



AI-Based Website for Integrating STEM and ESD: Enhancing Students' Creative Thinking, Creative Products, and Self-Reflection

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Articles Information

Abstrak

Keywords:

Artificial Intelligence;
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Creative Product;
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Penelitian ini bertujuan untuk mengkaji efektivitas sebuah website berbasis kecerdasan buatan (AI) yang dirancang untuk mengintegrasikan STEM (Science, Technology, Engineering, and Mathematics) dengan Education for Sustainable Development (ESD) dalam meningkatkan berpikir kreatif, produk kreatif, dan refleksi diri siswa sekolah dasar. Penelitian menggunakan desain metode campuran dengan melibatkan 240 siswa kelas IV dari empat sekolah dasar negeri di Jakarta dan Bekasi. Data dikumpulkan melalui tes berpikir kreatif, observasi produk, serta survei refleksi diri. Hasil analisis kuantitatif menunjukkan peningkatan signifikan pada semua indikator berpikir kreatif, yaitu kelancaran ($N\text{-Gain} = 0,59$), orisinalitas (0,56), dan fleksibilitas (0,49), dengan ukuran efek besar (Cohen's $d > 1,0$). Analisis produk kreatif mengungkap bahwa kelompok eksperimen menghasilkan artefak dengan tingkat kebaruan, fungsionalitas, dan keselarasan keberlanjutan yang lebih tinggi dibanding kelompok kontrol. Sementara itu, analisis tematik terhadap refleksi diri siswa menunjukkan lima tema utama, yaitu pengembangan berpikir kreatif, keterlibatan dalam produk kreatif, kolaborasi, kesadaran keberlanjutan, serta motivasi. Temuan ini menegaskan bahwa integrasi AI dalam pembelajaran STEM-ESD dapat memperkuat keterampilan kognitif, afektif, dan metakognitif siswa sekaligus menumbuhkan kesadaran akan nilai keberlanjutan. Implikasi penelitian ini relevan bagi guru, perancang kurikulum, dan pembuat kebijakan dalam mengadopsi teknologi AI untuk mendukung pembelajaran kreatif dan berorientasi pada keberlanjutan di sekolah dasar.

Abstract

This study aims to examine the effectiveness of an artificial intelligence (AI)-based website designed to integrate STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD) in enhancing elementary students' creative thinking, creative products, and self-reflection. The research employed a mixed-method design involving 240 fourth-grade students from four public elementary schools in Jakarta and Bekasi. Data were collected through creative thinking tests, product observations, and self-reflection surveys. Quantitative analysis revealed significant improvements across all indicators of creative thinking, namely fluency ($N\text{-Gain} = 0.59$), originality (0.56), and flexibility (0.49), with large effect sizes (Cohen's $d > 1.0$). Analysis of creative products indicated that the experimental group produced artifacts with higher levels of novelty, functionality, and sustainability alignment compared to the control group. Meanwhile, thematic analysis of students' self-reflections identified five main themes: creative thinking development, engagement in creative products, collaboration,

sustainability awareness, and motivation. These findings highlight that integrating AI into STEM-ESD learning can strengthen students' cognitive, affective, and metacognitive skills while also fostering awareness of sustainability values. The implications of this research are relevant for teachers, curriculum designers, and policymakers in adopting AI technology to support creative and sustainability-oriented learning in elementary education.

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INTRODUCTION

In today's rapidly evolving educational landscape, integrating Artificial Intelligence (AI) with STEM (Science, Technology, Engineering, and Mathematics) and Education for Sustainable Development (ESD) has become increasingly critical. The urgency of this study is anchored in the demand for educational frameworks that not only impart interdisciplinary knowledge but also foster creative thinking, product innovation, and reflective learning, which are skills essential for addressing complex sustainability challenges. AI-based platforms have the potential to personalize instruction, offer real-time feedback, and support self-regulation, thereby enhancing students' creative outcomes and self-reflection abilities in meaningful ways (Lin et al., 2024; Xu & Ouyang, 2022; Glick et al., 2024).

