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Implementation of Robotics-Integrated ESD STEM Learning to Improve Elementary School Students' Creative Thinking and Communication Skills

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Abstract: The study aims to analyze the effectiveness of the implementation of STEM ESD learning integrated with robotics in improving students' creative thinking and communication skills on environmental material. The study used a quasi-experimental method with a one-group pretest-posttest design for 118 sixth-grade students from four elementary schools in Bogor. The single-group design was chosen because the research focused on implementing learning innovations directly in the context of partner schools without changing the class divisions that have been established by the schools. The intervention was implemented over six meetings through ecosystem guard robot and trash cleaning robot projects that involved stages of environmental problem exploration, design, assembly, testing, and product presentation. Data were collected through creative thinking skills tests, peer assessments, observations, presentation assessments, and student interviews, then analyzed using descriptive statistics, the Wilcoxon test, and qualitative analysis. The results showed a significant increase in creative thinking skills with an average pretest score of 4.950 increasing to 7.710 in the posttest and an N-gain value of 0.688 (medium-high category). The highest increase occurred in the generate diverse ideas indicator with an N-gain of 0.864, followed by generate creative ideas at 0.645 and evaluate and improve ideas at 0.584. Communication skills also increased from an average pretest of 40.200 to 45.610 in the posttest with an N-gain of 0.304 (medium category). The communication aspects that experienced the most prominent improvement were the ability to discuss, convey ideas verbally, and collaborate in groups, while formal communication during presentations still needed strengthening. The Wilcoxon test results showed a significant difference between the pretest and posttest in creative thinking skills ($Z = -8.536$; $p < 0.05$) and communication ($Z = -9.460$; $p < 0.05$). Thus, project-based robotics-integrated STEM ESD learning is effective in improving elementary school students' creative thinking and communication skills while supporting the development of 21st-century competencies in a contextual and sustainable manner.

Keywords: Communication skills; Creative thinking skills; Education for sustainable development (ESD); Primary school; Project-based learning (PjBL); Robotics; STEM

Introduction

Education plays a fundamental role in shaping human civilization and fostering national character. In the twenty-first century, rapid technological advancement has significantly transformed social interaction, economic systems, and educational practices. Although digitalization facilitates access to information and communication, it also presents challenges related to social interaction, environmental

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awareness, and character development if not accompanied by meaningful and value-based education (Parthama et al., 2025). Consequently, contemporary education must not only emphasize technological literacy but also develop students' creativity, communication, collaboration, and social responsibility.

The transformation of education in the digital era requires a shift from teacher-centered instruction toward student-centered and problem-oriented learning. Twenty first century education emphasizes the development of creativity, critical thinking, communication, and collaboration (4C skills), which are considered essential competencies for addressing complex global challenges, including environmental degradation and technological disruption (Muliyadi et al., 2026; Safitri et al., 2024). However, classroom practices in many Indonesian elementary schools remain dominated by lecture-based approaches that limit opportunities for students to explore ideas, solve authentic problems, and actively participate in collaborative learning activities (Anjarwati et al., 2022).

These challenges are reflected in international assessment results. The Programme for International Student Assessment (PISA) reported that Indonesian students continue to experience difficulties in applying knowledge and reasoning within real-world contexts, particularly in creative thinking and problem-solving domains. According to the PISA 2022 creative thinking framework, creative thinking includes the abilities to generate diverse ideas, generate creative ideas, and evaluate and improve ideas. These competencies are essential for enabling students to produce innovative solutions and adapt to future societal demands.

One instructional approach considered effective for developing these competencies is STEM (Science, Technology, Engineering, and Mathematics) education. STEM learning integrates interdisciplinary knowledge through inquiry, engineering design, and problem-solving processes. Previous studies have shown that STEM-based instruction can improve students' creativity, critical thinking, and problem-solving skills (Khafidh et al., 2025; Lianti et al., 2023; Susilawati et al., 2022). In addition, the engineering design process embedded within STEM activities encourages students to identify problems, design prototypes, test solutions, and evaluate outcomes, which directly supports the development of creative thinking skills.

