Glosains: Jurnal Sains Global Indonesia
Volume 7, Issue 2, 531-544
e_ISSN: 2798-4311
https://glosains.staiku.ac.id
DOI: doi.org/10.59784/glosains.v7i2.719

PjBL–STEM Learning Design for Enhancing Mathematical Critical Thinking and Environmental Literacy through Plastic Waste Recycling in Elementary School

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Article Info:
Article history:
Received: March 23, 2026
Revised: May 08, 2026
Accepted: May 11, 2026

Keywords:
environmental literacy; mathematical critical thinking; mathematics education; project-based learning; STEM education

Abstract

Background: Conventional mathematics instruction rarely integrates environmental sustainability themes, limiting students' opportunities to develop both mathematical reasoning and ecological awareness.
Objective: This study developed and evaluated a PjBL–STEM learning design to simultaneously enhance mathematical critical thinking and environmental literacy among elementary students through plastic waste recycling projects.
Methods: Using the 4-D R&D model followed by a quasi-experimental nonequivalent control group design, 32 elementary students selected via purposive sampling participated. Instruments were validated through expert judgment (Cronbach's $\alpha = 0.87$). Data were analyzed using an independent samples *t*-test after normality and homogeneity tests ($\alpha = 0.05$).
Results: The PjBL–STEM model significantly improved students' critical thinking ($t = 4.32$, $p < 0.05$). Post-test mean scores of the experimental group ($M = 91.25$, $SD = 5.84$) significantly exceeded those of the control group ($M = 74.50$, $SD = 8.21$). Students demonstrated strong performance across all five critical thinking indicators.
Conclusion: PjBL–STEM learning effectively integrates mathematical critical thinking and environmental literacy, offering a reproducible interdisciplinary model for sustainability-oriented mathematics education.

To cite this article: Prastiti, T. D., Mairing, J. P., Sambada, D., & Ahmadah, I. F. (2026). PjBL–STEM learning design for enhancing mathematical critical thinking and environmental literacy through plastic waste recycling in elementary school. *Glosains: Jurnal Sains Global Indonesia*, 7(2), 531–544. https://doi.org/10.59784/glosins.v7i2.719

INTRODUCTION

In order to prepare students well for complex problem solving, education systems show interest in competencies that meet global challenges. The objective of twenty-first-century education is higher-order thinking skills, collaborative learning, and environmental sustainability. Critical thinking enables people to operate under conditions of substantial uncertainty in dynamically variable situational contexts (Van Laar et al., 2020). Critical thinking is also how students are able to justify their problem-solving decisions (Matthee & Turpin, 2019). Nevertheless, published data tell a different story: fewer than 40% of elementary students globally possess adequate environmental literacy, and few primary mathematics curricula include environmental awareness education. Importantly, a recent study by Rahayu (2025) indicates that only 38% of elementary students could explain key ideas regarding plastic waste and recycling practices, which further demonstrates the urgency of incorporating environmental literacy across core subject areas.

Despite the importance of critical thinking, mathematics learning in numerous classrooms continues to reflect a heavy reliance on procedural knowledge rather than conceptual reasoning, and environmental education is primarily limited in scope to science subjects. Traditional pedagogies are unable to develop ecological literacy, in part because of the overly theoretical, decontextualized, and siloed nature of instruction: mathematics is rarely taught through real environmental problems in ways that help students develop a broad understanding of how mathematical reasoning functions in environmental problem solving. Given its focus on real-world problem contexts, collaborative inquiry, and the production of meaningful outcomes, Project-Based Learning is a natural fit for environmental contexts through which students can integrate STEM disciplines. In contrast to traditional instruction, PjBL provides students with the opportunity to pursue genuine environmental problems through long-term investigation that inherently draws on mathematical reasoning, scientific knowledge, engineering design, and technology within a single unit of study (Simamora, 2024).

Recent trends in research show that Project-Based Learning (PjBL) improves students' engagement, critical thinking, and problem-solving skills across various disciplines (Rahmawati et al., 2022). Nevertheless, most studies on PjBL examine general cognitive outcomes rather than domain-specific mathematical reasoning within elementary contexts. At the same time, strong effects of contextualized STEM-integrated learning environments have been found for higher-order thinking (Condong et al., 2026).