Recent advancements demonstrate that AI can significantly elevate STEM education outcomes. For example, integrating generative AI as a learning aid within experiential learning models, such as the GPT-Assisted Summarization Aid (GASA), has been shown to improve students' reflective thinking, collaborative engagement, and problem-solving skills (Lin et al., 2024). The development of the Constructivist Inquiry-Based Learning with Prompting (CILP) framework illustrates how generative AI can be leveraged through iterative engagement, inquiry, and metacognitive reflection to deepen conceptual understanding in STEM disciplines (El Fathi, 2025). Moreover, case studies involving ChatGPT and Bing Chat reveal that conversational AI tools can act as "objects to think with," enhancing creativity, critical thinking, and concept comprehension in STEM learning contexts (Vasconcelos & dos Santos, 2023).

Other innovations, such as AI-powered virtual-human training modules focused on planning, self-monitoring, and reflection, also show promise in promoting self-regulated learning behaviors among STEM students (Glick et al., 2024). Notably, tools like MindScratch, a multimodal generative AI visual programming support for K–12 learners, have been found to enhance creative thinking and computational thinking within classroom activities (Chen et al., 2024). Similarly, a human-in-the-loop adaptive learning system using generative AI enables students to critically shape AI-generated responses, resulting in improved engagement and learning outcomes in STEM contexts (Tarun et al., 2025).

Comprehensive reviews further reinforce the growing impact of AI in STEM education. A systematic review focusing on peer-reviewed studies from 2020 to 2025 emphasizes emerging themes such as student

agency, AI-mediated adaptive assessment, and ethical considerations like transparency and equity in AI-driven learning environments (Xu & Ouyang, 2022; Frontiers, 2025). Additionally, broader surveys of AI-based learning technologies underscore AIED's transformative potential while calling for attention to ethical design and equitable implementation (CADRE, 2025). The role of AI in enhancing engagement through personalized, adaptive, and immersive learning activities has also been documented (STEM Minds, 2025; SchoolAI, 2025; eLearning Industry, 2024).

Yet, gaps remain in the literature. Despite the proliferation of AI tools in STEM, most studies emphasize reflection or creativity in isolation, and often lack a cohesive platform that integrates all three outcomes: creative thinking, creative product development, and self-reflection, within a single AI-based learning environment. Moreover, there is a scarcity of research that explicitly aligns AI-enhanced STEM education with ESD principles, leaving unexplored the potential synergies between sustainability education and AI-facilitated creative learning. Finally, while AI tools have been studied in discrete contexts (for example, programming, virtual-human training, and conversational agents), there is limited empirical evidence on the effectiveness of a holistic AI-based website designed to integrate STEM and ESD to foster a comprehensive blend of creativity, product creation, and reflective self-awareness.

In response, this study proposes to fill this gap by developing and evaluating an AI-based website that intentionally integrates STEM and ESD content to enhance students' creative thinking, creative production, and self-reflection. By doing so, it aims to contribute new empirical insights at the intersection of AI-mediated learning, sustainability education, and creative metacognition.

METHOD

Research Design

This study employed a mixed-methods research design combining quantitative and qualitative approaches to comprehensively evaluate the effectiveness of an AI-based website integrating STEM and ESD principles. The design aimed to investigate three specific learning outcomes: students' creative thinking, creative product development, and self-reflection. The quantitative component included pre- and post-intervention measures, while the qualitative component employed open-ended responses and observational data to capture rich insights into students' creative processes and reflective experiences. This design allows for triangulation of data to enhance the validity and reliability of the findings (Creswell & Plano Clark, 2021).

Participants

The participants were four public elementary schools located across Jakarta and Bekasi, Indonesia. A total of 240 fourth-grade students were selected using purposive sampling based on school accessibility and willingness to participate in an AI-assisted learning intervention. Each school contributed approximately 60 students. The selected schools represented a diverse demographic in terms of socio-economic background

and prior STEM learning exposure, ensuring that the study findings would be generalizable to a broad urban elementary population.

Data Collection Instruments

Data collection was conducted using three complementary instruments that correspond to the study's targeted learning outcomes. Students' creative thinking was assessed through open-ended essay questions designed to explore their innovative problem-solving strategies and their ability to generate multiple solutions in STEM-ESD contexts. The essays were evaluated using a rubric adapted from Torrance's Creativity Test (Torrance, 2020), which emphasized fluency, originality, and flexibility. Creative products were measured through systematic observation of student-generated artifacts created during AI-assisted STEM-ESD activities. Observers applied a structured rubric focusing on novelty, functionality, and alignment with sustainability principles to ensure consistent evaluation across participants. Self-reflection was captured using a structured open-ended survey that invited students to describe their learning experiences, challenges encountered, and personal growth throughout the intervention. The responses were assessed for depth of reflection and alignment with metacognitive learning objectives. All instruments underwent validation by a panel consisting of three STEM education experts and two ESD specialists to ensure content validity and alignment with the study's objectives.