Alongside STEM education, global educational discourse increasingly emphasizes the importance of Education for Sustainable Development (ESD). ESD aims to equip learners with the knowledge, skills, values, and attitudes necessary to support environmental, social, and economic sustainability. In environmental education contexts, ESD encourages students to understand ecological problems and participate actively in developing sustainable solutions. Environmental issues, particularly waste management, remain a significant challenge in Indonesia due to increasing waste production, inadequate waste processing systems, and limited environmental awareness among communities (Rando et al., 2022). Therefore, integrating sustainability-oriented learning into elementary education is essential to cultivate ecological responsibility from an early age.

Another emerging innovation in education is robotics-based learning. Educational robotics allows students to transform abstract scientific and mathematical concepts into concrete technological products. Robotics activities also support collaboration, experimentation, computational thinking, and iterative problem-solving processes. Through robotics projects, students engage in designing, testing, and improving technological solutions, thereby strengthening both creative thinking and communication skills.

Project Based Learning (PjBL) provides a suitable pedagogical framework for integrating STEM, ESD, and robotics. PjBL encourages students to investigate authentic problems, collaborate in teams, and produce meaningful products through inquiry and design processes. In environmental learning contexts, robotics-based PjBL can facilitate experiential learning by engaging students in designing technological solutions for waste management problems. Through these activities, students are expected not only to understand environmental concepts theoretically but also to apply sustainability principles in real-life contexts.

Despite the growing body of research on STEM, ESD, robotics, and PjBL, several critical gaps remain in the literature. Existing studies generally examine STEM, robotics, or sustainability education independently, with limited efforts to integrate these approaches into a unified pedagogical framework. Research on robotics-based learning frequently focuses on computational or technical skills, while sustainability-oriented ESD studies often emphasize conceptual environmental awareness without integrating technological problem-solving experiences. Furthermore, most previous studies have been conducted at the secondary or higher education level, leaving elementary school contexts underexplored, particularly in developing countries such as Indonesia.

Another important limitation is that prior studies rarely examine creative thinking and communication skills simultaneously within sustainability-oriented robotics learning. Although creative thinking is increasingly emphasized in the PISA 2022 framework, classroom learning in Indonesian elementary schools still tends to prioritize content mastery and memorization over idea generation, innovation, and collaborative communication. Consequently, there is insufficient empirical evidence regarding how integrated STEM–ESD robotics learning can support both cognitive and social competencies through authentic environmental problem-solving activities.

The novelty of this research lies not merely in using STEM or robotics in learning, but in the comprehensive integration of four educational dimensions within a single instructional model. First, this study integrates STEM and Education for Sustainable Development (ESD) frameworks simultaneously, enabling students to combine scientific-technological problem-solving with sustainability values and environmental responsibility. Second, the study applies robotics within Project Based Learning (PjBL) specifically in elementary environmental education contexts, where students collaboratively design and develop waste-cleaning robot prototypes as solutions to real-world waste management problems (Susilawati et al., 2023). Third, this research adopts the PISA 2022 creative thinking framework to measure students' abilities in generating diverse ideas, generating creative ideas, and evaluating and improving ideas, which is still rarely implemented in Indonesian elementary education research. Fourth, the study simultaneously evaluates communication skills as complementary twenty-first century competencies, thereby providing a more holistic understanding of student learning outcomes.

This research is important for several logical and practical reasons. First, environmental degradation and waste management problems in Indonesia continue to increase, while environmental education in elementary schools is often delivered theoretically and lacks meaningful student engagement. Integrating sustainability issues into hands-on robotics projects allows students to experience authentic problem-solving processes and develop environmental awareness through direct action.

Second, the demands of twenty-first century education require instructional models that not only improve academic achievement but also strengthen creativity, collaboration, communication, and innovation (Muliyadi et al., 2023). However, many elementary classrooms still rely heavily on teacher-centered approaches that limit student participation and inquiry. Therefore, there is an urgent need for innovative learning models capable of transforming passive learning into active, collaborative, and contextual learning experiences.

Third, the implementation of Kurikulum Merdeka emphasizes project-based and competency-oriented learning, yet many teachers still face difficulties in designing interdisciplinary learning activities that integrate technology and sustainability issues meaningfully. This study provides an empirical model that demonstrates how STEM, ESD, robotics, and PjBL can be implemented cohesively in elementary education.