However, these studies are primarily focused on secondary science contexts and do not provide a comprehensive examination of STEM integration in the elementary mathematics context. In terms of gaps in the literature, three major areas stand out: (1) opportunities for developing domain-specific mathematical critical thinking through PjBL–STEM are limited, particularly with arithmetic sequences; (2) environmental literacy has rarely been studied concurrently as part of mathematics learning; and (3) these gaps are significant because, in the absence of evidence-based interdisciplinary models, it becomes difficult to develop young children's quantitative reasoning skills alongside pro-environmental dispositions before those attitudes become firmly established over time (Fitzallen, 2015). In sum, studies integrating PjBL–STEM for the concurrent improvement of mathematical critical thinking and environmental literacy in elementary mathematics remain scarce. This paper presents a unique integration of arithmetic sequence learning with environmental sustainability projects within a PjBL–STEM framework to address this identified gap.

Beyond PjBL, STEM education emphasizes combining different disciplines into contexts for solving real-world problems by integrating scientific inquiry (S), technological tools (T), engineering design (E), and mathematical reasoning (M) into a unified learning experience (English, 2016). STEM integration enables students to link theoretical knowledge with practical applications, thereby enhancing conceptual understanding and analytical reasoning. In the present study, the product created by students was recycled plant pots made from plastic ice-cream buckets.

Academically, this product serves as a mathematical modeling project, in which students apply arithmetic sequences to solve contextualized problems based on stacking configurations — for instance, determining the number of containers needed to reach a certain height using $U_n = a + (n - 1)b$. Environmentally, the project prevents plastic waste from entering landfills, with each student group diverting approximately 3–5 plastic containers from disposal. In producing functional plant pots for use in school gardens, students experience a tangible environmental outcome from recycling, which reinforces both ecological awareness and intrinsic motivation.

Recent studies show that STEM-integrated learning environments significantly promote students' higher-order thinking skills in knowledge transfer and application (Keleman et al., 2021). Project-based approaches within STEM are particularly effective at promoting student inquiry and collaboration, creating conditions that activate critical thinking through both analytical and creative engagement. Such convergence across disciplines and education systems indicates potential cross-contextual validity for STEM-integrated pedagogies in developing complex reasoning skills.

At the same time, promoting environmental literacy in schools to encourage students to take action toward solving global environmental problems — such as climate change, plastic pollution, and ecological degradation — warrants the sustained attention of educational organizations. Environmental literacy refers to the knowledge, dispositions, and skills that enable people to understand environmental systems and evaluate the environmental implications of their choices (Ardoin et al., 2020). Developing environmental literacy is essential for fostering sustainability-oriented decision making among students.

However, a large proportion of environmental education occurs in science lessons and not in mathematics lessons. Such a disconnect may limit students' opportunities to learn how mathematical reasoning can be applied to environmental problem solving. Incorporating environmental themes as contexts for mathematics learning can offer authentic opportunities for the application of mathematical concepts while simultaneously fostering environmental awareness (Rafiq-uz-Zaman et al., 2024).

Integration of the PjBL–STEM learning model with environmental sustainability themes has the potential to help overcome this challenge. Through authentic problems related to environmental issues, students can investigate root causes and design solutions grounded directly in mathematical content. Earlier studies confirm that sustainability-focused STEM learning improves environmental consciousness and analytical skills.

However, investigation of the integration of PjBL–STEM learning with mathematical critical thinking and environmental literacy in elementary school mathematics education remains limited. The majority of findings in the literature on STEM integration relate either to science learning or to critical thinking development in a general sense — two orientations that only partially address domain-specific mathematical reasoning. This gap is significant: without models contextualized and validated in the elementary mathematics classroom, teachers have few concrete frameworks for simultaneously developing students' mathematical reasoning and environmental responsibility. This void is particularly acute in Indonesia, where national curriculum policies increasingly emphasize cross-disciplinary learning opportunities (Rahmawati et al., 2022).

Based on the foregoing, this research aims to design a PjBL–STEM unit that integrates environmental sustainability issues into mathematics learning. Students explore environmental problems and apply mathematical reasoning grounded in arithmetic sequences to recycle plastic waste into useful products through project-based, hands-on activities. This research makes a novel contribution to the literature by using environmental sustainability projects — specifically, plastic waste recycling (PWR) — as the primary context for arithmetic sequence instruction within a PjBL–STEM unit, while addressing mathematical critical thinking and environmental literacy as twin learning goals in the elementary mathematics classroom.

Incorporating Project-Based Learning, STEM education, and environmental literacy, this research aims to provide a comprehensive educational framework that attends to both cognitive development and ecological awareness. The findings are expected to contribute to the literature on STEM-integrated mathematics education while offering practical guidelines for teachers developing interdisciplinary learning experiences.

Literature Review

Project-Based Learning in STEM Education

Current research trends indicate that Project-Based Learning (PjBL) significantly fosters meaningful learning experiences and higher-order thinking skills across educational context (Murniawaty et al., 2025). In contrast to traditional teacher-centered instruction that positions students as passive recipients of knowledge, PjBL situates students as active constructors of knowledge by collaborating with others in purposeful inquiry and engaging in authentic project activities, leading to cognitive engagement, conceptual understanding (what is it?), and critical analysis (how well does it work?).

