Integrated Science Education Journal
Vol. 7, No. 4, July 2026, pp. 639~649
ISSN: 2716-3725, DOI: 10.37251/isej.v7i4.3462



Research Article

# STEM-ESD Learning Based on Engineering Design Process and Reverse Engineering Toward Student Action on SDG-6

Ayudya Fitriyani[1,*], Rini Solihat[1], Ari Widodo[1]
[1] Department of Biology Education, Faculty of Mathematics and Science Education, Indonesia University of Education, Jawa Barat, Indonesia

**Article Info**

***Article history:***

Received May 16, 2026
Revised Jun 17, 2026
Accepted Jul 19, 2026
OnlineFirst Jul 28, 2026

***Keywords:***

Clean Water and Sanitation
Education for Sustainable Development
Engineering Design Process
Reverse Engineering
Student Action

**ABSTRACT**

**Purpose of the study:** This study aims to analyze the effect of STEM-ESD learning—implemented through two engineering approaches, Engineering Design Process (EDP) and Reverse Engineering (RE)—on student action competency related to SDG-6 (clean water and sanitation) among secondary school students.

**Methodology:** Mixed-methods convergent design. Participants: 108 students in three groups (two experimental: EDP and RE; one control; 36 per group). Instruments: action questionnaire, student worksheets, open-ended questionnaires, structured interviews. Analysis: descriptive statistics, Shapiro-Wilk normality test, Levene homogeneity test, one-way ANOVA, Kruskal-Wallis test.

**Main Findings:** Neither EDP nor RE produced a statistically significant overall improvement in student action compared to the control group. However, at the indicator level: the RE group showed significant gains in competency achievement; the EDP group consistently outperformed others on current action and future action indicators. Both approaches demonstrate distinct, complementary mechanisms of influence.

**Novelty/Originality of this study:** This study uniquely integrates STEM-ESD with two contrasting engineering approaches (EDP and RE) to address SDG-6, revealing their differential effects on student action competency. It advances knowledge by demonstrating that EDP and RE are not interchangeable but serve complementary functions—RE builds conceptual competence while EDP fosters action orientation and behavioral commitment.



***Corresponding Author:***
Ayudya Fitriyani,
Departement of Biology Education, Faculty of Mathematics and Science Education, Indonesia University of Education, Jl. Dr. Setiabudi No.229, Isola, Kec. Sukasari, Kota Bandung, Jawa Barat, 40154, Indonesia
Email: ayudya@upi.edu

## 1. INTRODUCTION

The crisis of clean water and sanitation is one of the most pressing environmental challenges of the 21st century and is a central focus of Sustainable Development Goal 6 (SDG-6), which targets universal access to clean water and adequate sanitation. Pressure on water resources continues to intensify in line with population growth, changing consumption patterns, and the impacts of climate change, leaving the world to grapple with complex socio-hydrological issues that involve both scientific and non-scientific dimensions [1]. Addressing these challenges requires evidence-based water management, yet such efforts will be insufficient without a generation of young people equipped with environmental literacy and the disposition to act. Within the context of biology and environmental biology education, schools play a strategic role as spaces for cultivating ecological awareness from an early age, including awareness of water conservation as part of ecosystem sustainability [2], [3].

Ideally, biology instruction in schools should not only aim for conceptual mastery but also nurture students' genuine concern and action toward environmental problems in their surroundings. The integration of STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD) is regarded as a relevant strategy for achieving this goal, as it connects sustainability concepts with contextual, problem-based learning experiences [4]. Systematic reviews indicate that STEM learning integrated with ESD is effective in promoting education quality while simultaneously building students' sustainability literacy [5]. Furthermore, recent studies on STEM integration for sustainability show that socio-scientific issue-based learning accompanied by action-taking can enhance students' literacy as well as their agency, values, and emotions when deliberation leads to concrete actions such as environmental campaigns, while engineering design approaches have been consistently shown to develop students' design and problem-solving skills [6]. In this ideal context, biology instruction is expected to facilitate students in designing innovative solutions to clean water issues through Engineering Design Process (EDP) and Reverse Engineering (RE), while simultaneously fostering concrete student action in support of SDG-6 [7], [8].

In practice, however, a first gap separates this ideal from the reality of biology instruction in schools. Research shows that environmental conservation activities, including water conservation, are still not optimally integrated into educational systems, despite the breadth of the problem [9]. Biology learning in many schools remains predominantly conventional, emphasizing rote memorization of concepts, leaving students with limited opportunity to independently identify environmental problems, design solutions, or translate conceptual understanding into concrete action in their surroundings [10]. Yet the selection of appropriate instructional methods including hands-on practice is believed to have a substantial impact on students' application of conservation understanding in daily life [11]. Moreover, engineering-based learning approaches such as Reverse Engineering which allows students to disassemble, analyze, and redesign a product or system in order to understand its working principles are still rarely applied in biology instruction in Indonesia, despite their considerable potential to build design thinking and authentic problem-solving skills related to environmental issues such as water treatment and conservation.

A second gap is evident in the scarcity of biology lessons that are explicitly designed to promote, and structured assessments that are designed to measure, student action (student action) toward specific SDG targets. Most innovations in conservation- or environment-based biology learning remain focused on improving cognitive learning outcomes and science process skills, with comparatively few structured approaches to measuring and developing the dimension of students' concrete action as an outcome of the learning process [12], [13]. As a result, students tend to possess knowledge about the importance of water conservation but have not been sufficiently motivated to translate this into actual behavior or concrete actions contributing to SDG-6 attainment within their schools and communities.

To address this gap, a model or learning strategy is needed that integrates STEM-ESD with Engineering Design Process and Reverse Engineering in an integrated manner within environmental biology content, with a focus on clean water and sanitation issues in line with SDG-6. Prior research indicates that EDP-based learning can enhance student engagement (engagement) in STEM learning through iterative cycles of problem identification, design, testing, and refinement [12]. Additionally, the application of EDP in science instruction has been shown to enhance students' understanding of the nature of science while developing design-thinking skills through concrete content contexts [14]. By combining EDP and RE, students are not only guided to design new solutions to water challenges, but are also trained to analyze existing simple water-treatment systems or technologies to understand their operating principles before developing innovations better suited to their local environment. This approach is expected to bridge conceptual understanding of environmental biology with the capacity to design real solutions, ultimately driving student action that contributes to the achievement of SDG-6 targets.

