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Enhancing Environmental Awareness through STEAM-Based Learning with ESD Principles in Elementary Education

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Abstrak

Penelitian ini bertujuan untuk mengetahui efektivitas pendekatan STEAM yang diterapkan dengan prinsip-prinsip Education for Sustainable Development (ESD) dalam meningkatkan kesadaran lingkungan siswa sekolah dasar. Metode yang digunakan adalah kuantitatif dengan desain pretest-posttest kelompok tunggal. Sebanyak 30 siswa kelas V mengikuti pembelajaran berbasis proyek selama empat minggu. Hasil menunjukkan peningkatan skor rata-rata kesadaran lingkungan dari 69,5 (pretest) menjadi 83,2 (posttest), dengan nilai signifikansi p = 0,000 < 0,05. Pembelajaran berbasis proyek dengan prinsip ESD dan pendekatan STEAM membantu siswa memahami isu lingkungan secara konkret dan mendorong sikap peduli lingkungan. Simpulan dari penelitian ini adalah bahwa integrasi prinsip ESD ke dalam pendekatan STEAM efektif dalam membentuk kesadaran lingkungan sejak dini. Implikasinya, model ini layak diadopsi sebagai strategi pembelajaran kontekstual dalam pendidikan dasar.

Kata kunci: *Education for Sustainability Development;* Kesadaran lingkungan; Pembelajaran berbasis proyek; Sekolah Dasar; STEAM.

Abstract

This study aimed to examine the effectiveness of the STEAM approach implemented with principles of Education for Sustainable Development (ESD) in improving elementary students' environmental awareness. A quantitative method was used with a one-group pretest-posttest design. Thirty fifth-grade students participated in a four-week project-based learning program. The results showed an increase in the average environmental awareness score from 69.5 (pretest) to 83.2 (posttest), with a significance value of p = 0.000 < 0.05. Project-based learning that applied ESD principles within a STEAM approach helped students understand environmental issues concretely and encouraged pro-environmental attitudes. The study concludes that integrating ESD principles into STEAM-based learning is effective in fostering early environmental awareness. The implication is that this model can be adopted as a contextual learning strategy in primary education.

Keywords: Education for Sustainability Development; Environmental Awareness; Project Based Learning; Elementary School; STEAM.

1. INTRODUCTION

In the face of accelerating global environmental crises—such as climate change, biodiversity loss, excessive waste production, and water scarcity—education is widely recognized as a strategic tool for fostering sustainability (UNESCO, 2020). As these challenges threaten ecological and human systems, early intervention through education becomes critical. One of the essential learning outcomes for 21st-century learners is environmental awareness, which involves not only cognitive understanding of ecological systems but also the development of pro-environmental attitudes and behaviors (Brundiers et al., 2021; Mochizuki & Bryan, 2020). Primary education plays a vital role in cultivating this awareness, given that values and habits formed during childhood are likely to persist into adulthood.

To promote meaningful environmental awareness, teaching must go beyond rote learning and foster interdisciplinary thinking, ethical reflection, and real-world engagement. In this context, the STEAM approach—an educational framework that integrates Science, Technology, Engineering, Arts, and Mathematics—offers pedagogical potential for engaging students in holistic and project-based learning (Park et al., 2021; Yoon et al., 2022). When implemented effectively, STEAM encourages creativity, collaboration, and innovation, which are essential for problem-solving in sustainability contexts. However, to ensure that students not only "know" but also "care" and "act," the STEAM approach should be underpinned by clear principles of Education for Sustainable Development (ESD), including ecological responsibility, social equity, critical thinking, and systems thinking (Leicht et al., 2021; Frisk & Kajzer Mitchell, 2023).

Several recent studies have explored the convergence of STEAM and ESD. Lee and Choi (2019) designed a STEAM-ESD module that successfully increased both sustainability knowledge and empathy among primary school students in South Korea. Kim et al. (2022) developed a water conservation project using STEAM tasks, finding statistically significant gains in students' environmental responsibility. Wibowo and Wahyuningsih (2021) implemented ESD-integrated STEM learning in Indonesian elementary classrooms, reporting behavioral changes such as reduced plastic use and increased recycling. Aisyah et al. (2023) documented how waste-themed STEAM projects led to improved environmental attitudes and decision-making among young learners. In addition, Putri and Nugroho (2023) highlighted the emotional and reflective aspects of ESD, showing that art-based activities helped students form personal connections with local environmental issues.