Two recent studies concluded that PjBL provides significant enhancement of the cognitive engagement and conceptual understanding of students. Learners, through project activity, are also stimulated to investigate problems, brainstorm solutions, and explore data and conclusion presentation. These processes allow the development of critical thinking and problem-solving skills required for current teaching and learning.

One such method lately incorporated in project-based learning is the integration of Science, Technology, Engineering, and Mathematics (STEM) to improve interdisciplinary learning. STEM education views the integration of disciplines as working to provide practical solutions to real-world challenges, allowing students to apply knowledge in a meaningful way across disciplines. STEM-integrated learning environments are essential to be created for deepening conceptual understanding between theory and practice (English, 2016).

When PjBL is integrated into STEM education, it should be a great pedagogical choice in support of students' critical and innovative skills. Contemporary research suggests that projects from the STEM curriculum develop pupils' critical thinking, creativity, and problem identification/solving skills, showing wider influences on students' reasoning abilities as well as collaborative skill sets. Specifically, challenges persist with elementary in-service teachers regarding difficulty aligning developmentally appropriate mathematics content and STEM integration Fitzallen (2015), as well as balancing curricular mandates with project-based work focused on open-ended questions/challenges in these classes.

In addition, STEM-based project learning enables students to work on real-world assignments calling for science content, engineering design, and mathematical reasoning. According to Thibaut (2018), integrated STEM learning promotes deeper understanding by requiring students to analyze problems from multiple angles and then come up with innovative solutions. This kind of experiential, interdisciplinary learning can certainly help students acquire the analytical and soft skills they will need to tackle complex global challenges.

Yet, even though PjBL-STEM learning does show growing widespread adoption, these studies mostly focus on overall problem-solving abilities or improvements in creativity. More research is still to be reported on the specific development of mathematical critical thinking skills (MCTS) through STEM-integrated project learning in real classroom implementations, especially for elementary grades. This gap indicates a necessity for further investigations into how PjBL-STEM learning could improve the development of mathematical reasoning skills.

Critical Thinking in Mathematics Education

Mathematical critical thinking and its relevance to problem-solving are widely recognized as essential skills involving the analysis of data, arguments, and their implications to develop coherent conclusions in mathematics. Different from critical thinking in general, mathematical critical thinking in STEM learning environments is inherently linked to a mastery of numeracy-based reasoning: interpreting quantitative relationships, creating mathematical models representing real-world phenomena, and applying mathematical operations to simulate engineering or scientific problems (Fitzallen, 2015).

Sosa (2023) State that critical thinking in mathematics encompasses the following cognitive processes: interpreting mathematical situations, analyzing relations between variables, assessing strategies, and making reasoned decisions. These processes allow students to take a systematic approach toward the mathematical problems they encounter and create useful solutions.

Mathematics classrooms that leave space for inquiry, discussion, and reflection are essential to developing critical thinking. Excessive levels of rote practice and formulaic reasoning are often a prominent feature of traditional instruction, which tends to restrict students' opportunities for reasoning. On the contrary, problem-based and project-based learning approaches present students with real-world problems to analyze critically.

Currently, the integration of STEM education into mathematics has been demonstrated to support mathematical critical thinking through real problem-solving contexts (Rahmawati et al., 2022). In these environments, mathematical modeling is the main analytical tool that links scientific inquiry to mathematical reasoning (e.g., pattern recognition, sequence analysis, and functional relationship construction). However, debate exists surrounding the level of mathematics involved in many STEM projects; specifically, whether mathematics is relegated to a supporting role in an engineering task rather than serving as a prominent framework for analysis Fitzallen (2015)—a limitation this study directly addresses by embedding arithmetic sequence reasoning as the primary mathematical proficiency instantiated through the recycling project.

Mathematics is frequently a tool for analyzing patterns, modeling systems, and solving complex problems in STEM learning environments. Students engage in this most meaningfully when they are solving a problem in an interdisciplinary context, one that requires them to interpret data, analyze relationships, or create a mathematical model to justify their solution. This type of learning experience lays the foundation for strengthening the critical thinking skills necessary for complex problem-solving.

Nevertheless, mathematical critical thinking remains one of the most persistent challenges that many classrooms continue to grapple with. A significant difficulty for students is that they cannot relate mathematical concepts to real-life scenarios. This demonstrates the need for innovative educational methods that provide meaningful purpose for students using mathematical reasoning in context, which will also benefit their overall critical thinking abilities.