Based on Gap this study aims to analyze the effect of STEM-ESD learning based on Engineering Design Process and Reverse Engineering on student action regarding SDG-6 (access to clean water and sanitation). To respond directly to these gaps, the study seeks to (1) describe how STEM-ESD learning based on EDP and RE is implemented in environmental biology content, and (2) measure and compare its impact on the four dimensions of students' concrete action (past, present, future action, and competency achievement) in support of SDG-6 attainment, so that findings can contribute to the development of sustainability- and action-oriented biology learning models.

## 2. RESEARCH METHOD

This study employed a mixed-methods approach with a convergent design—a design that integrates the collection and analysis of both quantitative and qualitative data simultaneously in a single phase, then merges the two sets of results for a more comprehensive understanding of the phenomenon under investigation [15]. This approach was selected because the complexity of the student action variable related to SDG-6 (Clean Water and Sanitation) cannot be fully captured through numerical data alone; it also requires narrative meaning-making and direct experiential accounts from participants. On the quantitative side, a quasi-experimental design with three groups was employed: Experimental Group 1, which received STEM-ESD instruction based on Engineering Design Process; Experimental Group 2, which received STEM-ESD instruction based on Reverse Engineering; and a Control Group, which received no special treatment. Each group consisted of 36 students, yielding a total of 108 participants (N = 108).

Data sources comprised students from all three groups. Primary data were obtained directly through instruments including Creative Problem Solving (CPS) student worksheets addressing the thinking and design dimensions, a student action questionnaire measuring four main indicators past action, present action, future action, and competency achievement related to clean water and sanitation and open-ended follow-up questionnaires. Qualitative data were drawn from semi-structured interviews with student representatives from each group. The use of multiple data sources was intended to strengthen the validity of findings through triangulation between written and verbal data [16], thereby ensuring an adequate degree of trustworthiness in the conclusions drawn.

Data collection proceeded through two complementary channels. On the quantitative channel, data were gathered using student action questionnaires administered at the pretest and posttest stages, as well as CPS worksheets completed individually during the learning process. On the qualitative channel, data were collected through open-ended follow-up questionnaires and semi-structured interviews conducted with student representatives from all three groups. Interviews were designed to explore students' perceptions, motivations, and experiences in depth regarding their concrete action on clean water and sanitation management. All instruments underwent expert validation to ensure alignment of content with the research objectives.

Table 1. Data Collection Instrument Grid

| Indicator / Focus | Instrument | Data Type | Data Source | Timing |
|---|---|---|---|---|
| Implementation of STEM-ESD (EDP/RE) | Classroom observation & CPS worksheet | Qualitative & quantitative | All groups (Exp. 1, Exp. 2, Control) | During learning process |
| Past action | Action questionnaire (past-action items) | Quantitative (ordinal) | All groups | Pretest & posttest |
| Present action | Action questionnaire (present-action items) | Quantitative (ordinal) | All groups | Pretest & posttest |
| Future action | Action questionnaire (future-action items) | Quantitative (ordinal) | All groups | Pretest & posttest |
| Competency achievement | Action questionnaire (competency items) | Quantitative (ordinal) | All groups | Pretest & posttest |
| Students' perceptions & motivation | Open-ended follow-up questionnaire | Qualitative | Student representatives | After treatment |
| In-depth experience of action | Semi-structured interview | Qualitative | Student representatives per group | After treatment |

Table 1 maps each research indicator onto its corresponding instrument, data type, data source, and timing of collection, ensuring that every dimension of student action addressed in the research questions is captured by at least one validated instrument.

Statistical analysis was performed with SPSS at a significance level of $\alpha = 0.05$. The analytic sequence followed three stages. First, descriptive statistics (mean, standard deviation, minimum, and maximum) characterized pretest and gain scores for each group. Second, assumption tests—the Shapiro-Wilk test for normality and Levene's test for homogeneity of variance—determined the appropriate inferential test for each dataset. Third, where both assumptions were satisfied, a parametric one-way ANOVA compared group means; where either assumption was violated, the non-parametric Kruskal-Wallis test was used instead, followed by Post Hoc testing to localize significant pairwise differences. This same three-stage sequence was applied separately to the overall action score and to each of the four action indicators (past, present, future action, and competency achievement), so that both aggregate and indicator-level research questions could be answered with the statistically appropriate test.

Statistical power was assessed given the achieved sample size of n = 36 per group (N = 108). A sensitivity power analysis (G*Power 3.1, one-way ANOVA, three groups, $\alpha = 0.05$, power = 0.80) indicated that this sample size is sufficient to detect a medium-to-large effect ($f \approx 0.35$) but is underpowered for small effects. This constraint is consistent with the pattern of results: several indicator-level comparisons showed descriptively meaningful mean differences that did not reach statistical significance, suggesting that the true effect of EDP and RE on some action indicators may be real but too small, given the available power, to be detected as statistically significant. This limitation is taken into account when interpreting non-significant findings in the Results and Discussion sections and is addressed further under Limitations.

For qualitative data, analysis followed the three interactive stages of data reduction, data display, and conclusion drawing [17]. Responses from open-ended questionnaires and semi-structured interviews were first coded and reduced into categories aligned with the four action indicators, then displayed in matrices comparing groups, and finally interpreted to draw conclusions about students' perceptions, motivations, and experiences. Quantitative and qualitative results were subsequently merged through a side-by-side comparison procedure characteristic of the convergent design, in which statistically significant and non-significant quantitative findings were cross-checked against qualitative themes to explain why, and under what conditions, each approach influenced student action.

