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Research Article

Effectiveness of Reverse Engineering STEM-ESD on Students' Creative Problem-Solving Ability: A Quasi-Experimental SDG-12 Topic Study

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ABSTRACT

Purpose of the study: This study examines the effectiveness of a Reverse Engineering-based STEM-Education for Sustainable Development (STEM-ESD) learning model in improving tenth-grade students' Creative Problem Solving (CPS) Thinking ability on the SDG-12 topic, compared with an Engineering Design Process-based STEM-ESD (STEM-EDP) model and conventional instruction.

Methodology: A mixed-methods explanatory sequential design combined a quasi-experimental non-equivalent control-group pretest–posttest design with 108 tenth-grade students in three intact classes (STEM-RE, STEM-EDP, and Control) at a public senior high school in Bandung, purposively selected at the class level, and semi-structured interviews with 9 purposively selected students. Quantitative data were analyzed using normalized gain (N-Gain), the Shapiro–Wilk normality test, the Kruskal–Wallis test, and the Mann–Whitney post hoc test with Bonferroni correction in SPSS; qualitative data were analyzed using Braun and Clarke's thematic analysis.

Main Findings: The STEM-RE group achieved the most consistent improvement in CPS Thinking across all four indicators (N-Gain = 0.255–0.301), with statistically significant differences among the three groups (Kruskal-Wallis and Mann-Whitney, $p < 0.05$). Idea flexibility was the only indicator to reach the moderate category, while the STEM-EDP group showed fluctuating, low-category gains and the Control group showed negligible or negative change.

Novelty/Originality of this study: This study provides indicator-level comparative evidence that a Reverse Engineering-based STEM-ESD sequence, contextually integrated with SDG-12, produces more consistent CPS Thinking gains than an Engineering Design Process-based alternative within the same sustainability context a comparison not previously reported thereby advancing both creative problem-solving pedagogy and sustainability-oriented science education.

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1. INTRODUCTION

The environmental crisis resulting from unsustainable production and consumption patterns is one of the most pressing global challenges of the 21st century. The United Nations Environment Programme (UNEP) reports that the world generates more than 2.1 billion tons of solid waste per year, a figure projected to reach 3.4 billion tons by 2050 without a substantial change in consumption behavior [1]. Indonesia itself produced 68.5 million tons of waste in 2023, making it one of the largest waste producers in Southeast Asia [2], a situation worsened by low public awareness of sorting, managing, and recycling organic, inorganic, and hazardous waste [3]. This problem is directly connected to Sustainable Development Goal (SDG) 12, Responsible Consumption and Production [4]-[6].

Addressing this crisis requires an education system that produces a generation able to think creatively about real solutions, not merely understand the issues conceptually. Creative Problem Solving (CPS) is widely regarded as an essential 21st-century competency for science learning [7], encompassing problem analysis, flexible idea generation, critical evaluation of alternatives, and detailed product-design elaboration [8]-[10]. This competency aligns with the Framework for 21st Century Learning [11], and with Indonesia's Merdeka Curriculum, which positions creative and critical reasoning as core dimensions of the Pancasila Student Profile [8].

In practice, however, a substantial gap remains between this ideal and students' actual CPS ability. Science learning in Indonesia is still frequently dominated by a conventional, teacher-centered approach that emphasizes rote memorization and leaves little room for creative exploration [12]-[15]. This pattern was also evident in the present study's baseline data: before treatment, students' CPS Thinking scores on all four indicators were in the low-to-moderate range, and initial interviews confirmed that students had never experienced project-based learning that holistically integrates sustainability issues. This is consistent with Hidayat et al. [16], who linked weak CPS ability to a lack of learning experiences that require students to identify, define, and solve real-world problems independently and collaboratively [17].

A Reverse Engineering-based STEM-Education for Sustainable Development (STEM-ESD) approach offers a promising alternative. STEM-ESD integrates science and technology literacy with sustainability values [18]-[21], while Reverse Engineering invites students to disassemble, analyze, and modify existing products as a starting point for new solutions [22], [23]. Because students begin from an in-depth understanding of an existing product rather than a blank slate, this strategy has been shown to activate analytical and creative thinking more effectively than conventional design tasks [24]-[27]. Within the context of SDG-12, this combination encourages students to analyze real waste-management problems, redesign products from recycled or environmentally friendly materials, and evaluate the sustainability of their solutions.

