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Enhancing Quality Education in Indonesia: A Literature Review of STEM-ESD Landscape Contributions

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ABSTRACT Integrating STEM-ESD enhances educational quality through interdisciplinary, hands-on learning experiences that foster deeper understanding and cultivate skills for real-world challenges. This paper presents a systematic review examining STEM-ESD implementation in Indonesia's educational context. Guided by four research questions, the study investigates the integration of STEM with ESD, its effectiveness, practical implementation approaches, and encountered constraints. Twenty-two articles published between 2018 and 2024 were analyzed from databases using a systematic review methodology, focusing on Scopus-indexed international journals accredited by SINTA. Articles were selected through keyword searches and screened for relevance based on specific criteria. The review involved data selection, adaptation of a coding instrument, identifying article patterns, and synthesizing findings. Results indicate that STEM-ESD is widely implemented in Indonesian education, significantly enhancing students' sustainability awareness and critical thinking skills. Effective approaches identified include project-based learning, the integration of STEM modules with Sustainable Development Goals (SDGs) principles, and inquiry-based teaching methods. Nonetheless, challenges remain, such as the predominance of scientific perspectives in ESD and the need for holistic approaches incorporating social sciences. This study contributes valuable insights into STEM-ESD integration within Indonesian education. It highlights the need for policy reforms emphasizing interdisciplinary approaches, enhanced teacher training, and a curriculum that comprehensively integrates STEM and sustainability concepts. Such reforms are essential to equipping educators to deliver effective learning experiences that prepare students for the complexities of sustainability challenges.

Keywords: STEM-ESD, Quality of education, Indonesia, Systematic literature review

1. INTRODUCTION

Education is a critical investment for sustainable development, promoting sustainable consumption, and empowering individuals for societal change (Abera, 2023). As Rickinson et al. (2009) noted, a life-course approach to education is vital for understanding environmental learning from early childhood to adulthood. Educational institutions, including early childhood centers, schools, and universities, are crucial in disseminating knowledge about sustainability and fostering environmental responsibility through community engagement (Chesterman, 2008; Pauw et al., 2015).

However, mainstream education often prioritizes economic growth and consumerism, contributing to sustainability challenges (Kioupi & Voulvoulis, 2019). Therefore, a shift toward Sustainable Development Education (ESD) is necessary. Building on over four decades of environmental education, ESD promotes an understanding of the interconnectedness of humans and the natural world, as emphasized in the Tbilisi Declaration (UNESCO/UNEP, 1977). The urgency of such education has increased, notably as young people advocate for sustainable solutions through movements like "Fridays for Future" (Marquardt, 2020; Kowasch et al., 2021).

Students face many complex global issues, such as climate change, microplastic pollution, and biodiversity

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loss, underscoring the importance of scientific literacy in navigating these challenges (von Braun, 2020; Ghosh et al., 2020). Despite barriers like urban migration and cultural diversity, schools must equip students with the knowledge and skills to understand and address these issues (O'Donnell, 2018; Modeme & Onwuegbuna, 2023).

Globalization emphasizes the need for education that fosters awareness and responsiveness to contemporary challenges (Sihombing et al., 2024; Khadri, 2022). A robust STEM education curriculum, aligned with the UN Sustainable Development Goals (SDGs), is essential to prepare students and communities to tackle societal issues (Davidi et al., 2021; Sihombing et al., 2024). Education is a specific SDG (Goal 4: Quality Education) and a fundamental driver of progress across all goals (Žalėnienė & Pereira, 2021; Shayan et al., 2022). Therefore, ensuring learners acquire the necessary competencies for sustainable development is a key focus of the SDGs.

STEM-ESD explicitly supports the achievement of the SDGs by equipping learners with interdisciplinary skills and knowledge needed to address global challenges (Olsson et al., 2022; AlAli et al., 2023). For example, it enhances educational quality (Goal 4) by integrating sustainability concepts into STEM subjects, fostering critical thinking. It also encourages project-based learning on local issues like clean water (Goal 6), promotes sustainable urban solutions (Goal 11), empowers climate action initiatives (Goal 13), and fosters partnerships for sustainable development (Goal 17). By bridging scientific understanding with social context, STEM-ESD prepares students to tackle complex, real-world problems while driving progress toward the SDGs.

The education required to advance the SDGs is still evolving. Effective SDG-focused education should motivate individuals to take meaningful action and address complex global challenges through sustained engagement (Gaill et al., 2022). STEM education must provide students with the skills to confront pressing global issues. Exposure to science, technology, engineering, mathematics, and social-emotional learning should be integral to education and accessible to all (Bybee, 2013; Shelley & Kiray, 2018).