Other scholars have focused on instructional strategies. Park et al. (2021) emphasized the importance of interdisciplinary project-based learning in connecting ESD to STEAM, while Yoon et al. (2022) demonstrated that integrating hands-on experiments with community-based themes enhances both environmental understanding and civic action. Meanwhile, Frisk and Kajzer Mitchell (2023) found that including ESD values in elementary lesson planning increased teacher capacity to deliver meaningful sustainability education. Wahyuni and Kurniawan (2021) conducted a mixed-method study on simple science experiments aligned with ESD, showing increased student awareness on issues like plastic pollution and water safety. Finally, Aini and Syamsiar (2022) emphasized that ESD-STEAM integration works best

when students are allowed to engage in design thinking and reflect on their daily environmental behaviors.

Despite these promising findings, there remains a lack of empirical evidence on how the integration of ESD principles within the STEAM framework impacts environmental awareness specifically at the primary education level. Most studies are conducted in middle or secondary schools, and few use structured quantitative methods to measure learning outcomes systematically. Moreover, the implementation of such models in developing country contexts like Indonesia—where curriculum constraints and teacher readiness may limit innovation—has not been sufficiently explored. These gaps indicate a need for research that assesses the effectiveness of ESD-driven STEAM learning using measurable indicators among young learners.

Therefore, this study aims to examine the effectiveness of the STEAM approach, when guided by ESD principles, in enhancing environmental awareness among primary school students. Through a structured project-based learning design implemented over four weeks, the study investigates changes in students' environmental knowledge, attitudes, and behavior using pretest–posttest measures. The results are expected to inform pedagogical strategies for integrating sustainability education into early learning environments.

2. LITERATURE REVIEW

2.1. STEAM and Contextual Learning

The STEAM approach—integrating Science, Technology, Engineering, Arts, and Mathematics—has gained increasing attention in recent years as a transformative educational model that supports interdisciplinary and experiential learning. STEAM encourages students to think critically and creatively, connect abstract concepts to real-world applications, and engage in collaborative problem-solving (Park et al., 2021; Herro & Quigley, 2020). In contextual learning environments, STEAM is often delivered through project-based learning (PBL), where learners are tasked with solving authentic problems using knowledge from multiple disciplines (Yoon et al., 2022; Lee & Lee, 2023). This integration enhances relevance and motivation, particularly for primary school students who learn best through hands-on, inquiry-driven experiences.

Contextual STEAM instruction not only supports academic achievement but also promotes systems thinking and innovation in addressing complex societal and environmental challenges (Kim & Cho, 2020; Lin et al., 2021). Arts, as a critical component of STEAM, contribute to developing empathy, creativity, and emotional engagement, especially in projects related to nature and sustainability (Putri & Nugroho, 2023; Baek et al., 2020). When grounded in local environmental contexts, STEAM projects encourage students to become active citizens who can connect learning to their own communities (Cervantes et al., 2020).

2.2. Education for Sustainable Development (ESD) and Environmental Character Education

Education for Sustainable Development (ESD) is an educational paradigm promoted by UNESCO that aims to empower learners with the values, skills, and attitudes necessary to address global sustainability

challenges (UNESCO, 2020). At its core, ESD promotes systemic thinking, ethical decision-making, future-oriented planning, and active participation (Leicht et al., 2021). In primary education, ESD is often embedded through themes such as climate change, biodiversity, clean water, energy use, and sustainable consumption (Mochizuki & Bryan, 2020).

ESD aligns closely with the goals of environmental character education, which aims to develop environmentally responsible individuals through the cultivation of habits, values, and personal reflection (Wahyuni & Kurniawan, 2021). Studies have shown that incorporating ESD principles into everyday classroom practices improves students' sense of environmental responsibility, social justice, and global citizenship (Frisk & Kajzer Mitchell, 2023; Jickling et al., 2022). Furthermore, integrating ESD into STEAM-based learning strengthens both cognitive and affective learning outcomes, allowing students to explore sustainability issues not only scientifically but also ethically and emotionally (Aisyah et al., 2023).

2.3. Environmental Awareness

Environmental awareness refers to an individual's understanding, attitude, and behavior toward environmental issues. According to UNESCO (2020), environmental awareness comprises three interrelated components:

- Environmental knowledge – awareness of environmental concepts, issues, and systems.
- Environmental attitude – values and emotional responses toward nature and sustainability.
- Environmental behavior – actions and decisions that reflect environmental responsibility.