Data analysis was carried out in parallel and integrated in accordance with the characteristics of the convergent design. For quantitative data, analysis began with descriptive statistics to characterize the distribution of scores in each group, followed by assumption tests prior to the application of inferential statistics. Descriptive statistics computed included mean, standard deviation, maximum value, and minimum value for pretest data and pretest–posttest difference scores (gain) across the three groups. Homogeneity testing using Levene's test on pretest data yielded a significance value of 0.300, indicating that variances across groups were homogeneous. By contrast, Levene’s test on gain data produced a significance value of 0.001, indicating non-homogeneous variances across groups. Because pretest data met both normality and homogeneity assumptions, hypothesis testing was conducted using a One-Way ANOVA with the formula 1.

$$F = \frac{MSB}{MSW} \ldots (1)$$

Where F is the test statistic, MSB (Mean Square Between) is the average squared deviation between groups, and MSW (Mean Square Within) is the average squared deviation within groups. The One-Way ANOVA applied to pretest data yielded a significance value of 0.022, which is less than $\alpha = 0.05$ ($p = 0.022 < 0.05$), indicating a significant difference in students' initial action status across the three groups. This finding prompted Post Hoc testing, which identified that the significant difference occurred specifically between Experimental Group 2 and the Control Group, while other group pairs did not differ significantly. Because gain data did not meet the assumptions of normality and homogeneity, hypothesis testing was redirected to the non-parametric Kruskal-Wallis test with the formula 2.

$$H = \left[\frac{12}{N(N+1)}\right] x \sum \left(\frac{Rj^2}{nj}\right) - 3(N+1) \ldots (2)$$

Where H is the test statistic, N is the total sample size, Rj is the sum of ranks in group j, and nj is the sample size of group j. The Kruskal-Wallis test on gain data yielded a significance value of 0.410, which exceeds $\alpha = 0.05$ ($p = 0.410 > 0.05$), indicating that there is no statistically significant difference in student action improvement across Experimental Group 1, Experimental Group 2, and the Control Group. Accordingly, STEM-ESD learning based on Engineering Design Process and Reverse Engineering did not produce a statistically significant effect on overall student action improvement related to SDG-6. Nevertheless, descriptively, Experimental Group 1 recorded the highest mean gain (M = 4.74) compared to Experimental Group 2 (M = 3.99) and the Control Group (M = 2.76), suggesting a practical difference even though statistical significance was not attained [18].

Further analysis was conducted on each student action indicator. For the past action indicator, inferential tests showed no significant difference for either pretest ($p = 0.200 > 0.05$) or posttest data ($p = 0.099 > 0.05$), although descriptively Experimental Group 2 recorded the highest mean posttest score. For the present action indicator, pretest data differed significantly, so testing was redirected to gain data; results showed no significant difference ($p = 0.343 > 0.05$), yet Experimental Group 1 recorded a higher gain than the other groups. Similar findings emerged for the future action indicator, where no significant difference in gain values was found ($p = 0.328 > 0.05$), although Experimental Group 1 again showed the highest gain. For the competency achievement indicator, pretest data did not differ significantly ($p = 0.057 > 0.05$), so testing continued on posttest data, which revealed a significant difference ($p = 0.037 < 0.05$); Post Hoc testing confirmed that this difference occurred specifically between Experimental Group 2 and the Control Group.

Qualitative data analysis was conducted through three stages developed by Miles, Huberman, and Saldana [17], data reduction, data display, and conclusion drawing. Qualitative findings were then integrated with quantitative results through a merging process—comparing and connecting the two sets of findings to achieve a more comprehensive and mutually reinforcing interpretation. This integration enabled cross-confirmation between numerical data and student narratives, allowing findings to be explained not only in terms of statistical significance but also from the perspective of students' direct experiences and understanding.

## 3. RESULTS AND DISCUSSION

The processed and analyzed data pertaining to student action on SDG-6 (Clean Water and Sanitation) are presented below to answer the two research questions stated in the Introduction: (1) how STEM-ESD learning based on Engineering Design Process (Exp. 1) and Reverse Engineering (Exp. 2) was implemented relative to the Control Group, and (2) what effect this instruction had on students' concrete action toward SDG-6. Consistent with the Statistical Analysis procedure described in the Research Method, findings are presented as descriptive statistics, assumption tests, overall inferential test results (one-way ANOVA or Kruskal-Wallis, as appropriate), and per-indicator analysis of student action, followed by the qualitative themes used to interpret and corroborate the quantitative results.

Descriptive statistics computed included mean, standard deviation, maximum value, and minimum value for pretest data and pretest–posttest difference scores (gain) across the three groups. The resulting figures are presented in Table 2.

Table 2. Descriptive Statistics of Student Action

| Statistic | Pretest | | | Gain | | |
|---|---|---|---|---|---|---|
| | Exp. 1 | Exp. 2 | Control | Exp. 1 | Exp. 2 | Control |
| N | 36 | 36 | 36 | 36 | 36 | 36 |
| Highest Score | 82.99 | 86.81 | 79.17 | 18.40 | 30.56 | 10.42 |
| Lowest Score | 59.38 | 50.35 | 60.42 | -4.51 | -9.38 | -3.47 |
| Mean | 69.75 | 72.63 | 69.02 | 4.74 | 3.99 | 2.76 |
| Std. Deviation | 4.903 | 7.014 | 5.039 | 5.378 | 7.374 | 2.130 |

Before inferential tests were applied, all data were tested for normality using the Shapiro-Wilk test. Results for pretest data showed that all three groups were normally distributed, with significance values of 0.732 (Experimental Group 1), 0.127 (Experimental Group 2), and 0.364 (Control Group), all exceeding $\alpha = 0.05$. For gain data, however, Experimental Group 1 and Experimental Group 2 did not conform to a normal distribution ($p = 0.007$ and $p = 0.010$, respectively), while the Control Group remained normal ($p = 0.370$). Homogeneity testing using Levene's test on pretest data yielded a significance value of 0.300, indicating that variances across groups were homogeneous. By contrast, Levene's test on gain data produced a significance value of 0.001, indicating non-homogeneous variances across groups.