Despite this potential, three gaps remain in the literature. First, although STEM research in Indonesian science education has grown considerably, the integration of STEM with an ESD perspective and a Reverse Engineering strategy within a single learning design remains very limited, particularly for developing CPS Thinking [28]-[30]. Second, most existing STEM studies still focus on cognitive achievement rather than the creative-evaluative thinking dimension at the core of CPS [31]-[33]. Third, the SDG-12 topic remains rarely used as a context for senior-high-school science learning, despite its potential to build early sustainability literacy [34]-[37]. No prior study, to the authors' knowledge, has examined how a Reverse Engineering-based STEM-ESD model specifically affects the four CPS Thinking indicators on the SDG-12 topic, nor compared it directly against an Engineering Design Process-based STEM-ESD alternative and conventional instruction. This study addresses that gap.

This study aims to examine the effectiveness of a Reverse Engineering-based STEM-ESD learning model (STEM-RE) in enhancing tenth-grade students' CPS Thinking ability on the SDG-12 topic, compared with an Engineering Design Process-based STEM-ESD model (STEM-EDP) and conventional instruction. Specifically, it analyzes the development of four CPS Thinking indicators—(1) problem analysis, (2) flexibility of solution ideas, (3) solution evaluation, and (4) product design elaboration—across the three groups, and explores students' experiences of the learning process through qualitative interviews.

The novelty of this study lies in integrating three elements rarely combined within a single learning design: a sustainability-expanded STEM approach (ESD), a product disassembly-and-reconstruction strategy through Reverse Engineering, and a learning context grounded in SDG-12 issues. This integration is intended to create an authentic learning experience in which students both understand environmental issues theoretically and design innovative, scientifically and ethically justified product solutions, contributing theoretically to sustainability-based science learning models [38] and practically to educators designing creativity-oriented environmental learning [39].

Based on this rationale, the study addresses the following research questions: (1) Is there a significant difference in CPS Thinking improvement among students taught with the STEM-RE model, the STEM-EDP model, and conventional instruction? (2) Which of the four CPS Thinking indicators shows the most consistent improvement under the STEM-RE model? (3) What mechanisms, as reflected in students' learning experiences, explain the differences in CPS Thinking improvement among the three groups?

2. RESEARCH METHOD

This study employs a mixed-methods approach with an explanatory sequential design. In the first phase, quantitative data were collected and analyzed to examine the statistical effect of the treatment. The second phase involved collecting and analyzing qualitative data to clarify and deepen the understanding of the mechanisms behind the quantitative results [40]. This design was chosen because it is suitable for testing the effectiveness of a learning intervention while also gaining an in-depth understanding of students' experiences and perceptions. Quantitatively, this study uses a quasi-experimental design with a non-equivalent control group pretest-posttest pattern. Three class groups were purposively selected based on the equivalence of their initial abilities, consisting of: (1) the Reverse Engineering-based STEM-ESD Group (STEM-RE), (2) the Engineering Design Process-based STEM-ESD Group (STEM-EDP), and (3) the Control Group receiving conventional instruction.

Table 1. Quasi-Experimental Research Design

Group	Treatment	Pretest	Posttest
STEM-RE (X-3)	Reverse Engineering-based STEM-ESD	O_1	O_2
STEM-EDP (X-5)	EDP (Engineering Design Process)-based STEM-ESD	O_1	O_2
Control (X-4)	Conventional learning (no treatment)	O_1	O_2

Note: O_1 = CPS Thinking pretest; O_2 = CPS Thinking posttest.

