Additionally, integrated STEM learning has been reported to significantly enhance cognitive engagement and learning motivation (English, 2020; Zuza et al., 2024).

However, this integration was not yet fully achieved across all students. Some still demonstrated a separation between conceptual understanding and design practice, indicating that cognitive integration had not fully occurred. This is consistent with previous research highlighting that one of the main challenges in STEM implementation is the difficulty of consistently integrating multiple disciplines in instructional practice (Kelley & Knowles, 2016; Winarti et al., 2025). In addition, without adequate scaffolding, students tend to revert to intuitive approaches in design activities (Purzer et al., 2015; Razzouk & Shute, 2012).

From a research gap perspective, most previous studies have examined scientific literacy and engineering literacy separately or have focused on only one construct. Studies explicitly investigating the synergistic relationship between the two using a mixed-methods approach remain limited. This study contributes by demonstrating that improvements in both variables do not occur merely in parallel but are also conceptually and procedurally interconnected (Cao et al., 2025; Zuza et al., 2024). Thus, this integration becomes a key element in developing 21st-century competencies that emphasize critical thinking, problem-solving, and knowledge transfer (Li et al., 2020; OECD., 2019). These findings also carry important implications for elementary education in Indonesia, as they illustrate how integrated STEM learning can operationalize the

goals of *Kurikulum Merdeka* through meaningful, student-centered, and interdisciplinary learning experiences. By engaging students in authentic problem solving, iterative design, and evidence-based reasoning, this instructional approach reflects the curriculum's emphasis on deep conceptual understanding, real-world application, and the active construction of knowledge. At the same time, the Green Refrigerant Box project provides a concrete context for strengthening the *Profil Pelajar Pancasila*, particularly in the dimensions of critical reasoning, creativity, collaboration, and environmental responsibility. Through this process, students not only acquire scientific and engineering concepts but also develop the capacity to apply their knowledge to socially and environmentally relevant challenges. Accordingly, STEM-based learning integrated with the Engineering Design Process offers a practical and pedagogically robust strategy for translating national curriculum aspirations into meaningful classroom practice at the elementary level.

CONCLUSION

This study demonstrates that STEM-based learning integrated with the Engineering Design Process (EDP) is effective in enhancing both scientific literacy and engineering literacy among elementary school students. Quantitative findings revealed significant improvements in both competencies in the experimental group, with large effect sizes confirmed through ANCOVA analysis, indicating that the instructional intervention had a substantial impact on students' cognitive achievement. Qualitative findings further showed that students' scientific literacy progressed from descriptive explanations to mechanistic reasoning, improved interpretation of data and evidence, and stronger application of scientific concepts in real-life contexts. At the same time, engineering literacy developed from trial-and-error approaches toward more systematic design thinking characterized by structured problem framing, ideation, conceptual integration, iterative testing, and reflective improvement. The integration analysis confirmed that both literacies developed in a mutually reinforcing manner, with scientific understanding serving as the conceptual foundation for engineering decision-making and engineering activities strengthening scientific understanding through experiential and iterative learning processes. Although not all students achieved the same level of cognitive integration, the findings indicate that sustained instructional scaffolding is essential to support deeper connections between scientific and engineering thinking. Overall, this study provides strong evidence that STEM-based instruction supported by EDP fosters not only academic achievement but also meaningful transformations in students' ways of thinking, problem-solving abilities, and knowledge transfer essential for 21st-century competencies. Therefore, teachers are encouraged to prioritize iterative design processes, scientific reasoning, and reflective evaluation rather than focusing solely on the final product in order to promote deeper and more meaningful student learning.

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