An overview of the distribution of student action scores for pretest and gain (pretest–posttest difference) data across the three groups is provided in Table 2. Descriptively, Experimental Group 2 recorded the highest mean pretest score (M = 72.63; SD = 7.014), followed by Experimental Group 1 (M = 69.75; SD = 4.903) and the Control Group (M = 69.02; SD = 5.039). For gain data, Experimental Group 1 registered the highest mean (M = 4.74; SD = 5.378), followed by Experimental Group 2 (M = 3.99; SD = 7.374) and the Control Group (M = 2.76; SD = 2.130). The wide gain range in Experimental Group 2 (−9.38 to 30.56) indicates more heterogeneous student responses to the Reverse Engineering treatment.

Prior to hypothesis testing, all data were subjected to assumption checks. Shapiro-Wilk normality tests on pretest data showed that all groups were normally distributed (Exp. 1: $p = 0.732$; Exp. 2: $p = 0.127$; Control: $p = 0.364$; all $> 0.05$). Levene's homogeneity test yielded $p = 0.300$, confirming homogeneous variances. With both assumptions satisfied, One-Way ANOVA was applied to pretest data and produced $p = 0.022$ ($< 0.05$), indicating a significant difference in students' initial action status across the three groups. Post Hoc testing identified that this difference occurred specifically between Experimental Group 2 and the Control Group, while other group pairs did not differ significantly. A summary of inferential test results is presented in Table 3.

Table 3. Inferential Test Results for Student Action

| Statistical Test | Data | p-value | α | Interpretation |
|---|---|---|---|---|
| Shapiro-Wilk (Exp. 1) | Pretest | 0.732 | 0.05 | Normal |
| Shapiro-Wilk (Exp. 2) | Pretest | 0.127 | 0.05 | Normal |
| Shapiro-Wilk (Control) | Pretest | 0.364 | 0.05 | Normal |
| Levene | Pretest | 0.300 | 0.05 | Homogeneous |
| One-Way ANOVA | Pretest | 0.022* | 0.05 | Significantly different |

| Statistical Test | Data | p-value | α | Interpretation |
|---|---|---|---|---|
| Shapiro-Wilk (Exp. 1) | Gain | 0.007 | 0.05 | Not normal |
| Shapiro-Wilk (Exp. 2) | Gain | 0.010 | 0.05 | Not normal |
| Levene | Gain | 0.001 | 0.05 | Not homogeneous |
| Kruskal-Wallis | Gain | 0.410 | 0.05 | No significant difference |

Note: * significant at α = 0.05

For gain data, Shapiro-Wilk normality tests showed that two groups were not normally distributed (Exp. 1: $p = 0.007$; Exp. 2: $p = 0.010$), and Levene's test produced $p = 0.001$ (non-homogeneous). Because parametric assumptions were not met, testing was redirected to the Kruskal-Wallis test, which yielded $p = 0.410$ (> 0.05). This indicates that student action improvement across the three groups did not differ significantly; therefore, STEM-ESD instruction based on Engineering Design Process or Reverse Engineering did not statistically produce a significant effect on overall student action improvement related to SDG-6.

More detailed analysis was conducted for each of the four student action indicators. Mean scores and statistical significance values by indicator are summarized in Table 4.

Table 4. Summary of Analysis Results per Student Action Indicator

| Indicator | Test Data | Mean Exp.1 | Mean Exp.2 | Mean Control | p-value |
|---|---|---|---|---|---|
| Past Action | Posttest | — | Highest | — | 0.099 (not sig.) |
| Present Action | Gain | Highest | — | — | 0.343 (not sig.) |
| Future Action | Gain | Highest | — | — | 0.328 (not sig.) |
| Competency Achievement | Posttest | — | Highest* | — | 0.037* |

Note: * significant at α = 0.05

For the past action indicator, pretest data showed no significant difference ($p = 0.200$), so testing proceeded to posttest data; results likewise showed no significant difference ($p = 0.099 > 0.05$). Nevertheless, descriptively Experimental Group 2 recorded the highest mean posttest score, suggesting that the Reverse Engineering treatment influenced students' reflection on water conservation actions they had undertaken previously. For the present action and future action indicators, because pretest data differed significantly, testing was redirected to gain data. Neither indicator showed significant group differences (present action: $p = 0.343$; future action: $p = 0.328$), yet Experimental Group 1 consistently recorded the highest gain on both indicators. This pattern suggests that the Engineering Design Process approach tends to be more effective in motivating students to plan and commit to water conservation actions—both ongoing and projected into the future.

The only indicator to show a statistically significant difference was competency achievement. Pretest data did not differ significantly ($p = 0.057$), but posttest data revealed a significant difference across groups ($p = 0.037 < 0.05$). Post Hoc testing confirmed that this difference occurred between Experimental Group 2 and the Control Group, while pairs involving Experimental Group 1 and the Control Group, and between Experimental Group 1 and Experimental Group 2, did not differ significantly. This finding suggests that STEM-ESD instruction based on Reverse Engineering produced a more measurable impact on students' knowledge, attitudes, and values related to clean water and sanitation compared to no treatment.

These quantitative results are corroborated by the qualitative data collected through open-ended questionnaires and semi-structured interviews. Consistent with the higher gain scores of Experimental Group 1, students in the EDP group most frequently described concrete, self-initiated plans to conserve water at school and at home, indicating stronger action orientation. Students in Experimental Group 2 more often referred to explanations of how existing water-treatment systems work, consistent with the RE group's significant advantage on the competency achievement indicator. This convergence between the numerical and narrative data directly answers the second research question by showing that EDP and RE affect student action through different, method-consistent mechanisms rather than a single uniform effect.

Results of this study show that STEM-ESD instruction integrating Engineering Design Process (EDP) and Reverse Engineering (RE) did not, in aggregate, produce a statistically significant difference in overall student action improvement related to SDG-6 ($p = 0.410$). This finding initially appears to contradict the consensus in the literature that STEM project-based approaches can promote measurable pro-environmental behavioral change [19], [20]. However, statistical non-significance does not automatically indicate that the intervention was ineffective. Explicitly argues that a non-significant statistical result can reflect limited sample size or high inter-individual heterogeneity rather than an absence of a real effect. A similar view is expressed by Coe [11], who cautions that p-values alone are insufficient for assessing the practical effectiveness of an educational intervention; effect size is needed as a complementary interpretive measure. In this study, descriptive data reveal a consistent improvement trend in experimental groups relative to the control group, with the EDP group recording the highest mean gain ($M = 4.74$). The gap between statistical significance and practical significance is a common phenomenon in small-scale educational research [22], and it opens a richer interpretive space for understanding the mechanisms by which the two approaches operate.