Education for Sustainable Development advocates for shifts in knowledge, skills, values, and attitudes toward a more equitable society (Al-Jaber & Al-Ghamdi, 2020). It empowers current and future generations to meet their needs through a balanced approach to sustainable development. STEM education fosters scientific competence and encourages informed action in addressing societal challenges (Bascopé & Reiss, 2021; Campbell & Speldewinde, 2022). Proficiency in STEM disciplines enables students to understand global issues and contribute effectively to initiatives based on sound knowledge (Pahnke et al., 2019; Lundell et al., 2023). Ensuring the sustainability of STEM education is critical for future generations. Pahnke et al. (2019) emphasized the link between STEM and sustainability, stating that STEM fields are essential for exploring, understanding, and creating solutions to global sustainability challenges. Similarly, Dotson et al. (2020) suggested that access to quality STEM education is associated with reduced poverty, increased economic growth, and more robust democracies. STEM is vital in achieving various Sustainable Development Goals (SDGs). This combination of STEM and Education for Sustainable Development is known as STEM-ESD learning. STEM education emphasizes an integrated approach combining science, technology, engineering, and mathematics (Bybee, 2013; Shelley & Kiray, 2018). By incorporating Education for Sustainable Development (ESD), students develop critical thinking skills to solve real-world challenges and foster sustainability (Fathurohman et al., 2023; Habibaturrohmah et al., 2023). Quality education is vital for equipping students with the skills to succeed in a globalized world (Nopas & Kerdsomboon, 2024). STEM-ESD improves education by providing interdisciplinary, practical, and genuine learning experiences (Margot & Kettler, 2019; Gamage et al., 2022; Fathurohman et al., 2023; Abdurrahman et al., 2023).

Implementing STEM Education for Sustainable Development (STEM-ESD) in Indonesian schools faces several practical challenges. A significant issue is the need for more resources for teachers to effectively implement inquiry-based learning and hands-on activities (Kurniawan et al., 2024; Sihombing et al., 2024). Many schools, particularly rural ones, often need adequate access to essential technology, materials, and training to provide a robust STEM-ESD curriculum (Firda et al., 2021; Khoiri et al., 2023). Additionally, continuous professional development is vital for teachers to meet the interdisciplinary requirements of STEM-ESD; however, such training is frequently unavailable. Another obstacle is that the traditional education system prioritizes rote learning over critical thinking and problem-solving skills (Habibaturrohmah et al., 2023; Maspul, 2024). This conventional approach can impede the active participation and engagement that STEM-ESD aims to foster (Fathurohman et al., 2023; Solihah et al., 2024a; Annisa et al., 2024). Moreover, the lack of STEM-ESD teaching materials further exacerbates the challenge, as many schools struggle to obtain relevant and context-specific instructional content to implement the curriculum effectively (Ekamilasari et al., 2021; Aswirna et al., 2022a; Solihah et al., 2024b). Furthermore, addressing local sustainability challenges often requires collaboration with communities, yet many schools need more frameworks and partnerships to effectively support such engagement.

Based on the challenges, the primary issues in Indonesian education are students' lack of awareness regarding the learning process, insufficient motivation to develop their abilities, and limited understanding of effective learning strategies. Addressing these issues

necessitates effective organization of the learning process, which can be achieved by integrating STEM-ESD into every educational endeavor. Therefore, the following research questions will guide our inquiries.

- Has STEM-ESD been implemented in Indonesian learning?
- How is STEM integrated with ESD, and can it be applied to learning in Indonesia?
- How can it be effectively implemented? What frameworks and practical approaches can be employed?
- What are the constraints of using STEM Education for Sustainable Development?

2. METHOD

2.1 Research Design

A systematic literature review represents a thorough and meticulous evaluation of a subject matter undertaken by scholars within a specific field. According to Xiao and Watson (2019), a Systematic Literature Review (SLR) is a method of reviewing literature that adheres to specific guidelines for selecting and synthesizing relevant research articles and evaluating the existing knowledge on a particular topic. These researchers utilized methodologies commonly employed in this type of research, aiming to give readers a comprehensive understanding of the existing knowledge on a particular topic while proposing potential avenues for future research. Additionally, the researchers endeavored to critically scrutinize deficiencies in current theories, methodologies, and conceptual or empirical findings within the subject area. This methodical evaluation involves scrutinizing the subject's components, strengths, and weaknesses to provide an insightful and nuanced interpretation. The researchers aim to contribute to the existing body of knowledge by offering a comprehensive and well-founded perspective on the subject (Wallace & Wray, 2016; Cottrell, 2017). The choice of this method is justified as it allows for a thorough exploration of STEM-ESD, ensuring a meticulous examination of their impact on science learning.

The researchers conducted their investigation through a systematic literature review, employing methods typically associated with this research. The main objective was to provide readers with an understanding of the existing knowledge on a particular topic and suggest potential future research directions. As a result, the study did not aim to conduct an exhaustive search, offer a retrospective analysis of past research, or establish a definitive set of best practices within the field. Rather, the emphasis was on critically assessing deficiencies in current theoretical frameworks, research methodologies, and conceptual or empirical findings. The study examined scientific articles related to STEM education, ESD, STEM-ESD, and the contribution in science subjects from 2018 to 2024 by employing a systematic review with a content analysis approach focused on overseas contexts.

2.2 Population and Sampling

The research sample comprises 22 articles sourced from 2018 to 2024, extracted from Google Scholar, Garuda, and SCOPUS databases, on STEM, ESD, and STEM-ESD. These articles were identified using specific keywords such as "STEM," "ESD," and "STEM-ESD."

2.3 Data Collections Process

The review process involved several key stages.