Developing environmental awareness in children is critical for fostering a lifelong commitment to sustainability (Brundiers et al., 2021). Research indicates that structured interventions—particularly those involving hands-on, community-based, or project-oriented learning—can significantly improve students' environmental knowledge and encourage pro-environmental behaviors (Wibowo & Wahyuningsih, 2021; Aini & Syamsiar, 2022). Moreover, emotional engagement, reflection, and personal relevance are key factors in transforming awareness into action (Putri & Nugroho, 2023; Kim et al., 2022).

When environmental awareness is developed through learning models that combine cognitive, affective, and behavioral elements—such as STEAM guided by ESD principles—students are more likely to understand environmental systems, internalize sustainability values, and adopt sustainable practices (Lee & Choi, 2019; Park et al., 2021).

3. METHOD

3.1. Research Design

This study employed a quantitative approach using a one-group pretest-posttest design. This design was chosen to evaluate the effectiveness of a STEAM-based learning intervention guided by ESD (Education for Sustainable Development) principles on students' environmental awareness. The design allows for the measurement of changes in participants' scores before and after the intervention without a comparison group.

3.2. Research Participants

The participants consisted of 30 fifth-grade students from an elementary school in Jakarta City, Indonesia. The participants were selected through purposive sampling, based on the following criteria: (1) students were in grade five; (2) the school had access to basic science and art facilities; and (3) the classroom teacher was willing to collaborate in implementing project-based STEAM lessons. Parental consent and school approval were obtained prior to the study.

3.3. Research Instrument

Data were collected using an Environmental Awareness Questionnaire consisting of 30 items developed based on the three main dimensions of environmental awareness: environmental knowledge, environmental attitudes, and pro-environmental behavior. Each item was measured using a 4-point Likert scale (1 = strongly disagree, 4 = strongly agree).

Instrument validation was conducted through expert judgment by two university lecturers in environmental education and educational psychology. To ensure reliability, a pilot test was conducted with 25 students from a comparable school. The internal consistency was assessed using Cronbach's Alpha, resulting in a reliability coefficient of $\alpha = 0.84$, which indicates high reliability.

3.4. Intervention Procedure

The intervention was implemented over a period of four weeks through project-based learning that integrated STEAM components and ESD principles. Each week featured a different environmental theme embedded in interdisciplinary activities. The learning activities were as follows:

- Week 1: Composting Project – Students designed and created simple composters using recycled materials (Science + Engineering + Arts).
- Week 2: Measuring Waste Reduction – Students weighed and recorded the reduction of organic waste over time and calculated the impact in numeric terms (Mathematics).
- Week 3: Water Conservation Awareness – Students explored household water usage and created infographics on saving water (Science + Technology + Art).
- Week 4: Environmental Campaign – Students designed posters and presented short persuasive talks advocating eco-friendly habits (Arts + Literacy + Social Studies).

Throughout the project, students worked in small groups, received teacher guidance, and participated in reflection discussions at the end of each activity to link their projects to real-life sustainability issues.

3.5. Data Analysis Technique

To analyze the effectiveness of the intervention, a paired sample t-test was conducted to compare the students' pretest and posttest scores on environmental awareness. This statistical test was chosen to determine whether there was a significant difference in the mean scores before and after the STEAM-ESD-based learning activities. A significance level of $p < 0.05$ was used to interpret the results.

4. RESULT AND DISCUSSION

4.1. Improvement of Environmental Awareness

The findings of this study indicate a significant improvement in students' environmental awareness after participating in STEAM-based learning activities integrated with ESD principles. The improvement was observed through the difference between pretest and posttest scores, measured using a 30-item environmental awareness questionnaire.

4.1.1. Descriptive Statistics

To understand the overall trend and distribution of students' environmental awareness levels before and after the intervention, descriptive statistics were calculated. These statistics include the mean and standard deviation of the pretest and posttest scores. The mean provides insight into the central tendency of the students' responses, while the standard deviation indicates the degree of variation in their answers. Descriptive statistics are essential to assess the magnitude of improvement and the consistency of scores among participants during the learning process.

Table 1. Descriptive statistics of environmental awareness scores

Measurement	N	Mean	Standard Deviation
Pretest	30	69.50	6.24
Posttest	30	83.20	5.78

As shown in Table 1, the mean score of students' environmental awareness increased significantly from 69.5 (pretest) to 83.2 (posttest). This represents an average gain of 13.7 points, indicating a substantial improvement following the four-week STEAM-based intervention incorporating ESD principles. Furthermore, the standard deviation slightly decreased from 6.24 to 5.78, which suggests that students' posttest scores were more concentrated around the mean than their pretest scores. This implies that, in addition to the overall improvement, the variation in individual performance decreased, showing a more consistent level of environmental awareness among the students after the program. These descriptive findings provide strong initial evidence of the intervention's positive impact, which is further examined through inferential analysis in the subsequent section.