The participants were tenth-grade students at a public senior high school in Bandung during the 2024/2025 academic year. Because random assignment of individual students was not feasible within the school's fixed class structure, this study used a non-probability purposive sampling technique at the class (cluster) level: three intact classes with equivalent initial CPS Thinking scores, comparable teacher availability, and confirmed willingness to participate were purposively selected and then purposively assigned to the STEM-RE, STEM-EDP, and Control conditions [41]. This procedure is consistent with the non-equivalent control-group design adopted for this study, in which intact groups rather than individually randomized participants serve as the unit of comparison. The total number of participants was 108 students, divided into three classes: class X-3 as the STEM-RE group (n = 36), class X-5 as the STEM-EDP group (n = 36), and class X-4 as the Control group (n = 36). For the qualitative phase, 9 students were purposively selected from the three classes using maximum-variation sampling based on high, medium, and low CPS Thinking pretest categories, to ensure that the interview data captured a range of learning experiences.

The independent variable in this study is the learning model, operationalized as three conditions: (1) Reverse Engineering-based STEM-ESD (STEM-RE), in which students disassemble and analyze an existing product before redesigning it; (2) Engineering Design Process-based STEM-ESD (STEM-EDP), which follows the standard design cycle without a disassembly phase; and (3) conventional instruction, consisting of lecture-based teaching without a design task. The dependent variable is students' Creative Problem Solving Thinking (CPS Thinking) ability, defined as the capacity to analyze a contextual problem, generate flexible and varied solution ideas, critically evaluate the novelty and feasibility of those ideas, and elaborate a systematic product design Treffinger [5], and Isaksen [6]. Operationally, this ability is measured through four indicators—(1) problem analysis, (2) flexibility of solution ideas, (3) solution evaluation, and (4) product design elaboration—each assessed using an analytic rubric with a score range of 1–4 (Table 3).

Data collection in this study employed four main instruments tailored to the quantitative and qualitative phases of the explanatory sequential design. All quantitative statistical procedures—normality testing, N-Gain computation, and between-group comparisons—were performed using IBM SPSS Statistics version 26. Non-parametric tests (Kruskal-Wallis and Mann-Whitney) were used instead of parametric alternatives such as ANOVA because the N-Gain data for each group (n = 36) did not meet the normality assumption verified by the Shapiro-Wilk test, and because the ordinal, rubric-based nature of the CPS Thinking scores made rank-based comparisons more appropriate [42], [43].

Table 2. Research Instruments and Data Analysis Techniques

Instrument	Data Type	Indicators Measured	Analysis Technique
Tes CPS Thinking (Pre-Post)	Quantitative	Analysis, Flexibility, Evaluation, Elaboration	N-Gain, Kruskal-Wallis Test, Mann-Whitney Test
Rubrik CPS Thinking	Qualitative-Quantitative	Assessment of the quality of student responses (Score 1–4)	Descriptive analysis & between-group comparison
Student Interview Guide	Qualitative	Learning experience, motivation, understanding of SDG-12, perceptions of CPS	Thematic analysis

The CPS Thinking test instrument consists of essay questions developed by the researchers and adapted from the Creative Problem Solving indicators of Treffinger et al, [7] and the creative-thinking assessment criteria of Torrance [10], contextualized to the SDG-12 waste-management theme. The content validity of the instrument was established through expert judgment involving two education experts and one biology content expert, who reviewed the alignment between items, indicators, and rubric descriptors; items were revised based on their feedback prior to use. Scoring consistency was maintained by having two trained raters independently score a subsample of student responses using the rubric and reconcile any discrepancies through discussion, ensuring consistent interpretation of the scoring criteria across raters. Each student response was subsequently assessed using this expert-validated, analytic assessment rubric. The following are the assessment criteria for the CPS Thinking rubric.

Table 3. CPS Thinking Assessment Rubric

Indicator	Score 1	Score 2	Score 3	Score 4
Problem Analysis	Unable to identify the problem context	Inaccurate in identifying the problem context	Able to identify the problem context but not concretely	Very able to accurately identify the problem context
Idea Flexibility	Idea is not a product, unclear, or does not solve the problem	One clear product idea but not varied	Two ideas: one clear, one less specific	≥2 clear and varied product ideas
Solution Evaluation	No novelty; advantages/disadvantages inaccurate	No novelty; advantages/disadvantages general	Some novelty; advantages/disadvantages general	Some novelty; advantages/disadvantages specific
Design Elaboration	Tools/materials incomplete; steps not systematic	Tools/materials partial; general steps not sequential	Tools/materials fairly complete; steps sequential and logical	Tools/materials complete and detailed; steps systematic and ready to implement