Data Analysis

The collected data were analyzed using a combination of quantitative and qualitative methods to provide a comprehensive understanding of the AI-based intervention's impact. For creative thinking, essay responses were scored quantitatively based on the rubric criteria of fluency, originality, and flexibility. Pre- and post-intervention scores were compared using descriptive statistics (mean, standard deviation) and inferential statistics, specifically paired-sample t-tests, to determine statistically significant improvements. For creative products, observational data were analyzed qualitatively using thematic analysis (Braun & Clarke, 2021). Observers coded recurring patterns and themes related to novelty, functionality, and sustainability alignment, allowing for identification of trends and exemplary practices. Self-reflection survey responses were subjected to content analysis, where student reflections were coded into categories representing levels of metacognitive awareness, self-assessment, and experiential learning. To enhance trustworthiness and validity, triangulation was conducted by comparing findings from the three data sources, ensuring that improvements in creative thinking, product development, and self-reflection were consistently supported across multiple measures. Additionally, inter-rater reliability was calculated for essay scoring and product observation to confirm consistency among evaluators.

RESULT AND DISCUSSION

Creative Thinking

Quantitative analysis of creative thinking focused on three key indicators: fluency, originality, and flexibility. These indicators were chosen to represent essential aspects of students' divergent thinking and

problem-solving skills in STEM-ESD contexts. Prior to conducting inferential analyses, the normality of pre- and post-test scores was verified using the Shapiro-Wilk test, confirming that all indicators were normally distributed ($p > .05$), thus meeting the assumptions for paired-sample t-tests.

Descriptive statistics for each indicator and the total creative thinking scores are presented in Table 1. The table shows the pre-test and post-test mean scores, standard deviations, and the mean differences, providing an overview of students' improvements across the intervention.

Table 1. Descriptive Statistics of Creative Thinking Indicators (Pre- and Post-Test)

Indicator	Pre-Test Mean (SD)	Post-Test Mean (SD)	Mean Difference	N-Gain	Interpretaiton
Fluency	21.3 (3.4)	27.6 (3.1)	6.3	0.59	Medium
Originality	22.0 (3.1)	27.9 (2.8)	5.9	0.56	Medium
Flexibility	21.9 (2.9)	26.2 (3.0)	4.3	0.49	Medium
Total	65.2 (8.4)	81.7 (7.5)	16.5	0.55	Medium

As shown in Table 1, all indicators exhibited substantial gains following the AI-based STEM-ESD intervention. Fluency demonstrated the largest mean increase (6.3 points), indicating that students generated a greater number of ideas and solutions after engaging with the AI-based platform. Originality increased by 5.9 points, reflecting students' enhanced ability to produce unique and novel solutions, while flexibility showed a slightly smaller gain of 4.3 points, suggesting improvements in students' capacity to approach problems from multiple perspectives. Overall, the total creative thinking score increased by 16.5 points, demonstrating a meaningful improvement in divergent thinking and problem-solving abilities. In terms of N-Gain interpretation, all indicators showed medium-level improvements. Fluency achieved the highest N-Gain (0.59), indicating substantial progress in students' idea generation. Originality (0.56) further confirmed students' ability to generate unique solutions, while flexibility (0.49) highlighted growth in adopting varied perspectives. The total N-Gain of 0.55 confirms that the AI-based STEM-ESD intervention effectively fostered a medium-level overall enhancement in creative thinking.

To examine whether these improvements were statistically significant, paired-sample t-tests were conducted, and the results are presented in Table 2. This table includes the t-values, degrees of freedom, significance levels, and Cohen's d effect sizes for each indicator and the total score.

Table 2. Paired-Sample t-Test Results for Creative Thinking Indicators

Indicator	t	df	p	Cohen's d
Fluency	22.78	239	<.001	1.47
Originality	20.95	239	<.001	1.35
Flexibility	16.89	239	<.001	1.09
Total	23.45	239	<.001	1.52

The t-test results in Table 2 show that the increases in all indicators were statistically significant at $p < .001$, confirming that the observed improvements were unlikely due to chance. The effect sizes (Cohen's d) were all greater than 1.0, indicating large practical significance. Specifically, the largest effect was observed in the total creative thinking score ($d = 1.52$), highlighting the strong overall impact of the AI-based STEM-ESD intervention. Fluency had the highest individual effect size ($d = 1.47$), suggesting that the intervention most strongly influenced students' capacity to generate a wide range of ideas. Originality and flexibility also showed large effect sizes ($d = 1.35$ and 1.09 , respectively), demonstrating meaningful gains in students' ability to produce novel solutions and adaptively approach problems from multiple angles. These results collectively indicate that the AI-based website effectively enhanced students' creative thinking skills across all measured dimensions.