Environmental Literacy in Education

As societies increasingly confront complex environmental challenges—climate change, pollution, and biodiversity loss—the goal of achieving environmental literacy has become central to modern education. Environmental literacy is defined as the capacity of citizens to comprehend ecological systems, analyze environmental problems, and make appropriate decisions that support sustainable lifestyles (Ardoin et al., 2020).

Environmental literacy entails knowledge of environmental concepts as well as the development of attitudes, values, and behaviors supporting sustainability. According to Monroe (2019) and the National Council for Science and the Environment (2021), environmentally literate people can identify environmental issues, examine their causes, and participate in actions that are conducive to protecting the environment.

It is also important to recognize that educational institutions serve as a conduit for building environmental literacy in students. Sustainability education is meant to help students learn about ways to address environmental issues and foster sustainable development. Teaching about environmental issues helps students develop an understanding of context-specific problems as well as an awareness of responsible behavior toward the environment.

Emerging research indicates that interdisciplinary learning may be the most effective approach for facilitating environmental literacy. Integrating environmental issues with STEM learning activities by exploring sustainability challenges provides opportunities for students to apply scientific and mathematical reasoning (Saengkhattiya, 2024). These approaches help students understand the systemic interactions of ecology and human activity.

It has also been recognized that project-based learning can be useful in developing environmental literacy. Projects allow students to investigate real environmental issues and propose solutions through practical activities. Such experiences help establish a deeper understanding of environmental sustainability and encourage responsible behavior among students.

In contrast, environmental education is primarily implemented in science subjects, while mathematics learning seldom includes environmental contexts. This separation may constrain students' opportunities to learn how mathematics can contribute to solving environmental problems. Integrating environmental literacy with mathematics learning could be a powerful way to make mathematical concepts more meaningful through real-world application, while also increasing students' awareness of issues related to sustainability.

Integrating PjBL-STEM Learning with Environmental Literacy

The integration of PjBL-STEM learning with environmental literacy can be an alternative, promising approach to meet both cognitive and environmental learning objectives. Integrating project-based learning with STEM activities allows students to use mathematical reasoning, scientific knowledge, and problem-solving within an environmental context.

Research has revealed that this integration enhances students' environmental awareness and critical thinking. According to Alkair (2023), STEM sustainability projects allow students to examine environmental challenges and construct new solutions. Likewise, Ramulumo (2025) reported significant increases in ecological awareness and nature-based environmental literacy among participants during interdisciplinary STEM learning activities.

Students can examine environmental issues, gather and analyze data, develop solutions, and assess the impact of their actions through project-based environmental activities. These activities foster both cognitive growth and environmental stewardship. Project-based sustainability education is one way to support solutions-oriented problem-solving skills while increasing the depth of understanding about environmental issues.

As education in sustainability-related knowledge and skills has garnered more attention, the characteristics of PjBL-STEM learning, mathematical critical thinking, and environmental literacy have increasingly entered empirical research questions. These studies primarily consider general STEM learning outcomes, or environmental education within science subjects. Research examining how project-based STEM learning in mathematics classrooms simultaneously cultivates (1) mathematical reasoning and (2) environmental awareness is limited.

Hence, this study bridges this research gap by developing and implementing a PjBL-STEM learning design that combines mathematical learning with environmental sustainability issues. The proposed learning design aims to develop mathematical critical thinking and environmental literacy among students by having them participate in project activities that closely relate to the recycling of plastic waste.

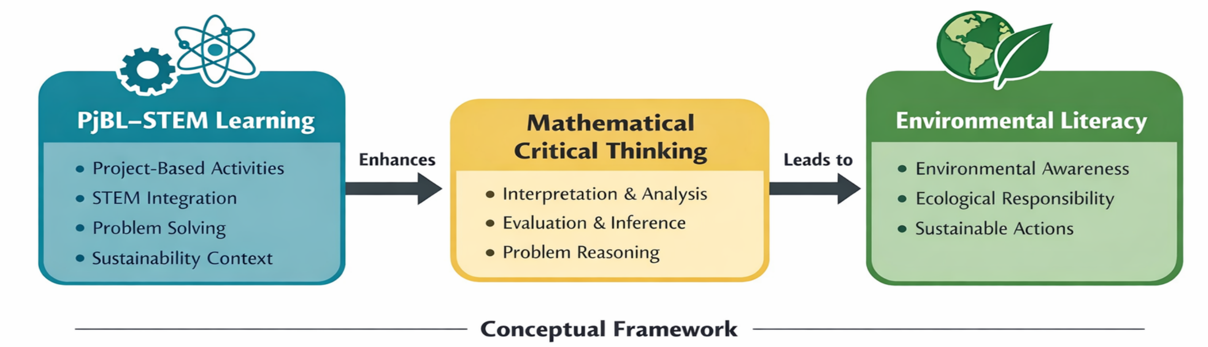

Figure 1. Conceptual Framework

METHOD

Research Design

This research used a Research and Development (R&D) design to develop and test the PjBL–STEM learning model, so that it can improve students' mathematical critical thinking and environmental literacy. The development process involved the 4D model (Thiagarajan, Semmel, & Semmel) and followed four stages: Define, Design, Development, and Dissemination.