The research procedure was carried out in three main stages. First, the preparation stage involved developing Reverse Engineering- and Engineering Design Process-based STEM-ESD learning tools, developing the CPS Thinking test instrument, validating the instrument with two education experts and one biology content expert, and administering the pretest to all three groups. Second, the implementation stage, in which the STEM-RE group followed a learning sequence consisting of: (a) problem scoping based on SDG-12 issues, (b) disassembly and analysis of an existing product (reverse engineering), (c) identification of product weaknesses and problem formulation, (d) redesign of an innovative product, and (e) presentation and evaluation of the product. The STEM-EDP group followed the Engineering Design Process flow without the reverse engineering phase. The Control group received conventional instruction in the form of lectures, discussions, and textbook-based assignments. Third, the evaluation stage, which included administering the posttest, conducting in-depth interviews with selected students, and integrated data analysis.

The increase in students' CPS Thinking ability was analyzed using the normalized gain (N-Gain) based on Hake’s formula [44].

$$NGain = \frac{Score\ Posttest - Score\ Pretest}{Score\ Maximum - Score\ Pretest} \ldots (1)$$

Table 4. N-Gain Score Categories

N-Gain Value	Category
N-Gain ≥ 0.70	High
0.30 ≤ N-Gain < 0.70	Moderate
N-Gain < 0.30	Low

Prior to the comparative test, a normality test was performed using the Shapiro-Wilk test because the sample size per group was ≤ 50 [42]. If the data were not normally distributed, the analysis proceeded with the non-parametric Kruskal-Wallis test to compare the three groups simultaneously, followed by the Mann-Whitney post hoc test with Bonferroni correction for pairwise comparisons [43]. All statistical analyses were conducted at a significance level of $\alpha = 0.05$.

Table 5. Between-Group Comparison Scheme (Mann-Whitney Test)

Group Comparison	Null Hypothesis (H_0)	Decision
STEM-RE vs Control	No significant difference in CPS Thinking	H_0 rejected if $p < 0.05$
STEM-RE vs STEM-EDP	No significant difference in CPS Thinking	H_0 rejected if $p < 0.05$
STEM-EDP vs Control	No significant difference in CPS Thinking	H_0 rejected if $p < 0.05$

Qualitative data derived from student interviews were analyzed using Braun and Clarke [45] six-step thematic analysis approach, comprising: (1) familiarization with the data, (2) initial coding, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) writing up the report. Qualitative data were used to clarify and interpret the quantitative findings, particularly regarding the mechanisms underlying the improvement or stagnation of CPS Thinking ability in each group. The trustworthiness of the qualitative data was ensured through source triangulation (interviews with students in the high, medium, and low ability categories), member checking, and a research audit trail [46]. Data integration was carried out at the interpretation stage by linking patterns in the quantitative findings (N-Gain, group comparisons) with themes emerging from the interview data.

3. RESULTS AND DISCUSSION

The quantitative data analysis in this study focused on assessing the improvement of students' Creative Problem Solving Thinking (CPS Thinking ability on the SDG-12 topic among tenth-grade students. Measurement was carried out by comparing pretest dan posttest scores, which were then converted into Normalized Gain (N-Gain). A summary of the data processing results on the effectiveness of improving CPS Thinking ability for each group is presented in Table 6. The following presents a summary of the mean pretest, posttest, and N-Gain scores for each CPS Thinking indicator across the three research groups as a preliminary overview before further discussion in the Results and Discussion section.