The statistical non-significance at the overall action dimension must be understood through the lens of the complexity of the action construct in education for sustainable development (ESD). Student action related to SDG-6 is not a singular behavior that can change instantly within a single learning cycle. Akinsemolu and Onyeaka [23], in their action competence framework, assert that authentic action in ESD encompasses the capacity to act on the basis of critical knowledge, intrinsic motivation, and collective awareness—not merely reactive behavior in response to instruction. Distinguish between individual pro-environmental behaviors that are routine in nature and collective action rooted in value transformation and future orientation. This multidimensional action construct encompasses reflection on past conservation behavior, continuity of present action, long-term future commitment, and the achievement of competencies integrating knowledge, skills, and values [24], [25]. Forming action of such complexity inherently requires more time than a single learning intervention, as emphasized by Alam [26], who distinguish between ESD that educates directly for sustainability and ESD that builds capacity for critical thinking and adaptive long-term action. Thus, non-significance at the aggregate action level is not a failure; rather, it reflects the temporal limitations of this study and reinforces the need for more comprehensive longitudinal intervention designs [27].

Nevertheless, there is a finding of substantial importance: the significant difference in the competency achievement indicator between the Reverse Engineering group and the control group ($p = 0.037$). This finding confirms that the RE approach possesses structural advantages in building a competency foundation encompassing conceptual knowledge, analytical skills, and internalized values related to clean water management. Epistemically, RE operates through the principle of real-artifact decomposition: students are first exposed to an existing product or system and then required to understand its mechanisms before they can critique, modify, or develop it. Cognitively, this positions students at the analysis and evaluation levels of the revised Bloom's taxonomy—the two highest levels in the cognitive domain [28]—so that the conceptual understanding produced tends to be more robust and durable than constructive approaches starting from scratch. This approach aligns with analogical reasoning theory [29], whereby understanding something through a physically familiar system deepens comprehension and facilitates knowledge transfer to new contexts. Hoque et al, [30] reported similar findings showing that product-analysis-based learning within STEM-ESD significantly enhanced students' science literacy and sustainability competence, particularly with respect to systemic understanding of environmental issues. Moreover, Li et al, [31], in a meta-analysis, found that the integration of technology artifact analysis in STEM learning consistently improved students' conceptual understanding with a mean effect size of $d = 0.68$—a moderate to large effect. The strong competency achievement from the RE approach in this study aligns with the view that a solid knowledge foundation is a prerequisite—though not a guarantee—for meaningful and sustained action [32], [33].

On the other hand, Engineering Design Process showed a different but complementary pattern: the EDP group consistently outperformed the control group on the present action and future action indicators, even though these differences did not reach statistical significance. This tendency can be understood through EDP's fundamental characteristics as an iterative, open-ended, real-problem-oriented process. Within EDP, students do not merely learn about problems but actively design, test, and refine solutions through repeated cycles known as design-build-test-reflect [34]. The experience of designing concrete solutions to real-life clean water problems psychologically creates a sense of ownership over those solutions, which in turn motivates long-term action commitment [35], [36]. Engineering design approaches consistently develop students' capacity to design solutions and solve problems, leading to more concrete and planned student action. Moreover, the EDP process—which integrates authentic problem identification has been shown to build higher intrinsic motivation compared to conventional instruction [37], and intrinsic motivation is among the strongest predictors of long-term pro-environmental behavior [38]-[40]. Le et al, [41] further support this argument by demonstrating that engineering design-based STEM learning significantly improves students' self-efficacy in solving environmental problems—an important mediator between knowledge and actual action. Accordingly, EDP's advantage on the action orientation dimension reflects that this approach is more effective at mobilizing behavioral commitment, while its cognitive foundation may require additional strengthening that the RE approach can provide.

From the perspective of action theory in ESD, findings from this study yield important insights regarding the distinct mechanisms through which EDP and RE shape multidimensional student action. RE-based learning proved more effective in building a foundation of cognitive competence and systemic understanding, while EDP demonstrated greater strength in fostering action orientation and long-term behavioral commitment. These two approaches can be understood as two complementary dimensions within the ESD action competence framework: RE builds 'what to know,' while EDP builds 'what to do'—or, in Weinert's [42] terms, RE builds declarative competence while EDP builds procedural and motivational competence [43]. This enriches the discussion in the literature, which has tended to examine the two approaches separately and oppositionally [44]. Synthesizing RE and EDP within a single integrated learning design has the potential to produce synergistic outcomes: a deep understanding of existing systems (RE) can serve as a stronger foundation for innovative redesign processes (EDP). This integration idea is supported by Apedoe [45], who showed that an analysis-before-design sequence in engineering-based science learning yields significantly higher conceptual understanding and design ability than the reverse sequence. Additionally, Pozuelo-Muñoz et al, [46] found that design-redesign cycles combining analysis of existing products with new solution design produced greater and more durable improvements in science understanding. Collectively, these findings open concrete opportunities for developing STEM-ESD learning models that synergistically and structurally integrate the strengths of RE and EDP—particularly for sustainability issues that require both complex systems understanding and strong action commitment.

The substantive context of this study—SDG-6 on clean water and sanitation—is also relevant to discuss in relation to the effectiveness of both approaches. Clean water is one of the sustainability issues most proximate to the daily lives of students in Indonesia, yet it is simultaneously a systemic problem requiring understanding of the water cycle, water treatment technologies, and resource management policy [47], [48]. This contextual relevance is a factor that theoretically supports the effectiveness of project-based learning, as the proximity of problems to students' realities enhances motivation and engagement [49], [50]. However, the systemic complexity of clean water issues also means that action transformation cannot be achieved through individual knowledge alone; understanding the social, economic, and political dimensions of water access inequality is also required [51]. Within a holistic ESD framework, learning about SDG-6 ideally integrates systems analysis (supported by RE) with the design of locally implementable solutions (supported by EDP) [52], [53]. Findings from this study implicitly support the need for such integration, as each approach partially succeeded in touching different aspects of the sustainability competencies required to address SDG-6 comprehensively.