Finally, this study contributes theoretically and empirically to the advancement of sustainability-oriented STEM pedagogy. By examining the combined effect of STEM ESD integrated robotics learning on creative thinking and communication skills, the study expands current educational research beyond isolated investigations of STEM or robotics instruction. The findings are expected to provide evidence-based recommendations for teachers, curriculum developers, and policymakers regarding innovative strategies to strengthen twenty-first century competencies in Indonesian elementary schools.

Based on these gaps and innovations, this study aims to investigate the effectiveness of STEM ESD integrated robotics learning through Project Based Learning in improving elementary students' creative thinking and communication skills within environmental education contexts. The learning activities involve contextual robotics projects focused on waste management, in which students design and develop waste-cleaning robot prototypes through collaborative inquiry and engineering processes.

Method

Research Location and Period

This research was conducted in four elementary schools located in Bogor and Bogor Regency, West Java, Indonesia. Two schools were situated in Bogor City, and two others were in Bogor Regency.

The study was implemented during the first semester of the 2025/2026 academic year, specifically in Phase C (upper elementary level). The research activities were carried out from April 2025 to January 2026, encompassing preparation, implementation of intervention, data collection, and data analysis stages.

Population and Sample

The population in this study consisted of phase C students at four primary schools located in the city and regency of Bogor, West Java Province.

The sample used in this study consisted of phase C students, using one class, namely the experimental class. Schools A, B, and C each consisted of 30 students, while school D consisted of 28 students, bringing the total number of students to 118. The sampling technique used in this study was purposive sampling, namely the selection of classes based on criteria of suitability with the research objectives.

Experimental Design

This study employed a quantitative research approach using a quasi-experimental method.

According Creswell et al. (2017) to quasi-experimental research resembles true experimental research; however, it does not involve random assignment of participants to groups. Quasi-experimental methods are used to examine causal relationships between variables by applying a treatment or intervention without randomization.

In this study, the quasi-experimental method utilized a Pretest Post-test One Group Design. This design involved only one sample group, namely the experimental class, which received the treatment in the form of STEM ESD integrated robotics learning. Students' creative thinking and communication skills were measured before and after the intervention to determine the effect of the treatment. The design of the study is illustrated in Table 1.

Table 1. Pretest Posttest One Group Design

Group	Pretest	Treatment	Posttest
Experimental Class	O_1	X_1	O_2

Description: O_1 (Pretest): Pretest administered to the experimental class to measure students' creative thinking and communication skills prior to the intervention. X_1 (Intervention): Implementation of STEM ESD integrated robotics learning. O_2 (Posttest): Posttest administered to the experimental class to measure students' creative thinking and communication skills after the intervention.

The variables in this study consisted of independent and dependent variables. The independent variable was STEM ESD integrated robotics learning. The dependent variables were students' creative thinking skills and communication skills.

Experimental Procedures

The procedures for conducting the research carried out by the researcher in this study are as follows:

Preparation Stage

At this stage, the researcher determines the research location, sample, time and materials to be used in the research, as well as coordinating with the school, confirming participant participation, prepares the facilities and learning tools to be used, namely integrated STEM ESD learning modules with robotics, and compiles a schedule for implementation at the school, designs research instruments (in the form of peer assessment questionnaires, pre-test and post-test of creative thinking skills, teacher observation, creative product assessment, and assessment rubrics), and validates the research instruments.

Implementation Stage

The research implementation stage includes:

Pretest

Before the implementation of learning, a pretest was conducted to assess students' initial understanding of creative thinking and communication skills, as well as to identify existing competency gaps. This step aimed to obtain an initial picture of the students' level of mastery of concepts so that it could be used as a basis for designing more targeted learning strategies.

Introduction and Practice

Teachers introduced basic STEM ESD concepts relevant to the topic to be studied, namely environmental material, covering the basic principles of programming (coding) and its application in the form of practical exercises. One of the activities carried out was the assembly and programming of simple robots. The learning activities were designed based on hands on experience, so that students were directly involved in exploring the working principles of robotics.