Table 6. Mean Pretest and Posttest Scores and N-Gain of CPS Thinking by Group

Indicator	Group	Mean Pre	Mean Post	N-Gain	Category
Problem Analysis	STEM-RE (X-3)	1.47	2.26	0.257	Low
	STEM-EDP (X-5)	1.31	1.78	0.157	Low
	Control (X-4)	1.39	1.50	-0.014	Low
Idea Flexibility	STEM-RE (X-3)	1.64	2.44	0.301	Moderate
	STEM-EDP (X-5)	1.64	2.17	0.097	Low
	Control (X-4)	1.64	1.75	0.014	Low
Solution Evaluation	STEM-RE (X-3)	1.58	2.22	0.255	Low
	STEM-EDP (X-5)	1.50	1.89	0.046	Low
	Control (X-4)	1.42	1.53	0.009	Low
Design Elaboration	STEM-RE (X-3)	1.56	2.28	0.296	Low
	STEM-EDP (X-5)	1.53	2.28	0.231	Low
	Control (X-4)	1.47	1.56	-0.014	Low

Note: Scores use a 1–4 scale (CPS Thinking rubric). N-Gain categories: High (≥ 0.70), Moderate (0.30–0.69), Low (< 0.30).

Based on Table 6, the STEM-RE group showed an increase in mean scores across all CPS Thinking indicators, with N-Gain values ranging from 0.255 to 0.301, all of which fall within the low-to-moderate category. The STEM-EDP group also showed an increase, but with more varied N-Gain values (0.046–0.231), while the Control group experienced only a very minimal increase, even negative on some indicators. These data indicate that the STEM-ESD treatment, particularly with the Reverse Engineering component, contributed more consistently to the development of students' CPS Thinking ability compared to the other approaches. The inferential statistical analysis and in-depth discussion are presented in the Results and Discussion section.

Based on the data description in Table 1, all three groups started from an equivalent initial condition in the CPS Thinking category, which was classified as low. After the intervention, experimental group 1 (STEM-RE) showed the most consistent growth trend among all indicators, with N-Gain values ranging from 0.255 to 0.301. The solution idea flexibility indicator in the STEM-RE class successfully reached the "Moderate" category (N-Gain = 0.301). On the other hand, the increase in experimental group 2 (STEM-EDP) tended to be fluctuating and generally remained in the low category (0.046–0.231). The control group, which used a conventional teaching model, showed no meaningful change dynamics, even recording negative growth values on the problem analysis and product design elaboration indicators (-0.014).

To test the statistical hypotheses regarding the significance of the differences between groups, the N-Gain data were first tested for normality using the Shapiro-Wilk. Because the data were not normally distributed, the testing proceeded by adopting a non-parametric Kruskal-Wallis analysis, followed by a pairwise comparison test using Mann-Whitney with Bonferroni correction. The results of the inferential Mann-Whitney test calculations are summarized in Table 7.

Table 7. Results of the Pairwise Comparison Test (Mann-Whitney) for CPS Thinking Effectiveness

Between-Group Comparison	Significance Value (p-value)	Hypothesis Test Decision	Significance Conclusion
STEM-RE vs Control	< 0,001	H_0 Rejected ($p < 0.05$)	Significant Difference
STEM-RE vs STEM-EDP	0,012	H_0 Rejected ($p < 0.05$)	Significant Difference
STEM-EDP vs Control	0,034	H_0 Rejected ($p < 0.05$)	Significant Difference

The results of the post hoc test in Table 2 confirm that the significance values (p-values) for all combinations of group comparisons fall below the alpha threshold of 0.05. Thus, the null hypothesis (H_0) is rejected, meaning there is a statistically significant difference in the improvement of CPS Thinking ability among the STEM-RE, STEM-EDP, and control classes. The group that received the STEM-ESD stimulation based on Reverse Engineering was shown to produce the highest creative-solutive thinking performance.

The results of the data analysis show that all three learning groups started from an equivalent initial condition of Creative Problem Solving Thinking (CPS Thinking) ability, namely in the low category. This condition indicates that, in general, tenth-grade students are not yet accustomed to dealing with complex, contextual problems that require creative thinking in problem solving, particularly on sustainability issues such as SDG-12 (Responsible Consumption and Production). This finding is consistent with the statement by Aprianti and Rustaman [47], who noted that science learning in schools generally remains dominated by the conventional transfer of concepts, leaving relatively limited room for students to practice analyzing problems independently and generating alternative solutions [48], [49].