The R&D approach was selected since the objective of the study was not only to validate an instructional strategy, but also to develop a learning design and instructional materials that could be implemented in mathematics classrooms. The developed learning devices included lesson plans, student worksheets, project guidelines, and assessment instruments.

To evaluate the effectiveness of the developed learning design, the study employed a quasi-experimental research design using a nonequivalent control group design. This design allows for the comparison of learning outcomes between students who experienced the PjBL–STEM learning intervention and those who participated in conventional instruction.

The experimental design is illustrated as follows:

Table 1. The Experimental Design

Group	Pre-test	Treatment	Post-test
Experimental	01	PjBL-STEM Learning	02
Control	03	Conventional Learning	04

The comparison of pre-test and post-test results between the experimental and control groups enabled the researchers to examine the impact of the PjBL-STEM learning design on students' mathematical critical thinking skills.

Participants and Research Context

The participants consisted of 32 elementary students selected using purposive sampling from two parallel classes at [School Name, City, Indonesia]: 16 students in the experimental class and 16 in the control class. Purposive sampling was employed because the quasi-experimental design required intact classrooms with comparable baseline characteristics, as verified by pre-test score equivalence (t = 0.84, p = 0.41).

The study was conducted during the second semester of the 2024/2025 academic year, focusing on the mathematics topic of arithmetic sequences and numerical patterns in Grade 5 elementary school. The link between the topic of arithmetic sequences and the recycling project is made explicit through students analyzing how many plastic ice cream buckets (3, 7, 11, 15, ... containers per row) are being stacked together and relating them using $U_n = a + (n - 1)b$ to determine how many containers are required for plant pot construction at different scales, thereby grounding an abstract concept of sequences in a concrete environmental engineering task. The experimental group learned through the PjBL-STEM learning design, while students in the control group were taught using conventional mathematics instruction. Through project-based learning activities, they aimed to engage students in collaborative problem-solving processes, apply mathematical reasoning to real-world situations, and address environmental sustainability problems.

Development Procedure

The development of the PjBL-STEM learning design followed the four stages of the 4-D development model:

1) Define Stage: The define stage involved analyzing curriculum requirements, learning objectives, and students' learning needs. Literature related to project-based learning, STEM education, mathematical critical thinking, and environmental literacy was reviewed to establish the theoretical foundation of the learning design. In addition, an analysis of mathematics learning materials was conducted to identify concepts that could be integrated with environmental sustainability issues.
2) Design Stage: In the design stage, the initial framework of the PjBL-STEM learning design was developed. This stage included the preparation of: (a) lesson plans, (b) student worksheets (LKPD), (c) project guidelines, and (d) assessment instruments. The learning activities were designed to integrate mathematics learning with environmental sustainability projects, allowing students to apply mathematical reasoning in authentic contexts.
3) Development Stage: This stage was conducted to develop and validate the learning devices, a process that included expert review and limited classroom trials. Two validators performed expert validation: (1) a scholar holding a doctorate in Mathematics Education and serving as an elementary mathematics curriculum lecturer, and (2) a science education lecturer specializing in sustainability pedagogy. Validation aspects measured include content accuracy and curriculum alignment, instructional design quality and pedagogical appropriateness, coherence of STEM component integration, clarity of project procedures and student worksheets, and alignment of the assessment with mathematical critical thinking criteria. Face and content validity were established through expert judgment, further supported by Cronbach's alpha (α = 0.87), indicating very high internal consistency of the instrument. The learning devices were revised and refined based on expert feedback to improve the clarity, feasibility, and instructional quality of each device.
4) Dissemination Stage: The final stage, dissemination, was carried out through implementation of the final learning design in classroom instruction and evaluation. This implementation involved guidance for the teachers and classroom observation to ensure that the learning activities were carried out according to the designed instructional procedures.