Data Selection

This step included formulating research questions and identifying articles relevant to the study. Criteria for inclusion were established, as outlined in Table 1. Articles were screened across multiple databases (e.g., Google

Table 1 Inclusion and exclusion criteria

No.	Category	Inclusion Criteria	Exclusion Criteria
1.	Type of Publication	Articles published in journals	Articles published in conference proceedings, books, websites, blogs, and other similar sources
2.	Journal Specifications	International journal minimum indexed Scopus and accredited by SINTA	National journal not accredited
3.	Country	Indonesia	Not in Indonesia
4.	Publication Year	2018 - 2024	Less than 2018
5.	Research Setting	Qualitative (Descriptive), Quantitative (Experimental), Mixed Method, Research and Development	Systematic Literature, Literature Review, Comparative Study, Phenomenology
6.	Independent Variable	STEM, ESD, and STEM-ESD	Not STEM, ESD or STEM-ESD
7.	Field	Science (i.e., Chemistry, Physics, and Biology)	Outside of science
8.	Research Subject	Students' formal education includes childhood, elementary, secondary, senior high, and universit y.	The study involved students and Teachers in nontraditional educational settings, such as special needs schools or nonformal schools.

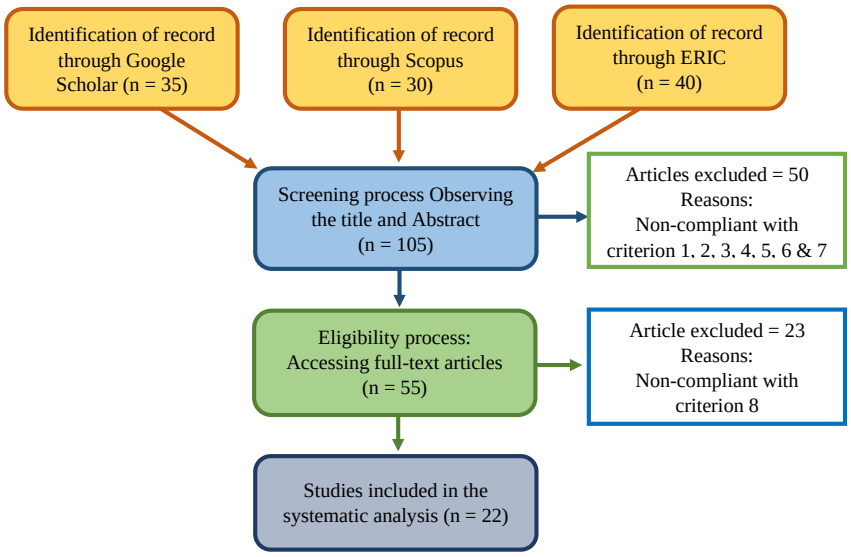

Figure 1 Flowchart of the article selection procedure (Giovannoli et al., 2020)

Scholar, Garuda, and SCOPUS) using Publish or Perish software. Researchers narrowed down the selection based on the predetermined criteria, resulting in the examination and analysis of 22 manuscripts. The review process involved assessing abstracts initially and then comprehensively reading the entire content of the selected articles.

Coding Instrument Adaptation

The researchers utilized a Paper Classification Form (PCF) developed by Kizilaslan et al. (2012) as the basis for their coding instrument. The PCF, known for its validity and reliability, encompassed various indicators such as title, author details, journal information, publication year, journal type, language, indexing, primary discipline, research methodologies, data collection methods, sample details, and data analysis techniques. Additionally, researchers created a data matrix containing information on research purposes, integrated learning models, thematic elements, and key findings. The collected data underwent analysis using percentage calculations.

Identifying Article Patterns

The researchers aimed to identify patterns within the selected articles, particularly focusing on findings, STEM, ESD, integration of STEM-ESD, and learning. These patterns were synthesized to address the research questions posed in the study.

Synthesizing Patterns to Address Research Questions

Figure 1 illustrates the process of synthesizing identified patterns to effectively address the research questions established in the study. This step involved integrating and analyzing the patterns identified across the selected articles to provide comprehensive answers to the research inquiries.

3. RESULT AND DISCUSSION

This systematic literature review examines articles published between 2018 and 2024, focusing on Indonesian studies. Table 2 presents the analysis results for 22 articles.

Table 2 Conducted articles data

Writer's Name	Year	Educational Levels	City	Findings	Effect Size
Ekamilasari et al.	2021	Junior High School	Bogor	The results showed that students had moderate sustainability awareness, with 37.95% in sustainable practices, 70.63% in behavior and attitude, and 86.92% in emotional awareness. However, their critical thinking skills were weak, with an average score of 28.68%.	-
Widarti & Roshayanti	2021	Senior High School	Demak	The study showed that most teachers are familiar with STEAM, with 52% applying it in fluid lessons and 86% linking it to environmental issues. Using project-based learning, STEAM-ESD helps overcome student learning difficulties through experiments with recycled materials.	-
Firda et al.	2021	Junior High School	Surabaya	The data analysis indicated that integrating sustainability issues into STEM learning improved junior high school students' sustainability consciousness, with an average N-gain of 0.18, reflecting a low category. (*to be continued*)	0.37

Table 2 Conducted articles data (*Continued*)