Creative Products

Observational data from Creative Products showed substantial improvements in novelty, functionality, and sustainability alignment of student-generated artifacts. Thematic analysis identified three recurring patterns: innovative problem-solving, practical application, and integration of sustainability principles. Inter-rater reliability was high (Cohen's kappa = 0.87), indicating strong agreement among evaluators regarding the quality of the creative products.

Table 3. Creative Products Evaluation by Group and School

School	Group	Novelty (H/M/L)	Functionality (H/M/L)	Sustainability Alignment (H/M/L)
School A	Experimental	80 / 17 / 3	75 / 20 / 5	83 / 14 / 3
	Control	52 / 34 / 14	48 / 38 / 14	50 / 36 / 14
School B	Experimental	79 / 18 / 3	71 / 23 / 6	82 / 15 / 3
	Control	55 / 33 / 12	50 / 37 / 13	53 / 35 / 12
School C	Experimental	77 / 19 / 4	70 / 24 / 6	81 / 16 / 3
	Control	50 / 36 / 14	46 / 40 / 14	52 / 35 / 13
School D	Experimental	76 / 20 / 4	72 / 22 / 6	79 / 17 / 4
	Control	53 / 35 / 12	49 / 38 / 13	51 / 37 / 12

As shown in Table 3, the experimental groups in all four schools consistently outperformed the control groups across all three dimensions of creativity. In terms of novelty, 76–80% of the products from the experimental groups were rated high compared to only 50–55% in the control groups, suggesting that the AI-based intervention was particularly effective in stimulating students' capacity to generate unique and unconventional ideas. A similar pattern was evident in functionality, where 70–75% of experimental group products achieved high ratings versus only 46–50% in the control groups, indicating that students not only proposed creative ideas but also transformed them into feasible and practical solutions. The most pronounced difference appeared in sustainability alignment, with 79–83% of experimental products rated high compared to just 50–53% in the control groups, implying that the intervention helped students

integrate sustainability values into their problem-solving processes. Medium-quality ratings were notably lower in the experimental groups (14–24%) than in the control groups (33–40%), suggesting that many control group products exhibited partial creativity but often fell short in originality, feasibility, or sustainability integration. Low-quality ratings were minimal in the experimental groups (3–6%) but consistently higher in the control groups (12–14%), reflecting greater struggles in developing novel, functional, and sustainability-oriented products.

Students' Self-Reflection Ability

Self-reflection is one of the essential aspects of STEM-ESD-based learning because it reveals the extent to which students understand, respond to, and internalize the materials presented. In this study, students' reflections were analyzed using a thematic approach. The data were obtained from students' responses to reflective questions developed with an Education for Sustainable Development (ESD) perspective and adapted to the cognitive and emotional development of elementary school students. The analysis focused on five main themes: creative thinking development, creative product engagement, collaboration and communication, sustainability awareness, and motivation and learning attitudes.