Learning Intervention

The experimental group received the PjBL-STEM learning design as a learning intervention centered on environmental sustainability issues. Its project activity was based on recycling plastic ice cream buckets into pots so that students could learn through practical sessions about environmental issues related to plastic waste. The learning process consisted of several stages:

1. Problem Identification: Students analyzed environmental problems related to plastic waste in their surroundings.
2. Project Planning: Students collaboratively designed a project to recycle plastic containers into functional products.
3. Investigation and Design: Students applied STEM concepts during the project process. Science concepts were used to understand environmental impacts, engineering principles were applied in product design, and mathematics concepts were used to analyze numerical patterns related to the project.
4. Product Development: Students constructed recycled plant pots and tested their functionality.
5. Reflection and Presentation: Students presented their projects and reflected on both the mathematical concepts and environmental lessons learned.

This learning intervention aimed to integrate mathematics, environmental awareness, and interdisciplinary STEM learning in a meaningful educational experience.

Research Instruments

Several instruments were used to collect data in this study:

Mathematical Critical Thinking Test: A written test was developed to measure students' mathematical critical thinking skills. The test items were designed to assess several critical thinking indicators, including: (a) interpretation, (b) analysis, (c) evaluation, (d) inference, and (e) explanation.

Observation Sheets: Observation sheets were used to document students' participation and engagement during project activities. The observations focused on students' collaborative learning behaviors and problem-solving processes.

Student Response Questionnaire: A questionnaire was administered to gather students' perceptions regarding the implementation of the PjBL-STEM learning model.

Data Collection Procedure

Data were collected through a sequence of research activities: (1) pre-test administration to measure students' initial mathematical critical thinking skills; (2) implementation of the PjBL-STEM learning intervention in the experimental group; (3) classroom observation during the learning process; (4) post-test administration to measure the improvement of students' critical thinking skills; and (5) collection of student responses regarding the learning experience.

Data Analysis

Descriptive and inferential statistical analyses were used for data analysis. Both the experimental and control groups were subjected to descriptive statistics (mean, standard deviation, and gain scores). Before proceeding with inferential testing, data normality was examined using the Shapiro–Wilk test and homogeneity of variance was assessed using Levene's test (both set at $\alpha = 0.05$). Normality (experimental: $W = 0.96$, $p = 0.67$; control: $W = 0.94$, $p = 0.43$) and homogeneity ($F = 1.82$, $p = 0.19$) assumptions were met. Following that, an independent samples t-test was performed to compare post-test scores between the experimental and control groups to assess the effectiveness of the PjBL-STEM learning design. Descriptive statistics were conducted to summarize students' critical thinking scores and characterize general trends in learning. An experimental study with a post-test control group design was conducted to examine whether the PjBL-STEM learning design could significantly improve students' mathematical critical thinking skills compared to conventional instruction.

RESULTS AND DISCUSSION

Results

Development and Validation of the PjBL–STEM Learning Design

The first aim of this study was to design a PjBL–STEM learning model based on mathematics combined with environmental sustainability contexts. Developed outputs included lesson plans, *LKPD* (student worksheets), project guidelines, and assessment instruments. Validation by experts showed that all components were ranked "highly valid" (mean validation score ≥ 85%), and the learning design meets or exceeds classroom implementation requirements across each of the five validation indicators.

The learning process focused on a contextual project called "Recycle Plastic Ice-Cream Buckets as Plant Pots." This project was designed to connect mathematical concepts with environmental sustainability by encouraging students to transform plastic waste into functional products.

Learning devices were examined prior to classroom implementation for their efficacy and usability through experts in mathematics education as well as environmental education. The validation results showed that the learning tools fell within the highly valid category, namely: (a) alignment with learning objectives, (b) integration of STEM components, (c) clarity of project procedures, and (d) consistency with mathematical critical thinking indicators. These findings suggest that the learning design developed addressed all classroom implementation criteria and was considered pedagogically viable for promoting interdisciplinary learning.

Students' Mathematical Critical Thinking Performance

A pretest–posttest control group design was adopted to collect quantitatively evaluable data on subjects' mathematical critical thinking skills by administering a pre-test and post-test to both the experimental group treated with the PjBL–STEM learning intervention and the control group. Table 2 presents comparative results including mean scores, standard deviations, gain scores, and inferential statistics.

Table 2. Distribution of Students' Mathematical Critical Thinking Scores

Score	Number of Students	Percentage
80	5	23%
90	7	32%
95	4	18%
100	6	27%

The results reveal that the experimental group had significantly higher post-test scores ($M = 91.25$, $SD = 5.84$) than the control group ($M = 74.50$, $SD = 8.21$). The experimental group has an N-Gain score (high category) of 0.74 and the control group an N-Gain score (low category) of 0.28. The difference was statistically significant as indicated by an independent samples t-test ($t = 4.32$, $p < 0.05$), indicating that students who received the PjBL–STEM learning design outperformed those in conventional instruction on mathematical critical thinking. Findings indicate that students' understanding of contextual problems, analyzing numerical patterns, and justifying their mathematical approaches when solving arithmetic sequences using these contexts was well demonstrated.