This active involvement aims to facilitate conceptual understanding while developing computational thinking skills, creative thinking, creativity, and problem-solving abilities. Thus, this treatment phase focuses not only on knowledge transfer but also on strengthening 21st century skills relevant to the research objectives.

Implementation

The implementation process of integrated robotics STEM ESD learning is carried out through several interrelated stages. The initial stage begins with problem formulation, where teachers facilitate discussions related to environmental issues, particularly waste problems, and guide students to identify and formulate relevant problems. The next stage is planning and assembling robot components, where students design solutions through simple robot designs, select appropriate components, and illustrate their designs in sketches. Next, students are directed to compile algorithms and develop program codes (coding) as the basis for robot control.

Figure 1. Implementation program code

This process continues with testing and implementation, where the designed robots are tested to ensure their functionality is in line with the predetermined objectives. If any obstacles are found, students reflect and make improvements to the design, algorithm, and program code (coding) to optimise the robot's performance. The final stage is the presentation of the project results, where students systematically present their group work, including explaining the process, obstacles, and solutions obtained during the learning process.

Each stage of learning, which is carried out simultaneously, contributes to the development of 21st century skills, including critical thinking, creativity, communication, and collaboration. In the problem formulation stage, students hone their critical thinking skills through the analysis of real issues while practising communication to express their ideas. In the planning stage, creativity and collaboration become dominant through activities to design innovative solutions together with the group. The development of algorithms and coding emphasises the strengthening of critical thinking and creativity in designing effective programming solutions. The testing and refinement stage encourages students to critically evaluate and optimise, while working together in teams.

Figure 2. Robot testing

Teacher observation during the learning implementation process aims to directly measure students' communication skills in the learning context. Observations are conducted to obtain authentic data on students' ability to convey ideas, express opinions, provide feedback, collaborate in group discussions, and present their work orally. Through these observations, researchers can assess the verbal and non-verbal communication aspects that arise during the learning process, there by obtaining a comprehensive picture of the development of students' communication skills. The observation data is then used to analyse the level of achievement of communication skill indicators, evaluate the effectiveness of the learning model applied, and serve as triangulation material with presentation assessment and peer assessment data to improve the validity of the research results.

Finally, the project presentation stage provides an opportunity to strengthen communication and collaboration skills, as students are expected to be able to convey their learning outcomes systematically while discussing with other groups. Thus, the implementation of learning not only produces applicable robotic products but also strengthens students' cognitive, affective, and social skills in an integrated manner.

Figure 3. Project presentation

Post-test

After the learning process, a post-test was conducted to measure the achievement of creative thinking skills. The post-test in this study aimed to measure the level of students' creative thinking skills after the implementation of the learning approach. This measurement was conducted to determine the students' final achievement based on creative thinking skill indicators, which included the ability to generate diverse ideas, generate creative ideas, and evaluate and improve ideas.

The post-test results were used to compare the students' initial and final conditions, so that the improvement in creative thinking skills after the treatment could be determined. In addition, the post-test data served as the basis for analysing the effectiveness of the learning model through the calculation of the N-gain score and relevant statistical analysis. The post-test instrument was developed based on the creative skills assessment framework developed by the Programme for International Student Assessment study, which emphasises flexibility, novelty, and evaluative skills in relation to ideas.

Peer Assessment

Peer assessment in this study aims to obtain data on students' communication skills through assessments conducted by peers during the learning process. This assessment is used to identify students' ability to convey ideas clearly, respond to others' opinions, collaborate in group discussions, and demonstrate effective communication skills. Through peer assessment, researchers obtain additional, more objective perspectives because students are assessed in real interaction situations by their peers. The data obtained is then used to complement the results of teacher observations and presentation assessments, thereby increasing the validity and reliability of the data through triangulation techniques. In addition, peer assessment also encourages students to reflect on themselves and develop awareness of the importance of communication skills in collaborative learning.

Final Stage

At this stage, researchers processed pretest and post test data using descriptive statistical techniques. From the data processing results, it was found that the data was not normally distributed, so the Wilcoxon nonparametric test was used to test the difference between the pretest and post test results. This test was chosen because it is suitable for data that does not meet the assumption of normality and aims to analyse the significance of changes in students' creative thinking skills and creativity after the implementation of integrated STEM Robotics project-based learning. In addition, supporting data was also collected through student self-assessment questionnaires, teacher observations, and creative product assessments, which served to provide a comprehensive picture of the development of student competencies during the learning process.