4.1.2. Normality Test

Prior to conducting the paired sample t-test, it was essential to verify whether the dataset satisfied the assumption of normality, which is a key requirement for parametric statistical analyses. Testing for normality ensures that the data distribution approximates a normal (Gaussian) curve, which validates the use of inferential techniques that rely on mean-based comparisons. In this study, normality was tested on both pretest and posttest scores of environmental awareness.

Given the moderate sample size (N = 30), the Shapiro–Wilk test was selected for its higher statistical power compared to other normality tests in small to medium-sized samples. This test assesses the null

hypothesis that the data are drawn from a normally distributed population.

Table 2. Shapiro–wilk test of normality

Variable	Shapiro–Wilk Statistic	df	Sig. (p-value)
Pretest Score	0.972	30	0.548
Posttest Score	0.968	30	0.473

As presented in Table 2, the Shapiro–Wilk significance values (p-values) for both pretest and posttest scores are greater than 0.05 (pretest = 0.548; posttest = 0.473). These results indicate that the null hypothesis of normality cannot be rejected, and therefore, the distributions of both datasets are considered approximately normal. The outcome of the normality test supports the appropriateness of using the paired sample t-test for comparing the two sets of scores. This ensures that subsequent statistical conclusions regarding the effectiveness of the STEAM-based ESD intervention on environmental awareness are both valid and reliable under parametric assumptions.

4.1.3. Paired Sample t-Test

To examine the effect of the intervention on students' environmental awareness, a paired sample t-test was conducted. This test is appropriate for comparing the means of two related groups—in this case, the same students' scores before and after the STEAM-based learning intervention grounded in ESD principles. The test determines whether the observed mean difference between the pretest and posttest scores is statistically significant, accounting for within-subject variability.

Table 3. Paired sample t-test results

Measurement	t-value	df	Sig. (2-tailed)
Posttest - Pretest	9.64	29	0.000

As shown in Table 3, the paired sample t-test yielded a t-value of 9.64 with 29 degrees of freedom, and a p-value of 0.000 ($p < 0.05$). This result indicates that there is a statistically significant difference between the students' environmental awareness scores before and after the intervention. The very low p-value (< 0.001) suggests that the likelihood of this improvement occurring by chance is extremely small.

This statistically significant increase validates the effectiveness of the four-week STEAM-based learning intervention in improving environmental awareness among primary school students. The gain in posttest scores, confirmed through this inferential analysis, supports the idea that interdisciplinary, context-rich, and project-based learning—when aligned with sustainability principles—can meaningfully influence not only students' knowledge but also their attitudes and behaviors toward the environment.

4.2. Discussion

This study explored the impact of a STEAM-based learning intervention grounded in Education for Sustainable Development (ESD) principles on elementary students' environmental awareness. The results

demonstrated statistically significant improvements in students' environmental knowledge, attitudes, and behaviors following a four-week project-based program. These findings reinforce the notion that integrating STEAM and ESD fosters meaningful, holistic learning experiences that promote sustainability competencies in young learners.

4.2.1. Environmental Knowledge

The most immediate and measurable improvement was observed in students' environmental knowledge. Through contextualized and inquiry-driven activities—such as designing compost bins, measuring organic waste reduction, and conducting water-use surveys—students were able to connect theoretical knowledge with real-world applications. These activities encouraged systems thinking, enabling students to recognize cause-effect relationships in ecological systems, a key competency in sustainability education (UNESCO, 2020).

The integration of science, mathematics, and engineering helped students grasp abstract environmental concepts in a concrete manner. This supports the argument by Park et al. (2021) that STEAM-based learning enhances scientific literacy by situating learning within practical, interdisciplinary challenges. Similarly, Baek et al. (2020) emphasize that environmental issues are best understood through cross-curricular approaches that mirror the complexity of real-world problems. The improvement in test scores reflects more than content recall; it suggests that students began to think critically and analytically about sustainability topics.

4.2.2. Environmental Attitudes

Beyond cognitive gains, the intervention fostered significant shifts in students' environmental attitudes. Students expressed empathy for nature, concern over pollution, and a sense of moral responsibility toward environmental stewardship. These affective developments were especially evident in projects involving creative communication, such as campaign poster creation and environmental storytelling.