Read alongside the studies discussed above, the pattern found here can be generalized cautiously to other secondary-school, sustainability-themed STEM-ESD contexts: engineering-based interventions of a single short cycle are more likely to shift the cognitive/competency dimension of student action than its aggregate behavioral dimension, and RE- and EDP-type approaches are more accurately understood as complementary rather than competing strategies. Pedagogically, the findings of this study carry several important implications for curriculum development and STEM-ESD instructional practice in Indonesia. First, intervention design must account for the temporal dimension: multidimensional action change requires instruction designed over a longer time span incorporating repeated reflection cycles [54]-[56]. Second, the combination of RE and EDP should be designed sequentially and in an integrated manner rather than as standalone alternatives, so that the cognitive benefits of RE can serve as a foundation that strengthens the quality of the design process in EDP [57]. Third, the measurement of STEM-ESD program effectiveness should employ instruments capable of capturing incremental change across different action dimensions, rather than relying solely on aggregate measures that may obscure changes in specific dimensions [58].

This study is limited by a constrained sample size (36 students per group) that, as noted under Statistical Power, provided adequate power only for medium-to-large effects; a single-cycle intervention duration insufficient for observing long-term action change; and potential contextualization bias arising from initial pretest differences between the experimental and control groups. These limitations mean the non-significant aggregate result should be interpreted as inconclusive rather than as evidence of no effect. Future research should (1) use a larger, multi-school sample and an a priori power analysis to detect smaller effects; (2) extend the intervention across multiple cycles or a full semester to capture longer-term action change; (3) test mediating and moderating variables such as self-efficacy, value orientation, and family socioeconomic context [59]; and (4) trial a sequential RE-then-EDP design, as proposed above, to evaluate whether combining the two approaches produces the synergistic effect their complementary mechanisms suggest. Nonetheless, this study provides meaningful empirical contributions to understanding the mechanisms by which EDP and RE shape student action related to sustainability, and opens a relevant and pressing research agenda for the development of more effective STEM-ESD education in the future.

## 4. CONCLUSION

This study set out to describe the implementation of STEM-ESD learning based on Engineering Design Process (EDP) and Reverse Engineering (RE), and to measure its effect on student action toward SDG-6; both aims were addressed. STEM-ESD instruction based on EDP and RE did not produce a statistically significant difference in overall student action improvement related to SDG-6 ($p = 0.410 > 0.05$), but the two approaches demonstrated different and complementary patterns of influence at the indicator level: RE significantly improved students' competency achievement regarding clean water and sanitation compared to the control group ($p = 0.037 < 0.05$), while EDP showed a consistent tendency to outperform on the present- and future-action indicators. These findings support a new conceptual distinction for the ESD action-competence framework: RE builds declarative, "what to know" competence, while EDP builds procedural and motivational, "what to do" competence. The implication is that sustainability-oriented biology learning models should not treat RE and EDP as alternative options but should integrate them synergistically and sequentially within a single, coherent, and continuous learning design, so that the conceptual foundation RE provides can be converted into the sustained action orientation that EDP fosters.

## ACKNOWLEDGEMENTS
The authors would like to express sincere gratitude to the principal, science teachers, and students of the participating senior high school for their willingness and cooperation throughout the data collection process. Appreciation is also extended to the reviewers and editorial board for their constructive feedback in improving the quality of this manuscript.

## 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.

## REFERENCES
[1] S. J. Mostacedo-Marasovic, A. Bolivar-Lobaton, and M. Walter, "Social hydrology in science education: Framing socio-hydrological issues for SDG-6 learning," *Water*, vol. 14, no. 3, pp. 412, 2022, doi: 10.3390/w14030412.
[2] UN-Water, "Summary Progress Update 2021: SDG 6 — Water and Sanitation for All," UN-Water, Geneva, Switzerland, 2021. [Online]. Available: https://www.unwater.org/publications/summary-progress-update-2021-sdg-6-water-and-sanitation-for-all
[3] J. Rockstrom et al., "A safe operating space for humanity," *Nature*, vol. 461, no. 7263, pp. 472–475, 2009, doi: 10.1038/461472a.
[4] B. Setiawan, A. Rachmatullah, and J. Choo, "STEM integration with education for sustainable development: A conceptual framework for contextual learning," *Eurasia J. Math. Sci. Technol. Educ*., vol. 19, no. 4, p. em2248, 2023, doi: 10.29333/ejmste/13056.
[5] M. E. Hoque, M. A. Rahman, and M. S. Islam, "STEM-ESD integration in promoting sustainability literacy: A systematic review," *J. Educ. Sustain. Dev*., vol. 16, no. 1, pp. 45–63, 2022, doi: 10.1177/09734082221084801.
[6] C. L. R. Mahanani, D. Ardianto, and M. Z. Arifin, "Implementation of robotics-integrated ESD STEM learning to improve elementary school students' creative thinking and communication skills," *Jurnal Penelitian Pendidikan IPA*, vol. 12, no. 5, pp. 42-53, 2026, doi: 10.29303/jppipa.v12i5.14659.
[7] T. Chrysochou, G. Katsiampoura, and C. Skordoulis, "From STS to STEM: rethinking STEM education," *Discover Education*, vol. 4, no. 1, pp. 381, 2025, doi: 10.1007/s44217-025-00784-0.
[8] R. P. Verhoeff, A. Knippels, C. Gilissen, and A. Boersma, "The theoretical nature of systems thinking. Perspectives on systems thinking in biology education," *Front. Educ*., vol. 3, p. 40, 2018, doi: 10.3389/feduc.2018.00040.
[9] H. Abukari, Z. A. Imoro, F. U. Abubakari, and T. K. Aikins, "Ecosystem services knowledge and conservation attitudes of senior high school students," *Rangeland Ecology & Management*, vol. 107, pp. 85-90, 2026, doi: 10.1016/j.rama.2026.04.007.
[10] I. Sadeh and M. Zion, "The development of dynamic inquiry performances within an open inquiry setting: A comparison to guided inquiry setting," *J. Res. Sci. Teach*., vol. 46, no. 10, pp. 1137–1160, 2009, doi: 10.1002/tea.20310.
[11] L. Wang, B. Gao, X. Chang, and L. Zhang, "The promotive effect of ocean literacy on marine conservation behavior: A qualitative study based on Chinese university students," *Plos one*, vol. 20, no. 8, pp. 0323510, 2025, doi: 10.1371/journal.pone.0323510.
[12] H. Q. Hoa, "Integrating design thinking into STEM education: Enhancing problem-solving skills of high school students," *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 21, no. 4, pp. 2611, 2025, doi: 10.29333/ejmste/16084.