Data Analysis

The data collected in this study were analyzed to answer research questions regarding the effectiveness of STEM ESD integrated robotics learning on students' creative thinking and communication skills.

Qualitative data in this study were obtained from student interviews conducted after the implementation of the STEM ESD integrated robotics learning model. The analysis was carried out through three stages: data reduction, data display, and conclusion drawing. Data reduction involved selecting, simplifying, and coding important responses related to students' creative thinking and communication skills. The reduced data were then organized and grouped based on relevant indicators to facilitate interpretation. Finally, conclusions were drawn to describe patterns and themes emerging from students' responses. The qualitative findings were used to support and strengthen the interpretation of the quantitative results.

Quantitative data were obtained from several instruments, including pretest and post test scores to measure students' creative thinking skills, peer assessment questionnaires to evaluate communication skills, teacher observation sheets to assess students' communication performance during learning activities, and prototype robot assessments to measure students' creativity in developing project products. These data were analysed statistically to determine the effectiveness of the implemented learning model.

Result and Discussion

Creative Thinking Skills

Descriptive analysis shows an increase in the average creative thinking skills scores of students in all schools after the implementation of integrated STEM–ESD robotics learning. The average pretest scores ranged from 6.00 to 6.43 and increased to 7.47 to 7.87 on the posttest. The Wilcoxon test showed that all differences were significant ($p < 0.05$). The N-Gain values were in the low to moderate category.

Table 2. Results of Students' Creative Thinking Skills Data

Sch.	N	M. Pre	M.Post	SD Pre.	SD Post.	M. N-Gain	SD N-Gain	p-Values
A	30	6.03	7.73	1.65	1.14	0.01	0.01	0
B	30	6.37	7.87	1.43	0.97	0.01	0.01	0
C	30	6.00	7.47	1.57	1.16	0.01	0.01	0
D	28	6.43	7.79	1.29	0.91	0.01	0.01	0

These findings indicate that environment themed robotics project-based learning effectively improves students' creative thinking skills consistently in four schools. The absence of significant differences between schools in the pretest and posttest indicates that the intervention had a relatively uniform impact.

When analyzed based on creativity indicators (generate diverse ideas, generate creative ideas, evaluate and improve ideas), all indicators showed a significant increase. The most consistent improvement was seen in the indicators of generating creative ideas and evaluating and improving ideas. This shows that student involvement in the process of designing, testing, and improving robot prototypes encourages them not only to generate ideas but also to reflect on and refine those ideas.

Table 3. Achievement of Creative Thinking Skills Indicators

School	Domain Creative Thinking Skills	Pretest Mean	Posttest Mean	p-value	N-Gain Mean
School A	Generate diverse ideas	2.70	2.90	0.00	0.04
	Generate creative ideas	1.70	2.53	0.00	0.28
	Evaluate and improve ideas	1.63	2.30	0.00	0.19
School B	Generate diverse ideas	2.23	2.73	0.00	0.21
	Generate creative ideas	2.33	2.63	0.00	0.13
	Evaluate and improve ideas	1.80	2.50	0.00	0.26
School C	Generate diverse ideas	2.20	2.57	0.00	0.13
	Generate creative ideas	2.10	2.50	0.00	0.16
	Evaluate and improve ideas	1.70	2.40	0.00	0.27
School D	Generate diverse ideas	2.32	2.89	0.00	0.26
	Generate creative ideas	2.14	2.54	0.00	0.13
	Evaluate and improve ideas	1.96	2.36	0.00	0.14

The important meaning of these findings is that the integration of STEM and ESD contexts creates a problem based and authentic learning environment. When students face real environmental problems and are asked to design technological solutions, their thinking process becomes more exploratory and reflective. However, the N Gain value, which is still in the low-medium category, indicates that creativity development requires long term intervention and continuous practice.