Writer's Name	Year	Educational Levels	City	Findings	Effect Size
Firda et al.	2021	Junior High School	Surabaya	This highlights the necessity for learning strategies that better promote engagement with sustainability topics and foster pro-sustainability attitudes and behaviors.	0.37
Davidi et al.	2021	Elementary School	Wae Ri'i	Thus, utilizing a STEM approach has been demonstrated to effectively enhance the critical thinking skills of elementary school students in the Wae Ri'i subdistrict.	2.15
Aswirna et al.	2022 (a)	Junior High School	Padang	The STEM-based e-book with gender-based sustainable development principles received validity, practicality, and effectiveness scores of 85.85%, 87.16%, and 83.5% for female students and 80% for male students, indicating it is highly valid, practical, and effective for classroom learning.	-
Zidny & Eilks	2022	University	Banten	Students gained insights into how this integration benefits modern science and sustainability goals, while hands-on activities enriched their learning experience by allowing them to compare conventional methods with alternatives.	-
Aswirna et al.	2022 (b)	Senior High School	Padang	The data analysis reveals that the STEM e-module based on SDG principles enhances students' scientific literacy and promotes environmentally friendly attitudes.	-
Setyowati et al.	2022	Junior High School	Bandung	The validation results showed that the critical thinking skills assessment received 85% (feasible), while the sustainability consciousness assessment received 97% (very feasible). These findings indicate that the developed teaching material is valid and suitable.	-
Wahono et al.	2023	University	Jember	The research revealed a validation score of 95.3% for STEM-based learning units, indicating their validity. A significant difference was found between the pretest and post-test results ($p < 0.001$), with an effectiveness score of 0.73, classified as high. Additionally, practicality tests averaged 89% and were categorized as high, highlighting the importance of system thinking skills in integrated STEM education.	4.67
Abdurrahman et al.	2023	Senior High School	Lampung	This study assesses the effectiveness of STEM in renewable energy education for high school students. Results show that the STEM approach enhances student performance and engagement in both cognitive and hands-on activities using simple and accessible resources.	1.08
Fitrianti et al.	2023	Senior High School	Karawang	The study concludes that the STEM-based physics module on alternative energy is feasible, achieving valid criteria across all validation categories, including material suitability (0.8) and readability (86.43%). These findings support the module's effective application in enhancing students' critical thinking and problem-solving skills.	-
Khoiri et al.	2023	Junior High School	Semarang	The study found that STEAM-based physics learning tools improved student creativity and learning outcomes. Creativity scores averaged 86.12%, categorized as very good. These tools, including STEAM and ESD-based worksheets, effectively enhance student performance and can be used to improve physics education.	-0.08
Nazhifah et al.	2023	Senior High School	Palembang	The study found that the STEM-based renewable energy e-learning product was 100% suitable in the alpha test and accepted by all students in the beta test. It concludes that the product is feasible for improving high school students' creative thinking skills and is ready for the effectiveness test stage.	-

Table 2 Conducted articles data (*Continued*)

Writer's Name	Year	Educational Levels	City	Findings	Effect Size
Firda et al.	2021	Junior High School	Surabaya	This highlights the necessity for learning strategies that better promote engagement with sustainability topics and foster pro-sustainability attitudes and behaviors.	0.37
Solihah et al.	2023	Junior High School	Majalengka	The study found that project-based learning significantly improved students' understanding of the greenhouse effect and problem-solving skills. Post-test scores increased, with high gains in areas like explaining the greenhouse effect and proposing solutions to global warming. This approach also enhanced student engagement and enthusiasm for learning.	-
Kurniawan et al.	2024	Senior High School	Lampung	This study shows that the STEM approach based on Education for Sustainable Development (ESD) is more effective than conventional learning in enhancing students' systems thinking skills, particularly on renewable energy topics.	-
Annisa et al.	2024	Junior High School	Subang	The study found that STEM ESD-based learning with the "Arduino UNO-Based Trash Can" slightly improved critical thinking skills but had minimal impact on sustainable awareness. These results can guide future research on integrating STEM and ESD.	0.47
Faizah et al.	2024	Junior High School	Bandung	The results suggest that creating an air quality monitor did not significantly improve sustainability understanding, possibly due to factors limiting the effectiveness of ESD-based STEM learning.	0.28
Solihah et al.	2024 (a)	Junior High School	Majalengka	The study found that existing teaching materials are inadequate, with 73% of students struggling and 81% dissatisfied. STEM-ESD-based materials are needed to improve critical thinking and problem-solving skills.	-
Muliakoswara et al.	2024	Senior High School	Bandung	The application of STEM-ESD learning improved all indicators of critical thinking skills, with an overall increase of 0.45 in the moderate category.	-
Rahman et al.	2024	Teacher in Junior High School	Sukabumi	The school's efficient energy system project engaged students and teachers in STEM, fostering innovative water reduction methods. Students who reduced energy consumption showed the highest awareness of the Sustainable Development Goals (SDGs), emphasizing the value of contextual practice in STEM for Sustainable Development.	-
Sholihah et al.	2024 (b)	Junior High School	Majalengka	Developing STEM-ESD textbooks using the Design-Based Research (DBR) model has proven feasible for science learning at the junior high school level. These textbooks emphasize project-based learning and 21st-century skills.	-

Findings from the analysis revealed the diverse utilization of research methods in STEM-ESD. Table 3 shows the trend of research using research methods.