After the learning intervention was administered, a fairly striking difference in improvement trends was found between groups. Experimental group 1, which used the STEM-Education for Sustainable Development (ESD) approach based on Reverse Engineering (STEM-RE) showed the most consistent improvement across all CPS Thinking indicators, with N-Gain values ranging from 0.255 to 0.301. In fact, on the solution idea flexibility indicator, this group succeeded in reaching the “moderate” category. This finding reinforces the argument of Hoßbach and Isaksen [50], who stated that reverse engineering activities provide students with direct experience in disassembling, analyzing the structure of, and understanding the working principles of a product before redesigning its solution, so that students’ thinking process becomes more reflective and trained to consider various alternative solutions [51]. The activity of disassembling an existing product (reverse forward engineering process) gives students a concrete thinking framework regarding the relationships between a product's function, structure, and environmental impact, which in turn encourages the emergence of more varied solution ideas (idea flexibility) compared to when students are simply asked to design from scratch without reference to an analysis of an existing product [52], [53].

Unlike the STEM-RE group, experimental group 2, which used a STEM-ESD approach based on Engineering Design Process (STEM-EDP), showed a more fluctuating improvement that generally remained in the low category (N-Gain 0.046–0.231). This pattern indicates that although EDP theoretically provides systematic stages (problem identification, design, prototyping, testing, and evaluation) that can support the development of higher-order thinking skills [54], [55], its implementation within limited learning time has the potential to produce a less in-depth understanding on some indicators, particularly solution evaluation, which recorded an N-Gain of only 0.046. This can be explained through the view of Belghith et al, [56] that the linear and sequential nature of the EDP stages sometimes causes students to rush through each phase in pursuit of a final product, so that the process of evaluating and reflecting on the feasibility of solutions is not carried out optimally.

Meanwhile, the control group, which received conventional instruction, showed no meaningful change dynamics, even recording negative N-Gain values on the problem analysis (-0.014) and product design elaboration (-0.014) indicators. These negative values can substantially be interpreted as a decline in student performance on the posttest compared to the pretest, which may have been caused by factors such as fatigue, a lack of meaningful learning experiences, or a mismatch between the conventional teaching method and the characteristics of CPS Thinking questions, which require higher-order analysis and elaboration skills. This finding is consistent with the results of Yun and Crippen [57], who found that lecture-based learning and routine practice exercises are less effective in fostering students’ creative thinking skills due to the lack of opportunities for exploration and experience in solving authentic problems.

To ensure that these trend differences were statistically significant, a Shapiro-Wilk normality test was conducted, which showed that the N-Gain data were not normally distributed. Therefore, hypothesis testing proceeded using the non-parametric Kruskal-Wallis test and the Mann-Whitney post hoc test with Bonferroni correction to control for the type I error inflation caused by multiple comparisons [42], [58]. The test results show that all comparison combinations—STEM-RE vs Control ($p < 0.001$), STEM-RE vs STEM-EDP ($p = 0.012$), and STEM-EDP vs Control ($p = 0.034$)—have significance values below the threshold of $\alpha = 0.05$. This means the null hypothesis (H_0) is rejected, so it can be concluded that there is a statistically significant difference in the improvement of CPS Thinking ability among the three learning groups.

Overall, these findings provide empirical evidence that integrating the STEM approach with an Education for Sustainable Development (ESD) perspective, particularly when combined with a reverse engineering strategy, can have a more significant impact on improving students' CPS Thinking compared to a conventional EDP approach or ordinary conventional learning. This is presumably because the characteristics of reverse engineering require students to think analytically and critically about existing products while also linking them to global sustainability issues (SDG-12), making the learning process more contextual and meaningful [58], [60]. Thus, the ESD-based STEM-RE approach can become a relevant alternative learning strategy for application in efforts to develop 21st-century skills, particularly creative thinking ability in solving environmental and sustainability problems. Taken together, these findings answer the study's research questions: a statistically significant difference in CPS Thinking improvement was found among the three groups, with idea flexibility showing the most consistent gain under the STEM-RE model, and the qualitative interviews indicated that the disassembly-and-redesign process was the primary mechanism through which STEM-RE fostered more reflective, evidence-grounded thinking compared to STEM-EDP and conventional instruction.