Integrated STEM ESD learning with robotics has been proven to contribute to the improvement of creative thinking skills in elementary school students. The integration of environmental issue-based engineering projects provides authentic learning experiences that encourage high level cognitive engagement. These findings are in line with international studies showing that project based STEM and engineering design approaches are effective in enhancing students' creativity and problem-solving abilities (Chung et al., 2022; Margot et al., 2019). However, most of these studies still focus on secondary education and have not explicitly integrated the dimension of sustainability in the context of elementary schools. In this study, the integration of STEM with Education for Sustainable Development (ESD) and robotics in phase C provides a more comprehensive and contextual approach.

Reviewed from the PISA 2022 framework, improvements in the indicators of generating diverse ideas, generating creative ideas, and evaluating and improving ideas show that learning not only increases ideas but also improves the quality and novelty of ideas. Unlike previous studies that measured creativity in general, this study uses creativity indicators based on the latest international framework, providing a more specific mapping of student ability development. Robot design and prototype testing activities enable an iterative cycle of exploration, evaluation, and refinement of ideas, which, according to Henriksen et al. (2021) and Thibaut et al. (2018), is at the core of creativity development in engineering design based STEM learning.

ESD integration also strengthens creativity stimulation through the presentation of authentic and meaningful environmental issues. Sustainability-based learning encourages students to think systemically and consider the social and ecological impacts of the solutions they design (Shulla et al., 2020; Vaughter & Yume Yamaguchi, 2023; Rieckmann, 2025). Thus, the creativity that develops is not abstract, but contextual and applicable. This approach expands STEM studies at the elementary school level by emphasizing sustainability as a conceptual framework, which is still relatively limited in empirical literature in the Indonesian context.

Although significant improvements have been achieved, N-Gain scores in the low to moderate range indicate that creativity development requires continuous and systematic implementation. Creativity develops through long-term practice, consistent pedagogical support, and reflective assessment that encourages idea refinement (Lancrin et al., 2019; Álvarez-Huerta et al., 2022). Therefore, strengthening the reflection stage, design iteration, and explicit creativity indicators in STEM ESD learning is recommended so that the impact of the intervention can be more optimal and sustainable.

Creative Robot Products

The robot product assessment shows that most students were able to produce prototypes that functioned well. Schools A, B, and C obtained the maximum robot function score (Mean = 4.00), while School D scored slightly lower (Mean = 3.50). This shows that, technically, students were able to implement scientific and engineering concepts appropriately.

In terms of creativity, innovation, and design, School B showed the most consistent and relatively higher achievements compared to other schools. The variation in scores for innovation and design shows that product quality is not only determined by technical function, but also by the depth of idea exploration and design freedom.

Table 4. Robot Assessment Data in Four Schools

School	Domain Creative Products	Mean	Std. Dev.	p-value
School A	Robot Function	4.00	0.00	0.00
	Creativity	3.23	0.43	0.00
	Innovation	3.23	0.43	0.00
	Design	3.23	0.43	0.00
School B	Robot Function	4.00	0.00	0.00
	Creativity	3.53	0.51	0.00
	Innovation	3.50	0.51	0.00
	Design	3.50	0.51	0.00
School C	Robot Function	4.00	0.00	0.00
	Creativity	3.23	0.43	0.00
	Innovation	3.00	0.00	0.00
	Design	3.03	0.18	0.00
School D	Robot Function	3.50	0.51	0.00
	Creativity	3.25	0.44	0.00
	Innovation	3.46	0.51	0.00
	Design	3.00	0.00	0.00

The significance of these findings shows that integrated STEM ESD learning with robotics does not stop mastering concepts but can produce tangible artifacts that reflect students' creative thinking processes. The variation between schools indicates that the quality of implementation, school culture, and learning support influences the quality of project outcomes.

Thus, robotics projects not only serve as an evaluation tool but also as a medium for students to actualize their creativity in the context of environment-based problem solving.

Analysis of the quality of robot creative products shows differences in achievement in terms of function, creativity, innovation, and design in four schools. In terms of function, Schools A, B, and C obtained perfect average scores, indicating the students' ability to apply science, technology, and engineering concepts appropriately so that the robots worked as intended. This achievement is in line with findings that project based STEM integration effectively improves problem solving skills and the application of cross disciplinary concepts (PISA, 2023). In contrast, School D showed lower and more varied function scores, indicating technical challenges or limitations in learning support facilities, as confirmed in studies that the quality of implementation and facility support greatly affects technology based learning outcomes (Sugeng, 2025).