Diverse learning strategies can integrate STEM and ESD into learning processes. Furthermore, STEM-ESD commonly correlates with specific thematic approaches in research, as indicated by the distribution of findings. Figure 2 below shows the number of articles published on integrating STEM-ESD in education from 2021 to 2024.

In recent years, an increasing focus has been on integrating STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD). Data shows that the number of articles discussing this theme has experienced significant growth year by year. In 2021, 4 articles were published, which increased to 4 more in 2022. The year 2023 recorded

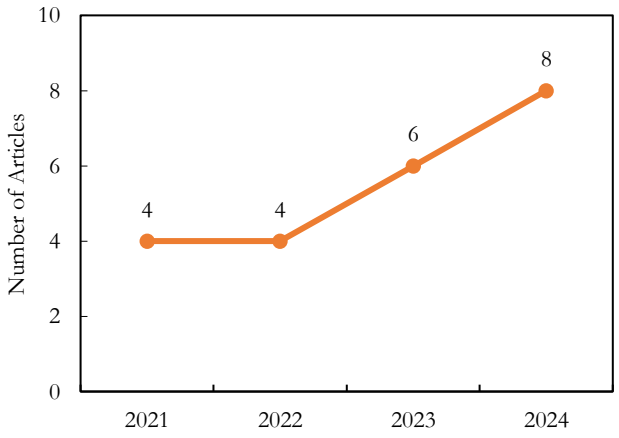

Figure 2 Distribution of article by year published

Table 3 The Trend of STEM education, ESD, STEM-ESD from research methods

Approach	Research Methods	Frequency	Percentage (%)
Quantitative	Survey	Zidny & Eilks, 2022;	4.54
	Quasi	Davidi et al. 2021; Firda et al. 2021; Abdurrahman et al. 2023; Faizah et al. 2024	18.1
	Descriptive	Ekamilasari et al. 2021; Rahman et al. 2023; Kurniawan et al. 2024;	13.6
	Pre-Experimental	Annisa et al. 2024; Muliakoswara et al. 2024	9.09
Qualitative	Interview and Observation	Widarti & Roshayanti, 2021;	4.54
Other	Research and Development	Aswirna et al. 2022 (a); Setyowati et al. 2022; Nazhifah et al. 2023; Aswirna et al. 2022 (b); Wahono et al. 2023; Khoiri et al. 2023; Fitrianti et al. 2023; Rahman et al. 2024; Solihah et al., 2024(b)	36.3
	Mixed method	Solihah et al. 2023; Solihah et al., 2024(a)	9.09
Total			100

a jump to 6 articles; in 2024, the number is predicted to reach 8.

This growth reflects the increasing importance of developing STEM-ESD-based curricula in education. It indicates that researchers and educators are becoming more aware of the need for a multidisciplinary approach to learning to enhance students' critical thinking and problem-solving skills while supporting sustainability.

3.1 STEM-ESD Implementation in Learning in Indonesia

Integrating STEM (Science, Technology, Engineering, and Mathematics) with Education for Sustainable Development (ESD) in Indonesian education reveals significant benefits and improvement areas. Studies indicate promising advancements in STEM-ESD integration while underscoring the need for further empirical research to quantify educational outcomes effectively. For instance, Ekamilasari et al. (2021) found that junior high school students in Bogor exhibited moderate sustainability awareness, with 37.95% engaged in sustainable practices; however, their critical thinking skills were notably weak, averaging only 28.68%. This highlights a gap in critical skills, with no effect size provided, leaving the impact quantification to be clarified. In a positive shift, Widarti and Roshayanti (2021) reported that 52% of senior high school teachers in Demak were familiar with STEAM and integrated it into their lessons, reflecting an encouraging trend in STEM adoption, although empirical data on effectiveness was lacking. Firda et al. (2021) indicated that while the integration of sustainability issues into STEM learning slightly improved junior high students' sustainability consciousness (N-gain of 0.18), the effect size of 0.37 suggests a small yet meaningful impact, emphasizing the need for enhanced engagement strategies.

In contrast, Davidi et al. (2021) demonstrated significant improvements in critical thinking skills among elementary students using a STEM approach, evidenced by a substantial effect size of 2.15, showcasing a strong positive influence of STEM integration. Aswirna et al. (2022a) assessed a STEM-based e-book for junior high students, yielding positive results; however, the absence of effect size data limited the evaluation of its educational impact. Zidny and Eilks (2022) noted that students gained valuable insights into modern science through integrated activities, but again, the need for quantifiable benefits made it challenging to assess the full impact. Similarly, Aswirna et al. (2022b) found that STEM e-modules grounded in Sustainable Development Goals (SDGs) enhanced scientific literacy and promoted environmentally friendly attitudes among senior high school students, though the absence of effect size data obscured the extent of these benefits. Setyowati et al. (2022) reported high validation scores for critical thinking and sustainability assessments in junior high school materials, suggesting their appropriateness for use; yet, without effect size data, the actual impact on learning outcomes remained uncertain.