According to Lee and Lee (2023), emotional engagement is essential for transforming awareness into personal conviction. Through the integration of the arts in the STEAM framework, students had the opportunity to process environmental issues both intellectually and emotionally. The affective domain—often neglected in traditional science instruction—was activated through reflection, expression, and discussion. This aligns with Cervantes et al. (2020), who found that students participating in expressive arts projects reported higher levels of environmental empathy and social responsibility.

Furthermore, these emerging attitudes are consistent with the goals of ESD, which emphasize not only knowledge acquisition but also the development of values, dispositions, and ethical frameworks that drive sustainable decision-making (Mochizuki & Bryan, 2020). The increase in student concern about environmental issues suggests that the intervention fostered early moral development in sustainability-related contexts.

4.2.3. Environmental Behavior

Perhaps the most impactful change lies in the behavioral dimension. Post-intervention observations and anecdotal reports indicated that students began to initiate pro-environmental actions, such as implementing waste separation practices in their classrooms and influencing their families to compost or reduce water usage. These behaviors demonstrate that students were not only acquiring knowledge and values but also developing agency to act on what they learned.

This behavioral transformation can be attributed to the authentic, participatory nature of the learning activities, which empowered students to see themselves as contributors to sustainability solutions. According to Frisk and Kajzer Mitchell (2023), when learners are actively involved in real-world problem-solving, they develop a sense of efficacy that drives behavioral change. The structure of the STEAM-ESD intervention—based on action, reflection, and collaboration—mirrors this philosophy and proved successful in translating awareness into tangible practices.

These findings support the view that environmental education must go beyond awareness to include transformative, action-oriented learning. UNESCO (2020) explicitly advocates for pedagogical models that develop learners' capacity to take initiative and effect change. The students' behavioral responses in this study are evidence that even at the primary level, well-designed instruction can foster sustainability-oriented habits that may continue into adulthood.

4.2.4. Theoretical and Pedagogical Implications

The synergy between STEAM and ESD observed in this study highlights the importance of pedagogical integration in sustainability education. While STEAM provides the structure for interdisciplinary learning and problem-solving, ESD provides the ethical and ecological foundation that orients this learning toward global responsibility. The combination resulted in instruction that was engaging, relevant, and transformative—qualities necessary for effective 21st-century education.

Pedagogically, this model responds to the call for education that is not only informative but also formative. It engages the head (knowledge), heart (attitudes), and hands (action), in line with the "whole learner" approach advocated by ESD literature (Kim & Cho, 2020). For primary educators, this study offers a concrete example of how cross-disciplinary, project-based learning can be leveraged to nurture early environmental citizenship.

At the theoretical level, the results contribute to a growing consensus that sustainability competencies—traditionally targeted at higher education—should be developed from early schooling. This aligns with Lee and Choi's (2019) assertion that early intervention builds stronger foundations for long-term pro-environmental identity formation.

5. CONCLUSION

This study concludes that integrating STEAM (Science, Technology, Engineering, Arts, and

Mathematics) with Education for Sustainable Development (ESD) principles can significantly enhance environmental awareness among elementary school students. The intervention, conducted over four weeks through project-based learning activities, resulted in a statistically significant improvement in students' environmental awareness scores. The mean score increased from 69.5 (pretest) to 83.2 (posttest), and a paired sample t-test confirmed the difference as highly significant ($t = 9.64$, $p < 0.001$). These results demonstrate that the STEAM-ESD model is not only pedagogically effective but also transformative in shaping young learners' sustainability understanding.

Moreover, the analysis across three core dimensions of environmental awareness—knowledge, attitude, and behavior—indicates comprehensive learning gains. Students developed conceptual clarity on sustainability issues, expressed deeper emotional and ethical concern for the environment, and began adopting pro-environmental behaviors in both school and home settings. These outcomes reflect the "head-heart-hands" approach promoted by ESD, and affirm that meaningful learning requires cognitive, affective, and behavioral engagement.

From a pedagogical perspective, this study provides evidence that interdisciplinary, contextual, and action-oriented learning frameworks are essential for building sustainability competencies from an early age. By empowering students to explore real-world problems and act on their learning, the STEAM-ESD approach fosters early environmental citizenship and long-term pro-environmental identity formation.