In terms of creativity, all schools were in the good category, with School B scoring the highest. This shows that project based and engineering learning encourages students to explore ideas and think flexibly. Recent literature confirms that the engineering design process approach in STEM significantly improves the ability to generate diverse and original ideas (Thibaut et al., 2018; Conradty, 2020). The variation is more evident in the aspect of innovation, where School B and D show stronger elements of novelty compared to Schools A and C. The low innovation score at School C indicates a tendency for products to still follow existing patterns, so that the strengthening of the iteration and idea evaluation stages needs to be optimized, as suggested in the 21st century creative problem solving framework (Kim et al., 2019).

In terms of design, School B again achieved the highest score with a more diverse range of products, reflecting the integration of technical and aesthetic functions. Recent research shows that the quality of design in robotics projects not only reflects an understanding of technical concepts but also the ability to reflectively evaluate and refine ideas (Zhang et al., 2024). Overall, the robot products were rated good to very good, with School B consistently excelling in creativity, innovation, and design, while Schools A and C stood out in functional consistency. These findings reinforce the argument that the quality of creative products in STEM robotics learning is influenced by a combination of instructional design, learning environment support, and opportunities for continuous idea exploration (Kotz et al., 2025).

Communication Skills

The observation results show that the average communication skills of students are in the good category (Mean total observation = 3.61). The presentation score is slightly lower (Mean = 3.25), indicating that students are stronger in collaborative communication than in formal communication in front of the class.

Table 5. Students' Communication Skills (Total Observation)

School	N	Mean	Std. Deviation	Std. Error	Min	Max
School A	30	3.47	0.57	0.10	2.00	4.00
School B	30	3.47	0.63	0.11	2.00	4.00
School C	30	3.83	0.38	0.07	3.00	4.00
School D	28	3.68	0.48	0.09	3.00	4.00
Total	118	3.61	0.54	0.05	2.00	4.00

Table 6. Students' Communication Skills (Total Presentation)

School	N	Mean	Std. Dev.	Std. Error	Min	Max
A	30	3.23	0.43	0.07	3.00	4.00
B	30	3.50	0.51	0.09	3.00	4.00
C	30	3.00	0.00	0.00	3.00	3.00
D	28	3.25	0.44	0.08	3.00	4.00
Total	118	3.25	0.43	0.04	3.00	4.00

School C received the highest observation score, indicating strong collaborative interaction during learning. However, the relatively low presentation scores indicate that formal speaking skills still need strengthening. In contrast, School B had the highest presentation scores, indicating better public communication habits.

Table 7. Student Communication Skills Based on Peer Assessment

School	Mean	N	Std. Deviation	Median	Min	Max
School A	45.30	30	8.10	47.00	23	57
School B	45.30	30	8.10	47.00	23	57
School C	45.30	30	8.10	47.00	23	57
School D	45.11	28	8.35	47.00	23	57
Total	45.25	118	8.05	47.00	23	57

Peer assessment data showed an average score of 45.25 with relatively little variation between schools. This confirms that, in general, students rated their peers' communication skills as moderate to high.

Conceptually, these results show that robotics-based learning encourages active interaction, discussion, idea negotiation, and team collaboration. This process naturally develops interpersonal communication. However, formal presentation skills require explicit practice and additional pedagogical strategies.

The results of the analysis show that students' communication skills are consistent with their creative thinking skills in each school. Schools that score high in creativity and robot product innovation also tend to perform better in presentation communication. These findings indicate that the ability to generate diverse and creative ideas is closely related to the ability to articulate and defend those ideas verbally. Recent literature confirms that creativity and communication are 21st century competencies that develop integrally in STEM project-based learning (PISA, 2023; Chafidah et al., 2024).