Further studies illustrate both the potential benefits and the challenges of implementation. Fitrianti et al. (2023) evaluated a STEM-based physics module that met high validation standards, showing promise in enhancing critical thinking and problem-solving skills; however, the lack of specific effect size data made it difficult to quantify these improvements. Similarly, Khoiri et al. (2023) found that STEAM-based physics learning tools improved creativity and learning outcomes, but the reported effect size of -0.08 raised concerns about their effectiveness. In contrast, Nazhifah et al. (2023) evaluated a STEM-based renewable energy e-learning product deemed 100% suitable. However, without an effect size, the impact on students' creative thinking skills remains unclear.

Furthermore, Rahman et al. (2023) identified a significant gap in junior high school teachers' knowledge of Education for Sustainable Development (ESD), underscoring enhanced training, although no effect size was provided. Solihah et al. (2024c) demonstrated that project-based learning significantly improved students' understanding of the greenhouse effect, indicating its effectiveness despite the absence of effect size data. Kurniawan et al. (2024) reported that a STEM approach based on ESD enhanced systems thinking skills compared to conventional methods, but the lack of quantifiable effect

size limited the assessment of this improvement. Annisa et al. (2024) noted a slight improvement in critical thinking skills with an effect size of 0.47, suggesting a small positive influence yet minimal impact on sustainability awareness. Faizah et al. (2024) found that creating an air quality monitor did not significantly enhance sustainability understanding, with an effect size of 0.28 indicating modest effectiveness. Solihah et al. (2024a) highlighted the inadequacy of existing teaching materials, stressing the need for further development of STEM-ESD resources. Muliakoswara et al. (2024) reported moderate improvements in critical thinking skills, with an effect size of 0.45 indicating meaningful enhancement due to STEM-ESD learning. Rahman et al. (2024) emphasized the role of contextual practice in promoting student engagement and awareness of SDGs, though they did not provide effect size data. Lastly, Sholihah et al. (2024b) discussed the feasibility of developing STEM-ESD textbooks through the Design-Based Research model for junior high school science learning. However, with effect size data, evaluating the impact of these textbooks on learning outcomes is easier. Collectively, these findings underscore the importance of rigorous evaluation and development in the integration of STEM-ESD to enhance educational outcomes in Indonesia.

The incorporation of STEM and ESD components in Indonesia's educational system is closely aligned with the country's Kurikulum Merdeka initiative. This curriculum emphasizes flexible and student-centered learning that aims to cultivate critical thinking and problem-solving skills necessary for sustainable development (Kemendikbud, 2016; Sihombing et al., 2024). As Zuhaida and Widodo (2023) highlighted, the dominance of science over other STEM components in textbooks signals a need to balance the integration of engineering and technology, which aligns with the goals of Kurikulum Merdeka.

Further supporting this approach, Indonesia's Peraturan Menteri Pendidikan dan Kebudayaan (Permendikbud) No. 22 of 2016 underscores the importance of developing students' competencies in both technical and non-technical aspects. The focus on preparing students to become adaptive, innovative, and able to engage in sustainable practices resonates with the broader goals of the national education policy (Kemendikbud, 2016).

Moreover, according to Purwianingsih et al. (2022) and Sihombing et al. (2024), integrating ESD into the national curriculum has been a priority for Indonesia, particularly as the government seeks to align education with the Sustainable Development Goals (SDGs). The synergy between STEM education and ESD provides a platform for fostering sustainability through interdisciplinary learning, which is essential for addressing Indonesia's environmental, economic, and social challenges (Adiatma, 2017).

The studies reviewed highlight several key findings regarding implementing STEM-ESD in Indonesian education. A recurring pattern is the widespread adoption of STEM-ESD approaches, with many educators and institutions incorporating project-based learning, STEAM, and interdisciplinary methods to promote sustainability. These efforts often focus on enhancing students' critical thinking, problem-solving, and scientific literacy and fostering environmentally friendly attitudes. Challenges that emerged include an uneven emphasis on the engineering component of STEM and the need for more contextualized and culturally relevant teaching materials. Despite these challenges, successes have been reported in raising students' awareness of sustainability issues, particularly through innovative teaching methods such as using e-modules and integrating indigenous knowledge into chemistry lessons. Moreover, research consistently highlights the importance of teacher training and curriculum alignment to ensure effective and sustained implementation of STEM-ESD.

3.2 STEM-ESD and Its Application in Learning in Indonesia

STEM Education for Sustainable Development (STEM-ESD) aims to cultivate reflective change agents who can positively impact their communities and society. This approach emphasizes a knowledge-based, action-oriented, participatory, and integrative approach. To effectively implement STEM-ESD, it is essential to integrate STEM fields of knowledge and experience with social and emotional learning and civic engagement. Children should be viewed as active participants in inquiry and sustainability issues, encouraged to seek out and solve problems in their local communities" (Abdurrahman et al., 2023; Bascopé & Reiss, 2021; Campbell et al., 2022; Campbell & Speldewinde, 2022).

This underscores the importance of nurturing scientific literacy among young learners, who must engage in practical science activities to develop scientific competencies. This involves integrating various fields of knowledge, such as interdisciplinary approaches, to address real-world issues like climate change within science education (Sass et al., 2021; Zowada et al., 2021). Additionally, STEM-ESD emphasizes the active involvement of local communities. This entails integrating scientific knowledge with other forms of local knowledge, spanning technology, engineering, mathematics, history, art, and culture, to tackle common challenges in a transdisciplinary manner collaboratively" (Sass et al., 2021; Trott & Weinberg, 2020; Kucuk et al., 2018).