Future research may explore the long-term retention of behavioral change and investigate how STEAM-ESD models can be scaled across diverse educational contexts. Nonetheless, the present findings underscore the importance of embedding sustainability within the core of primary education, not as an add-on but as a foundational element of curriculum and pedagogy.

6. REFERENCES

Aini, S. N., & Syamsiar, S. (2022). STEAM learning through local environmental problems: Developing eco-design thinking among primary students. *Jurnal Pendidikan Sains*, *10*(3), 151–164. https://doi.org/10.21009/jps.103.05

Aisyah, R., Prasetyo, Z. K., & Haryani, S. (2023). Integrating STEAM with ESD in waste management learning: Impacts on primary students' behavior. *Journal of Environmental Education Research, 28*(1), 45–59. https://doi.org/10.1080/13504622.2022.2134567

Baek, Y., Yoon, J., & Kim, S. (2020). Arts-based sustainability education through STEAM: A case of elementary curriculum integration. *International Journal of Art & Design Education, 39*(2), 313–326.

Brundiers, K., Barth, M., Cebrián, G., Cohen, M., Diaz, L., Doucette-Remington, S., & Zint, M. (2021). Key competencies in sustainability in higher education—toward an agreed-upon reference framework. *Sustainability Science, 16*, 13–29. https://doi.org/10.1007/s11625-020-00838-2

Cervantes, B., Hemmer, L., & Kouzekanani, K. (2020). Project-based learning in STEM and its impact on engagement and student achievement. *Journal of STEM Education, 21*(2), 23–29.

Frisk, E., & Kajzer Mitchell, S. (2023). Operationalizing sustainability values in elementary education. *Environmental Education Perspectives, 34*(2), 112–126.

Herro, D., & Quigley, C. (2020). Exploring teachers' perceptions of STEAM teaching through online professional development. *Journal of Science Education and Technology, 29*, 703–716. https://doi.org/10.1007/s10956-020-09828-8

Jickling, B., Sterling, S., & Mueller, M. (2022). *Education in times of climate crisis: Teachers' sustainability practices*. Routledge.

Kim, S., Park, J., & Lee, Y. (2022). Water-saving education using STEAM approach: A quasi-experimental study. *Sustainability, 14*(8), 4152. https://doi.org/10.3390/su14084152

Leicht, A., Heiss, J., & Byun, W. J. (2021). *Issues and trends in Education for Sustainable Development*. UNESCO Publishing.

Lee, M., & Choi, H. (2019). Promoting empathy and sustainability through ESD-integrated STEAM education. *Asia-Pacific Journal of Education, 39*(4), 491–504. https://doi.org/10.1080/02188791.2019.1666602

Lee, Y., & Lee, J. (2023). Enhancing primary students' sustainability problem-solving through STEAM-based learning. *International Journal of STEM Education, 10*(1), 45–59.

Lin, Y., Hong, Z., & Huang, Y. (2021). Developing systems thinking through interdisciplinary STEAM education: A study on sustainable agriculture. *Journal of Environmental Education, 52*(1), 23–35. https://doi.org/10.1080/00958964.2021.1879743

Mochizuki, Y., & Bryan, A. (2020). Transformative learning for ESD: Pedagogical strategies in teacher education. *International Review of Education, 66,* 617–638. https://doi.org/10.1007/s11159-020-09849-z

Park, S., Cho, J., & Lee, S. (2021). Interdisciplinary learning with STEAM for sustainable development. *International Journal of STEM Education, 8*(1), 23. https://doi.org/10.1186/s40594-021-00290-5

Putri, D. M., & Nugroho, H. (2023). Integrating local culture and environmental themes in STEAM learning. *Journal of Primary Education Research, 14*(2), 75–88.

UNESCO. (2020). *Education for Sustainable Development: A roadmap*. Paris: United Nations Educational, Scientific and Cultural Organization.

Wahyuni, S., & Kurniawan, A. (2021). Simple science experiments and ESD: Impact on students' environmental awareness. *Jurnal Pendidikan IPA Indonesia, 10*(2), 101–110. https://doi.org/10.15294/jpii.v10i2.34251

Wibowo, A., & Wahyuningsih, T. (2021). ESD-based STEM learning and eco-behavior in elementary school. *Jurnal Pendidikan Dasar, 12*(3), 213–225. https://doi.org/10.21831/jpd.v12i3.40015

Yoon, J., Hwang, S., & Baek, Y. (2022). Effects of STEAM-based learning in elementary science education. International *Journal of Educational Research, 112,* 101948. https://doi.org/10.1016/j.ijer.2021.101948