The higher average observation scores compared to presentation scores indicate that students are more skilled at communicating in a collaborative context during the robot design process than when formally presenting ideas in front of the class. This pattern is consistent with the creative thinking results, where some students have been able to generate diverse and innovative ideas but still need reinforcement in the evaluation and improve ideas dimension, which requires reflection and verbal argumentation skills. School B, which excelled in creativity and innovation, also had the highest presentation scores, while schools with lower innovation tended to have less varied presentation performances. This indicates that the depth of the creative thinking process contributes to the quality of students' formal communication.

Overall, the integration of creativity and communication results confirms that integrated STEM ESD learning with robotics not only encourages the production of ideas and product innovation but also facilitates the development of the ability to communicate ideas contextually. However, strengthening the aspects of formal presentation and reflective communication is still necessary so that students' creative processes develop comprehensively, from the idea creation stage to the mature evaluation and elaboration stages. The integration of these two competencies is key to shaping students' creative and communicative profiles in line with the demands of 21st century learning.

Synthesis of Findings

Overall, the results of the study show that integrated STEM–ESD learning with robotics: a) Significantly improves creative thinking skills. b) Produces functional and creative robot products. c) Develops communication skills, especially in a collaborative context.

The relatively consistent effectiveness across four schools shows that this learning model is adaptable to different school contexts. However, the low to moderate N Gain category confirms that the development of creativity and communication requires continuous intervention, not just short-term implementation.

Thus, integrated STEM ESD learning with robotics has the potential to become a relevant contextual learning model for science education in elementary schools, particularly in developing 21st-century competencies through authentic environmental issues and technology-based solutions.

Conclusion

This study concludes that the implementation of STEM ESD integrated robotics learning significantly enhances elementary students' creative thinking and communication skills within environmental education contexts. The findings demonstrate consistent improvements across the indicators of generating diverse ideas, generating creative ideas, and evaluating and improving ideas, indicating that students were able not only to produce original ideas but also to refine and justify them through iterative engineering and design processes. Although the N-Gain scores were generally in the low to moderate category, the statistically significant differences between pretest and posttest results confirm the effectiveness of the intervention across participating schools. The quality of students' robotic prototypes further supports these findings, as most products fulfilled functional criteria while demonstrating varying levels of creativity, innovation, and environmental problem-solving. Differences among schools suggest that learning environment, teacher facilitation, and resource availability influence the depth of creative exploration and product development. In addition, communication results reveal that students performed better in collaborative interactions than in formal presentations, indicating that while idea generation and teamwork improved substantially, the ability to articulate and defend ideas in structured academic settings still requires reinforcement through continuous practice. The novelty of this research lies in the integrated implementation of STEM, Education for Sustainable Development (ESD), robotics, and Project-Based Learning (PjBL) within elementary environmental education, a combination that remains underexplored in previous studies, particularly in Indonesian contexts. Unlike prior research that generally examines STEM, robotics, or sustainability education separately, this study combines interdisciplinary STEM learning, sustainability-oriented ESD principles, robotics-based technological design, and contextual project learning into a unified instructional model focused on waste management problems. Furthermore, the study simultaneously measures creative thinking based on the PISA 2022 framework and communication skills as complementary twenty-first century competencies, thereby providing a more holistic evaluation of student learning outcomes. Overall, STEM ESD integrated robotics learning creates a meaningful, contextual, and sustainability-oriented learning environment that fosters creativity, collaboration, communication, and technological problem-solving skills simultaneously. The findings highlight the importance of integrating sustainability issues and technology-based project learning into elementary education to prepare students for complex real-world challenges and support the implementation of competency-based curricula such as Kurikulum Merdeka. However, this study also has several limitations. First, the research employed a one-group pretest-posttest quasi-experimental design without a control group, limiting the ability to compare the intervention effects with other instructional approaches. Second, the study was conducted within a limited regional context involving elementary schools in Bogor, Indonesia, which may affect the generalizability of the findings to different educational settings or demographic conditions. Third, the intervention was implemented over a relatively short duration, so the long-term impact of STEM ESD integrated robotics learning on students' creativity, communication, and sustainability awareness could not be fully examined. Therefore, future research is recommended to involve larger and more diverse samples, include control group comparisons, and investigate the long-term effectiveness of sustainability-oriented robotics learning across broader educational contexts.

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Conflicts of Interest

The authors declare no conflict of interest.

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