Moreover, STEM-ESD advocates not only for workforce development but also for cultivating critical thinking skills and sustainability mindsets among students. It encourages the habit of using scientific evidence to support sustainable practices and underscores the broader societal value of STEM Education. STEM-SD Education

initiatives align with the sustainable development goals of the global community, indicating that a sustainability perspective extends beyond merely incorporating thematic content into STEM education programs (Vallera & Bodzin, 2020; Solihah et al., 2024b; Abdurrahman et al., 2023). Instead, it entails integrating sustainability goals and values into the discourse of inquiry-based learning within STEM Education, encouraging informed and responsible action for the common good. This approach is grounded in insights derived from STEM research and societal needs.

For instance, Olsson et al. (2022) found that education for sustainable development effectively enhances students' action competence for sustainability. Additionally, Aswirna et al. (2022b) implemented STEM e-modules with SDG principles, improving science literacy and environment-friendly attitudes among students.

The importance of addressing gender disparities in STEM education to achieve SDG 4 is highlighted by Campbell and Speldewinde (2022). This integrated approach to STEM and sustainability education is grounded in insights from STEM research and societal needs. By integrating sustainability goals and values into the discourse of inquiry-based learning within STEM Education, informed and responsible action for the common good can be encouraged (AlAli et al., 2023). With support from the research community and educational institutions, STEM-ESD can effectively prepare students to address complex sustainability challenges and actively contribute to sustainable development efforts. Consequently, STEM Education for Sustainable Development (STEM-ESD) should adhere to several guiding principles. First, it should encourage inquiry-based learning and applying scientific thinking and practices within educational settings (Sass et al., 2021; Firda et al., 2021). Additionally, it must foster interactive, learner-centered teaching methods that facilitate exploratory, action-oriented, reflective, and transformative learning experiences (Campbell & Speldewinde, 2022; Aswirna et al., 2022a). A comprehensive institutional approach is also essential, emphasizing the systemic development of educational institutions to promote quality education and sustainability, with consideration given to management at various levels (Campbell et al., 2022; Widarti & Roshayanti, 2021). Moreover, STEM-ESD should cultivate independent thinking and responsible action within the learner's context, engaging with both social and natural environments to implement tangible changes within their community, thereby enhancing their sense of agency (Oinonen & Paloniemi, 2023; Bosevska & Kriewaldt, 2020). Alignment with sustainable development objectives is crucial to ensure compatibility with broader societal goals (AlAli et al., 2023; Repanovici et al., 2021). Furthermore, STEM-ESD should strengthen learners' ability to construct evidence-based arguments, appreciate complexity, embrace diverse perspectives, and encourage critical reflection on values (Shephard et al., 2021; Qureshi, 2020). Finally, it must empower current and future generations to utilize STEM skills and reflective reasoning to address complex sustainability challenges (Torsdottir et al., 2024; Vallera & Bodzin, 2020).

The integration of STEM and Education for Sustainable Development (ESD) in Indonesia is vital for improving the educational landscape (AlAli et al., 2023; Aswirna et al., 2022b). However, several practical challenges are associated with implementing STEM Education for Sustainable Development (STEM-ESD) in Indonesian schools. A significant obstacle is the need for more resources to effectively carry out inquiry-based learning and hands-on activities (Kurniawan et al., 2024; Sihombing et al., 2024). Many schools, especially in rural regions, often need more access to the necessary technology, materials, and training to deliver an effective STEM-ESD curriculum. Furthermore, ongoing professional development is crucial for teachers to adapt to the interdisciplinary demands of STEM-ESD, but such training is only sometimes reliably available.

Another challenge is the traditional education system, which often emphasizes rote memorization over critical thinking and problem-solving. This pedagogical approach can hinder the active engagement and participatory learning that STEM-ESD promotes (Fathurohman et al., 2023; Annisa et al., 2024). Moreover, addressing local sustainability issues may necessitate collaboration with communities, but many schools need more frameworks and partnerships to facilitate such involvement effectively.

Teachers are responsible for designing comprehensive and challenging learning experiences for students through thematic approaches, collaborative projects, and problem-based learning (Bascopé & Reiss, 2021; Trott & Weinberg, 2020). Through this integration, students acquire STEM skills and develop a deep understanding of the importance of sustainable development (Firda et al., 2021; Widarti & Roshayanti, 2021). STEM e-learning modules developed based on the principles of SDGs have been proven effective in enhancing scientific literacy and environmental-friendly attitudes among students in Indonesia, offering significant potential in cultivating a generation skilled in STEM and committed to sustainable development (Aswirna et al., 2022b; Zidny & Eilks, 2022).

Additionally, encouraging inquiry-based learning and applying scientific thinking and practices within educational settings are fundamental aspects of this integration (Sass et al., 2021). Advocating for a comprehensive institutional approach that emphasizes the systemic development of educational institutions to promote quality education and sustainability is also vital (Campbell et al., 2022).