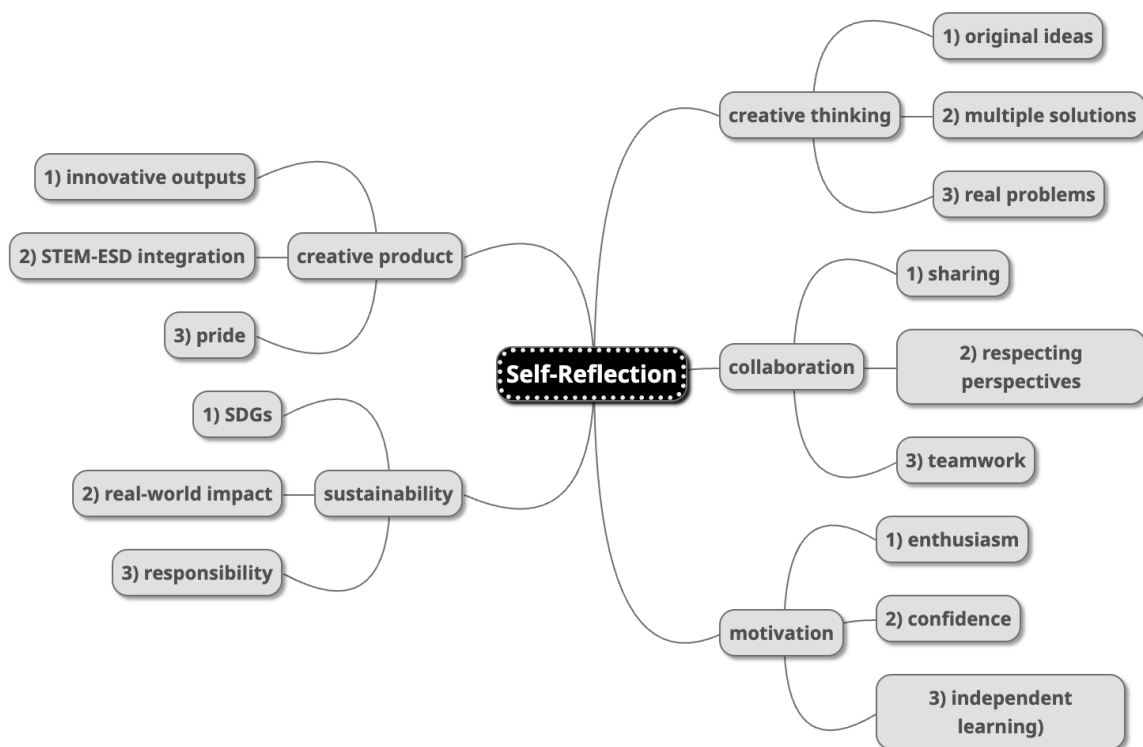


Figure 1. Visualization of themes derived from students' self-reflection

The results presented in Figure 1 indicate that students' reflections demonstrated strong awareness of how the AI-based STEM-ESD website shaped their learning process. Within the theme of creative thinking, students recognized their ability to generate original ideas, explore diverse solutions, and apply creativity to real-world contexts. Creative product engagement was also evident, as students expressed pride in designing innovative outputs and integrating STEM knowledge with sustainability values. Under the theme of collaboration and communication, many students highlighted the importance of teamwork, idea sharing, and respecting peer perspectives, which they found to be motivating and enjoyable. In terms of sustainability awareness, students made meaningful connections between their learning and broader global issues, such as responsible energy use and environmental care. Finally, the theme of motivation and learning attitudes showed that students experienced increased enthusiasm, gained confidence in solving problems, and displayed greater independence in managing their own learning. Collectively, these findings suggest that the AI-based STEM-ESD intervention not only enhanced academic competencies but also cultivated reflective, responsible, and adaptive learners prepared for twenty-first-century challenges.

Discussion

This study investigated the impact of an AI-based website integrating STEM and Education for Sustainable Development (ESD) on students' creative thinking, creative product development, and self-reflection. The findings confirm that the intervention produced significant and meaningful learning gains, aligning with contemporary research that highlights the potential of AI-enhanced STEM-ESD pedagogies to strengthen twenty-first-century skills (Xu & Ouyang, 2022).

Enhancement of Creative Thinking Skills

The results demonstrated medium-level N-Gain improvements in fluency (0.59), originality (0.56), and flexibility (0.49), with large effect sizes (Cohen's d between 1.09 and 1.52). These findings are consistent with previous studies showing that STEM-based curricula can substantially enhance creative thinking dimensions such as fluency, originality, and flexibility across different levels of education (Aslam et al., 2024). The integration of AI within this process further supports existing evidence that AI tools, when meaningfully applied, foster student engagement and promote divergent thinking and problem-solving skills (Glick et al., 2024; Lin et al., 2024; Shin et al., 2025). In this study, the largest improvement occurred in fluency, suggesting that the AI-based platform was particularly effective in encouraging students to generate a broader range of ideas.

Improvement in Creative Products

Beyond cognitive gains, the intervention also positively influenced students' ability to design creative products. Experimental groups consistently outperformed control groups in terms of novelty, functionality, and sustainability alignment. These results suggest that the AI-based platform not only facilitated ideation but also enabled students to transform abstract ideas into feasible and sustainability-conscious products. This aligns with the notion that AI in STEM education should emphasize "knowledge-in-use," encouraging

learners to apply concepts in authentic contexts (Shin et al., 2025). Furthermore, embedding ESD within STEM activities appears to strengthen students' sense of responsibility and creativity, echoing earlier findings on the value of integrating sustainability principles into classroom innovation (Aslam et al., 2024).