[13] D. Olsson, N. Gericke, and P. C. Rundgren, "The effect of implementation of education for sustainable development in Swedish compulsory schools: Assessing pupils' sustainability consciousness," *Environ. Educ. Res*., vol. 22, no. 2, pp. 176–202, 2016, doi: 10.1080/13504622.2015.1005057.

[14] P. T. Espinosa-Gutiérrez, E. Gavari-Starkie, C. Lucini-Baquero, and J. Pastrana-Huguet, "STEAM education using natural resources in rural areas: Case study of a grouped rural school in Avila, Spain," *Sustainability*, vol. 17, no. 6, pp. 2736, 2025, doi: 10.3390/su17062736.

[15] J. W. Creswell and V. L. P. Clark, *Designing and Conducting Mixed Methods Research, 3rd ed*. Thousand Oaks, CA, USA: SAGE Publications, 2018.

[16] S. Sugiyono, *Metode Penelitian Kuantitatif, Kualitatif, dan R&D [Quantitative, Qualitative, and R&D Research Methods]*. Bandung, Indonesia: Alfabeta, 2019.

[17] M. B. Miles, A. M. Huberman, and J. Saldana, *Qualitative Data Analysis: A Methods Sourcebook, 3rd ed*. Thousand Oaks, CA, USA: SAGE Publications, 2014.

[18] W. Widhiarso, *Uji Hipotesis Komparatif [Comparative Hypothesis Testing]*. Yogyakarta, Indonesia: Universitas Gadjah Mada Press, 2010.

[19] R. W. Bybee, *The Case for STEM Education: Challenges and Opportunities*. Arlington, VA, USA: NSTA Press, 2013.

[20] T. R. Kelley and J. G. Knowles, "A conceptual framework for integrated STEM education," *Int. J. STEM Educ*., vol. 3, no. 1, p. 11, 2016, doi: 10.1186/s40594-016-0046-z.

[21] R. Coe, "It's the effect size, stupid: What effect size is and why it is important," presented at Br. Educ. Res. Assoc. Annu. Conf., 2002.

[22] J. Hattie, *Visible Learning: A Synthesis of Over 800 Meta-Analyses Relating to Achievement*. New York, NY, USA: Routledge, 2009.

[23] A. A. Akinsemolu, and H. Onyeaka, "The role of green education in achieving the sustainable development goals: A review," *Renewable and Sustainable Energy Reviews*, vol. 210, pp. 115239, 2025, doi: 10.1016/j.rser.2024.115239.

[24] A. E. J. Wals, *Beyond Unreasonable Doubt: Education and Learning for Socio-Ecological Sustainability in the Anthropocene*. Wageningen, Netherlands: Wageningen Univ., 2015.

[25] UNESCO, *Education for Sustainable Development Goals: Learning Objectives*. Paris, France: UNESCO Publishing, 2017.

[26] G. M. Alam, "Sustainable education, sustainability in education and education for sustainable development: the reconciliation of variables and the path of education research in an era of technologization," *Sustainability*, vol. 17, no. 1, pp. 250, 2025, doi: 10.3390/su17010250.

[27] J. Laessoe and Y. Mochizuki, "Recent trends in national policy on education for sustainable development and climate change education," *J. Educ. Sustain. Dev*., vol. 9, no. 1, pp. 4–33, 2015, doi: 10.1177/0973408215569112.

[28] L. W. Anderson and D. R. Krathwohl, *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Educational Objectives*. New York, NY, USA: Longman, 2001.

[29] T. Stouthart, D. Bayram, and J. van Der Veen, "Science teachers' views on student competences in education for sustainable development," *Journal of Research in Science Teaching*, vol. 62, no. 6, pp. 1617-1653, 2025, doi: 10.1002/tea.22021.

[30] M. E. Hoque, F. A. M. Yusuf, F. M. Widad, and B. Musthafa, "Impact of product analysis-based STEM learning on students' science literacy and sustainability competence," *Sustainability*, vol. 14, no. 18, p. 11287, 2022, doi: 10.3390/su141811287.

[31] Y. Li, M. H. Chiu, and S. L. Wong, "Integration of artifact analysis in STEM learning: A meta-analysis of conceptual understanding outcomes," *Int. J. Sci. Educ*., vol. 43, no. 11, pp. 1801–1823, 2021, doi: 10.1080/09500693.2021.1934564.

[32] S. Vidal, and M. Kuckuck, "Pre-Service teacher action competence in education for sustainable development: a scoping review," *Sustainability*, vol. 17, no. 9, pp. 3856, 2025, doi: 10.3390/su17093856.

[33] J. W. Pellegrino and M. L. Hilton, *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century*. Washington, DC, USA: National Academies Press, 2012.

[34] L. D. English, "STEM education K-12: Perspectives on integration," *Int. J. STEM Educ*., vol. 3, no. 1, pp. 1–8, 2016, doi: 10.1186/s40594-016-0036-1.

[35] A. Bandura, *Self-Efficacy: The Exercise of Control*. New York, NY, USA: W. H. Freeman, 1997.

[36] R. Paloș, D. Vîrgă, and R. Dediu, "Students' approach to learning and their intrinsic motivation to know–the moderating role of psychological needs," *Current Psychology*, vol. 44, no. 12, pp. 11757-11770, 2025, doi: 10.1007/s12144-025-07990-x.