Analysis of Critical Thinking Indicators

A more detailed investigation showed how students scored on five measures of critical thinking. Table 2 presents the mean scores per indicator for the experimental group.

Interpretation

Interpreting was the strongest performance for students ($M = 92.5$, $SD = 4.1$): most students could identify the embedded arithmetic pattern and translate the real-world problem into a mathematical one when presented with visual representations of stacks of sequences of 3, 7, and 11 sets of plastic containers displayed to represent a generalized arithmetic sequence.

Analysis

In the analysis dimension (M = 90.3, SD = 5.2), students demonstrated that the common difference between successive terms is constant (d = 4) and used this to derive that $U_n = 3 + (n - 1) \times 4$ applies in the arithmetic sequence. This indicates that students are able to perceive quantitative relations when working within mathematical contexts.

Evaluation

In evaluative reasoning (M = 89.7, SD = 5.8), students validated their work through the coherence between differences in numbers within a container and their understanding of whether a sequence is linear or non-linear, as well as by verifying computed terms against the physically arranged objects in the container.

Inference

Using this pattern (M = 91.0, SD = 4.6), students applied the arithmetic sequence formula to correctly infer more distant terms in the sequence (e.g., $U_9 = 3 + (8 \times 4) = 35$; $U_{10} = 39$).

Explanation

The lowest-scoring dimension was explanation (M = 88.5, SD = 6.3), though still quite high; written responses indicated that some students incorrectly described each term as being multiplied by a factor of four from the previous term, rather than recognizing addition of a constant difference. Lower scores on this dimension suggest a need to focus on the written formulation of mathematical reasoning, as this is the area in which critical thinking performance at the elementary level is most challenged.

STEM Learning Outcomes

In addition to mathematical reasoning, the project activities also facilitated students' engagement with interdisciplinary STEM concepts.

1) Science: Students investigated the environmental impacts of plastic waste and discussed the importance of waste reduction and recycling.
2) Technology: Students used simple tools and materials to transform plastic containers into functional plant pots.
3) Engineering: Students designed and constructed recycled plant pots while considering structural stability and drainage systems.
4) Mathematics: Students applied arithmetic sequence concepts to analyze numerical patterns within the project tasks.

These activities allowed students to make a real-world connection between mathematics and environmental problem-solving.

Discussion

This study's results showed that the implementation of STEM-oriented PjBL significantly improved students' mathematical critical thinking ($t = 4.32$, $p < 0.05$, N-Gain = 0.74), consistent with evidence from Indonesian studies Rahmawati (2022) and global studies. This study further adds to the body of evidence demonstrating the PjBL–STEM effect on both mathematical reasoning and environmental literacy within an elementary mathematics learning context—an area not previously addressed in prior Indonesian PjBL–STEM studies.

First, the results demonstrate that PjBL–STEM learning provides students with authentic opportunities to engage in higher-order thinking processes. Students performed well on several indicators of critical thinking, including interpretation, analysis, evaluation, inference, and explanation. These cognitive processes are essential elements of critical thinking and mathematical reasoning.

The enhancement of students' reasoning skills reinforces previous research findings that project-based STEM learning environments can help develop analytical thinking and collaborative problem-solving (Zhang et al., 2024). The PjBL–STEM learning design nurtures students' engagement through an authentic problem-solving process in which students read contextual information, analyze patterns, and justify their reasoning.

The explicit connection between the recycling project and arithmetic sequence learning contributed to the gains demonstrated here. For stacks of ice-cream buckets, the formula $U_n = a + (n - 1)d$ applies: if each bucket adds 4 cm in height and the base height is 3 cm, the number of buckets needed to reach a total stack height of 75 cm is $n = (75 - 3)/4 + 1 = 19$. This real-world application produced meaningful engagement with abstract sequences in the practical tasks, thereby addressing the common problem of students perceiving mathematical concepts as irrelevant to real life. The mean post-test scores previously reported for STEM approaches without such contextual embedding were 78.4; the higher scores obtained in the present study ($M = 91.25$) suggest that the combination of project contextualization and situated, environmentally themed scaffolding may more effectively strengthen mathematical performance than decontextualized approaches. These findings provide support for prevailing models of contextual learning.

This is consistent with research suggesting that student-centered STEM pedagogy can help students conceptualize how mathematical inquiry relates to scientific inquiry and engineering design (English, 2016).