Deepened Self-Reflection and Metacognition

The thematic analysis of students' reflections revealed five key themes—creative thinking development, creative product engagement, collaboration, sustainability awareness, and motivation—showing that the AI-based website supported holistic learning outcomes. This resonates with the argument that AI functions not merely as a technical tool but as a reflective partner in the learning process (Vasconcelos & dos Santos, 2023). By stimulating reflection, AI encouraged learners to evaluate their own creativity, teamwork, and sustainability awareness. Similar to recent work on generative AI in reflective education, the findings indicate that AI-driven prompts enhance both metacognition and self-awareness, leading to deeper and more meaningful learning experiences (Yuan & Hu, 2024).

Implications and Theoretical Contributions

Taken together, these outcomes contribute to the growing body of scholarship on the transformative role of AI in STEM-ESD education. The findings align with recommendations from the CADRE network, which emphasize the importance of AI in supporting cognitive, metacognitive, motivational, and collaborative learning processes (Shin et al., 2025). They also support recent theoretical frameworks that highlight the role of generative AI in fostering reflective and adaptive learning environments (Lin et al., 2024; Yuan & Hu, 2024). By linking creative thinking, product innovation, and reflective practice, this study extends current literature and demonstrates how AI can cultivate responsible, creative, and sustainability-oriented learners.

Educational and Practical Implications

From an educational perspective, this research suggests several implications. For teachers, integrating AI-based platforms can provide structured scaffolds that enhance students' creativity and innovation beyond traditional classroom methods. For curriculum designers, embedding sustainability principles within STEM tasks is crucial for nurturing both creativity and environmental awareness. For policymakers, the demonstrated benefits of AI-based STEM-ESD interventions underscore the importance of supporting their adoption in primary education as part of broader educational reforms.

Limitations and Future Directions

Despite these promising results, the study has certain limitations. The intervention was conducted over a relatively short period and did not assess long-term knowledge retention or transfer of skills. Future research could employ longitudinal designs to explore sustained impacts of AI-supported STEM-ESD learning. Moreover, further studies should investigate the scalability of such interventions across diverse school contexts and examine their adaptability for teacher professional development. Addressing these gaps

will provide a deeper understanding of how AI can be effectively integrated into sustainable and creative education at scale.

CONCLUSION

This study explored the effectiveness of an artificial intelligence (AI)-based website designed to integrate STEM learning with Education for Sustainable Development (ESD) in supporting elementary school students. The focus of the study was on developing creative thinking, creative product creation, and self-reflection skills. The results showed that this intervention significantly improved students' learning experiences, not only academically but also in strengthening 21st-century competencies.

In terms of creative thinking, students demonstrated clear progress in generating ideas, formulating original solutions, and solving problems more flexibly. The greatest improvement was seen in the fluency indicator, indicating that the AI-based platform was able to encourage students to think more broadly and explore various possible answers. These findings confirm that AI-based STEM-ESD learning has the potential to foster creative problem-solving skills that are often difficult to achieve through traditional learning methods. The creative products produced by students also demonstrated the positive impact of this intervention. Students using the AI platform consistently produced work that was more original, functional, and aligned with sustainability principles compared to the control group. This demonstrates that the learning process does not stop at the ideation stage, but rather continues to create concrete solutions that consider both practical aspects and social and environmental values. The self-reflections written by students provide an additional layer of understanding to their learning experience. Students acknowledged developments in creative thinking, expressed pride in their products, and valued collaboration with peers. They also connected the learning experience to global sustainability issues. Furthermore, students reported increased motivation, self-confidence, and independence in learning. This demonstrates that the AI-based website serves not only as a learning aid but also as a reflective partner, helping students become more responsible and adaptive.

Overall, this study demonstrates that integrating AI into STEM-ESD learning can meaningfully enrich the learning experience. This approach supports the development of creativity, encourages sustainability-oriented thinking, and fosters self-awareness. All of these aspects are crucial for preparing students for future challenges. However, this study has limitations due to its short duration and focus on immediate outcomes. Further research is needed to evaluate the long-term sustainability of these positive impacts and to examine how similar interventions can be implemented across educational contexts and used for teacher professional development.

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