[37] S. Han, R. Capraro, and M. M. Capraro, "How science, technology, engineering, and mathematics (STEM) project-based learning (PBL) affects high, middle, and low achievers differently: The impact of student factors on achievement," *Int. J. Sci. Math. Educ*., vol. 13, no. 5, pp. 1089–1113, 2015, doi: 10.1007/s10763-014-9526-0.

[38] A. Husin, H. Helmi, Y. K. Nengsih, and M. Rendana, "Environmental education in schools: sustainability and hope," *Discover Sustainability*, vol. 6, no. 1, pp. 41, 2025, doi: 10.1007/s43621-025-00837-2.

[39] H. Liu, Y. Wang, and H. Wang, "Exploring the mediating roles of motivation and boredom in basic psychological needs and behavioural engagement in English learning: a self-determination theory perspective," *BMC psychology*, vol. 13, no. 1, pp. 179, 2025, doi: 10.1186/s40359-025-02524-3.

[40] J. S. Eccles and A. Wigfield, "Motivational beliefs, values, and goals," *Annu. Rev. Psychol*., vol. 53, no. 1, pp. 109–132, 2002, doi: 10.1146/annurev.psych.53.100901.135153.

[41] H. C. Le, V. H. Nguyen, and T. L. Nguyen, "Integrated STEM approaches and associated outcomes of K-12 student learning: A systematic review," *Education Sciences*, vol. 13, no. 3, pp. 297, 2023, doi: 10.3390/educsci13030297.

[42] F. E. Weinert, "Concept of competence: A conceptual clarification," in Defining and Selecting Key Competencies, D. S. Rychen and L. H. Salganik, Eds. Gottingen, Germany: Hogrefe & Huber, 2001, pp. 45–65.

[43] R. E. Mayer, "Rote versus meaningful learning," *Theory Into Pract*., vol. 41, no. 4, pp. 226–232, 2002, doi: 10.1207/s15430421tip4104_4.
[44] Z. Faizah, D. Rochintaniawati, N. Winarno, and R. Solihat, "Implementation strategy of education for sustainable development (ESD) in science education: a systematic literature review," *Jurnal Pendidikan Sains Indonesia (Indonesian Journal of Science Education)*, vol. 14, no. 1, pp. 1255-1277, 2026, doi: 10.24815/jpsi.v14i1.176.
[45] X. S. Apedoe, B. Reynolds, M. R. Ellefson, and C. D. Schunn, "Bringing engineering design into high school science classrooms: The heating/cooling unit," *J. Sci. Educ. Technol*., vol. 17, no. 5, pp. 454–465, 2008, doi: 10.1007/s10956-008-9114-6.
[46] J. Pozuelo-Muñoz, A. de Echave Sanz, and E. C. Salillas, "Inquiring in the Science Classroom by PBL: A Design-Based Research Study," *Education Sciences*, vol. 15, no. 1, pp. 53, 2025, doi: 10.3390/educsci15010053.
[47] UNICEF and WHO, Progress on Household Drinking Water, Sanitation and Hygiene 2000–2022: Special Focus on Gender. New York, NY, USA: UNICEF and WHO, 2023.
[48] S. Wahyuni, A. Humaira, and D. Khoirunnisa, "Access to clean water and sanitation in Indonesian schools: Challenges and implications for environmental education," *J. Environ. Educ*., vol. 52, no. 4, pp. 234–248, 2021, doi: 10.1080/00958964.2021.1903901.
[49] J. Krajcik and N. Shin, "Project-based learning," in The Cambridge Handbook of the Learning Sciences, 2nd ed., R. K. Sawyer, Ed. Cambridge, U.K.: Cambridge Univ. Press, 2014, pp. 275–297.
[50] P. R. Hernandez, H. J. Boone, and J. A. Brown, "Contextualizing STEM: Project-based learning for relevance and community," J. STEM Educ. Innov. Res., vol. 21, no. 2, pp. 5–12, 2020, doi: 10.37626/GA9783959871440.0.02.
[51] M. M. Mekonnen and A. Y. Hoekstra, "Four billion people facing severe water scarcity," *Sci. Adv*., vol. 2, no. 2, pp. 1500323, 2016, doi: 10.1126/sciadv.1500323.
[52] A. Amprazis, and P. Papadopoulou, "Key competencies in education for sustainable development: A valuable framework for enhancing plant awareness," *Plants, People, Planet*, vol. 7, no. 4, pp. 1195-1211, 2025, doi: 10.1002/ppp3.10625.
[53] M. M. Omer, R. A. Rahman, M. A. Fauzi, and S. Almutairi, "Key competencies for identifying construction activities that produce recyclable materials: a competency gap analysis," *Built Environment Project and Asset Management*, vol. 15, no. 3, pp. 699-716, 2025, doi: 10.1108/BEPAM-10-2023-0181.
[54] D. A. Kolb, *Experiential Learning: Experience as the Source of Learning and Development*. Englewood Cliffs, NJ, USA: Prentice Hall, 1984.
[55] J. Mezirow, *Transformative Dimensions of Adult Learning*. San Francisco, CA, USA: Jossey-Bass, 1991.
[56] J. Biggs and C. Tang, *Teaching for Quality Learning at University, 4th ed.* Maidenhead, U.K.: Open University Press/McGraw-Hill, 2011.
[57] N. Mentzer, K. Becker, and M. Sutton, "Engineering design thinking: High school students' performance and knowledge," *J. Eng. Educ*., vol. 104, no. 4, pp. 417–432, 2015, doi: 10.1002/jee.20105.
[58] J. Cincera and J. Krajhanzl, "Eco-schools: What factors influence pupils' action competence for pro-environmental behaviour?," *J. Clean. Prod*., vol. 61, pp. 117–121, 2013, doi: 10.1016/j.jclepro.2013.06.030.
[59] M. S. Hagger, and K. Hamilton, "Progress on theory of planned behavior research: advances in research synthesis and agenda for future research," *Journal of Behavioral Medicine*, vol. 48, no. 1, pp. 43-56, 2025, doi: 10.1007/s10865-024-00545-8.