Practically, these findings suggest that science teachers seeking to develop students' CPS Thinking ability on sustainability topics can adopt the STEM-RE sequence—problem scoping, product disassembly, weakness identification, redesign, and presentation—as a structured yet flexible framework that fits within a single instructional unit, rather than requiring the extended timeline typically associated with open-ended engineering design projects. The consistent gains observed on the idea-flexibility indicator in particular suggest that grounding student design tasks in an existing product, rather than starting from a blank problem statement, may be a practical entry point for teachers with limited experience facilitating open-ended STEM projects. The primary novelty of this study is empirical rather than conceptual: while Reverse Engineering and ESD have each been examined in prior STEM research, this study provides direct, indicator-level comparative evidence—drawn from a three-group quasi-experimental design—that a Reverse Engineering-based STEM-ESD sequence produces more consistent CPS Thinking gains than an Engineering Design Process-based alternative within the same SDG-12 context, a comparison not previously reported in the literature.

This study has several limitations. First, the N-Gain values obtained, although statistically significant between groups, remained in the low-to-moderate category in absolute terms, indicating that a single learning cycle was insufficient to produce high mastery of CPS Thinking; longer or repeated interventions may be needed to observe larger effects. Second, the study was conducted in a single public senior high school with three intact classes, which limits the generalizability of the findings to schools with different resources, student populations, or curricular contexts. Third, the quasi-experimental, non-randomized design cannot fully rule out selection effects associated with intact classes, despite efforts to select classes with equivalent initial ability. Future research is recommended to (1) extend the intervention across multiple learning cycles or semesters to examine the durability and ceiling of CPS Thinking gains, (2) replicate the STEM-RE model across schools with more diverse socioeconomic and geographic contexts, (3) employ a randomized or multi-site design to strengthen causal inference, and (4) examine additional outcome variables such as environmental attitudes, self-efficacy, or collaboration skills that may also be influenced by Reverse Engineering-based STEM-ESD learning, consistent with recent evidence that active, model-based learning approaches outperform conventional instruction in developing students' higher-order thinking skills [61].

4. CONCLUSION

This study demonstrates that a Reverse Engineering-based STEM-ESD learning model (STEM-RE) improves tenth-grade students' Creative Problem Solving (CPS) Thinking ability on the SDG-12 topic more effectively and more consistently than an Engineering Design Process-based STEM-ESD model (STEM-EDP) or conventional instruction, as shown by higher N-Gain values across all four indicators and statistically significant between-group differences (Kruskal-Wallis and Mann-Whitney tests, $p < 0.05$). The qualitative findings indicate that this advantage is driven by the disassembly-and-redesign sequence, which gives students a concrete analytical starting point before they generate and evaluate solution ideas. Theoretically, this study contributes indicator-level comparative evidence that integrating Reverse Engineering into an ESD-oriented STEM design—rather than relying on a standard Engineering Design Process alone—strengthens the creative-evaluative dimension of CPS that prior STEM research has often overlooked. Practically, the findings offer science educators a structured, classroom-feasible sequence for embedding sustainability content (SDG-12) into design-based science learning, and provide a rationale for curriculum developers and policymakers to consider Reverse Engineering-based STEM-ESD as a model for advancing both 21st-century creative thinking skills and sustainability literacy within the Merdeka Curriculum framework. Given the study's limitations in intervention duration and school-level generalizability, wider, longer-term, and multi-site studies are recommended to confirm and extend these findings.

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AUTHOR CONTRIBUTIONS

All authors contributed meaningfully to this work. The first author was responsible for conceptualization, research design, data collection, and manuscript drafting. The second author contributed to the development of learning instruments, data analysis, and interpretation of findings. The third author provided critical review of the theoretical framework, assisted in result validation, and revised the final manuscript. All authors have read and approved the published version of the manuscript.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

INFORMED CONSENT STATEMENT

Prior to participation, each subject was provided with a detailed explanation of the study's objectives, procedures, potential risks, and benefits. All participants voluntarily agreed to participate and signed a written informed consent form. All images in this article have been authorized and are the property of the authors.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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