Third, the project activities encouraged collaborative learning and active student engagement. Students worked together to design, build, and experiment with recycled plant pots as part of the project. These collaborative partnerships allowed students to verbalize their ideas, discuss different strategies, and refine their reasoning. Research supports the view that collaborative inquiry environments nurture cognitive development and critical thinking by encouraging students to articulate their thinking and engage with perspectives that may challenge their own (Budiman et al., 2021).

An equally important outcome of this research was the impact of the PjBL–STEM learning program on environmental literacy. In addition to engaging in mathematical reasoning, students investigated environmental problems related to plastic waste. By transforming discarded materials into functional products and repurposing plastic containers, students developed awareness of environmental sustainability and recycling. Environmental literacy is characterized as a combination of knowledge about environmental systems and values that motivate efforts to protect the environment (Ardoin et al., 2020). Incorporating environmental issues into STEM helps students engage meaningfully with real-world problems, thereby enhancing their problem-solving skills.

By integrating content from multiple disciplines, PjBL–STEM learning also facilitates the bridging of disciplinary boundaries and connections across subject areas. Students simultaneously negotiated scientific ideas related to environmental pollution, engineering concepts within product design, and mathematical reasoning with respect to pattern analysis. Such cross-disciplinary integration is a defining feature of effective STEM education (Thibaut et al., 2018).

Moreover, the learning design employed in this study cultivates 21st-century skills such as critical thinking, teamwork, creativity, and environmental awareness—competencies that students will need to address the complex global challenges they will face in the decades ahead (Van Laar et al., 2020).

Several limitations of this work should be explicitly acknowledged. The sample consisted of only 32 students from a single school, which restricts generalizability. In addition, the study did not measure whether students' environmental behaviors outside of school were meaningfully affected, nor did it assess whether gains in environmental literacy or recycling attitudes persisted beyond the duration of the project. Furthermore, teacher facilitation quality was not systematically assessed as a variable, though observations suggested that it influenced the depth of mathematical discussions throughout the project. These limitations can be addressed in future research through larger multi-site samples and longitudinal designs.

In general, these results demonstrate the value of combining project-based learning with STEM education themes and environmental sustainability in mathematics instruction. Interdisciplinary approaches of this nature contribute to both cognitive and environmental development, thereby supporting the broader goals of 21st-century education.

CONCLUSION

The results show that the PjBL-STEM learning design developed can significantly improve students' mathematical critical thinking ($t = 4.32$, $p < 0.05$; experimental M = 91.25 vs. control M = 74.50; N-Gain = 0.74). All five indicators of critical thinking were scored well by students, with the highest-performing dimensions being interpretation (M = 92.5) and inference (M = 91.0), whereas explanation (M = 88.5) indicated the greatest need for continued attention in instruction. The unique combination of learning about arithmetic sequences alongside a context of plastic waste recycling made it possible to provide valid and reproducible interdisciplinary practice through an authentic mathematical modeling process that appears to encourage environmental literacy simultaneously.

The recycling program focused on helping students practice turning plastic waste into something functional, which was directly aligned with their hands-on environmental literacy development. Post-project observations indicated increased student awareness of sustainable practices, though formal environmental literacy measurement tools should be incorporated in future studies. The PjBL–STEM framework developed here is thus effective as an interdisciplinary approach for integrating higher-order mathematical thinking and environmental responsibility within elementary mathematics education.

Suggestions

For curriculum developers and mathematics educators, this study recommends prioritizing arithmetic sequence topics as entry points for STEM integration, as the inherent pattern-recognition structure of sequences maps naturally onto engineering design and environmental measurement tasks. The most challenging STEM integration area identified was the technology component, where limited digital resources constrained deeper technological application; future implementations should incorporate digital measurement tools or data-logging applications to strengthen the technology dimension. Longitudinal studies examining whether early interdisciplinary mathematics–environmental learning predicts sustained environmental behavior and mathematical disposition are strongly recommended.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the elementary school teachers and students who participated in this study. Appreciation is also extended to the expert validators for their valuable feedback during the development and validation of the PjBL–STEM learning design. The authors are grateful to Universitas Terbuka and Universitas Palangka Raya for the academic support provided throughout this research process.

AUTHOR CONTRIBUTION STATEMENT

Tri Dyah Prastiti contributed to conceptualization, methodology, learning design development, data collection, formal analysis, and manuscript writing. Jackson Pasini Mairing contributed to supervision, validation, theoretical framework development, and manuscript review and editing. Dwi Sambada contributed to investigation, classroom implementation, and data analysis. Intan Fatimah Ahmadah contributed to instrument development, data interpretation, visualization, and manuscript preparation. All authors have read and approved the final version of the manuscript.

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