On the other hand, implementing ESD-oriented STEM approaches in various secondary schools in Indonesia has shown improvements in student engagement, creativity,

and awareness of sustainable development (Aswirna et al., 2022a). However, support and training for teachers are necessary to effectively implement these concepts (Agirreazkuenaga & Martinez, 2021). STEM-based learning on sustainability issues in Indonesia has highlighted the need for more effective teaching strategies to increase student awareness (Firda et al., 2021). With full support from the government, educational institutions, and society, the integration of STEM and ESD can be successfully applied at all levels of education (AlAli et al., 2023). Teachers can implement STEM-ESD contextually by designing learning activities relevant to students' local environment and everyday experiences. This approach uses real-world problems that students can relate to, such as local environmental issues, energy conservation, or community-based projects, to make the learning process more meaningful (Habibaturrohmah et al., 2023; Maspul, 2024). For example, teachers can guide students in a science lesson to investigate water pollution in nearby rivers, linking scientific inquiry with technology and engineering solutions. By incorporating local social and economic factors, teachers can also emphasize the importance of sustainability, encouraging students to develop projects that propose solutions for long-term environmental and societal well-being (Abo-Khalil, 2024).

Additionally, teachers can use project-based learning, where students are tasked with designing and developing technological innovations that address environmental challenges in their communities (Martín-Sánchez et al., 2022). This integrates STEM disciplines and promotes critical thinking, problem-solving, and collaboration—all key components of ESD. Through reflective discussions, students can further analyze the societal impact of their projects, fostering a deeper understanding of sustainability.

Developing an ESD-based science learning model is also a crucial step in introducing sustainability issues to students in Indonesia (Ekamilasari et al., 2021). Students can better understand the importance of sustainable development by developing learning models, learning media, and supporting learning tools. Additionally, implementing STEM in education in Indonesia has significantly enhanced students' critical thinking skills (Davidi et al., 2021). Teacher training and developing ESD-based lesson plans have also helped instill pro-environmental attitudes among students (Firda et al., 2021). Despite numerous challenges, the integration of STEM with ESD in Indonesia promises significant progress in preparing the younger generation to face global challenges and actively participate in sustainable development.

3.3 Effective Implementation of STEM-ESD through Various Frameworks and Practical Approaches

STEM-ESD underscores the significance of enhancing students' abilities to establish links between global and local contexts (Torsdottir et al., 2024; Zowada et al., 2020). A systems-oriented approach aids youth in comprehending both the vertical integration (global-local) and horizontal integration (inter-dimensional) of issues and solutions. It also equips them with the skills to recognize cause-and-effect relationships. Furthermore, as students develop their capacity to perceive connections, they can also discern correlations between various goals and actions, recognizing that several SDGs mutually reinforce each other (Al-Jaber & Al-Ghamdi, 2020; Xing & Ironsi, 2024).

Presently, substantial investments are being directed towards STEM as a primary avenue for generating ideas and opportunities to mitigate the adverse consequences of our unsustainable lifestyles. Examples include the development of low-emission vehicles, more efficient mass transit systems, investments in renewable energy, and water-saving technologies. However, this paper argues that STEM-based approaches to sustainable development have limitations in addressing the urgency and magnitude of our current challenges (Zowada et al., 2020; Abdurrahman et al., 2023). While valuable, these approaches are predominantly geared towards problem-solving, focusing on minimizing negative impacts rather than envisioning and creating fundamentally new approaches to sustainability. For over three decades, it has been understood that achieving sustainability requires the integration of economic, social, and environmental dimensions, which goes beyond mere scientific and technological solutions. Given that the essence of sustainability lies in the interconnectedness of social and ecological systems, the involvement of social scientists is imperative in sustainable development discussions. They should be engaged from the outset, formulating research questions rather than being added to the process as an afterthought (Zelenika et al., 2018; Schröder et al., 2023).

STEM can catalyze transformative innovation by enhancing students' ability to connect global and local contexts through Education for Sustainable Development (STEM-ESD). A systems-oriented approach helps students understand the vertical (global-local) and horizontal (inter-dimensional) integrations of issues, allowing them to recognize complex cause-and-effect relationships and the interrelations among Sustainable Development Goals (SDGs) (Pahnke et al., 2019). Despite significant investments in STEM initiatives yielding advancements like low-emission vehicles and renewable energy, these approaches often focus on damage mitigation rather than creating innovative sustainability solutions. True sustainability requires integrating economic, social, and environmental dimensions, necessitating social scientists' involvement from the beginning of discussions (Ly & Cope, 2023; Hariram et al., 2023). Addressing these multifaceted challenges, STEM can drive fundamental change in education and society.

3.4 Constraints of Using STEM Education for Sustainable Development

The constraints observed in STEM's contribution to sustainable development are equally applicable to STEM education for sustainable development. Despite calls in the 1970s for interdisciplinary approaches to environmental education, particularly the incorporation of social sciences, scientific perspectives continue to dominate in ESD, emphasizing the building of scientific and technological knowledge and skills as the primary means of addressing, managing, and mitigating the negative consequences of unsustainable lifestyles (Widarti & Roshayanti, 2021; Sass et al., 2021; Zidny & Eilks, 2022). The inclusion of social sciences in ESD acknowledges that sustainability is fundamentally a human issue, not solely a matter of science, engineering, or technology (Widarti & Roshayanti, 2021). As previously mentioned, the need to integrate economic, social, and environmental dimensions of development has been recognized for over three decades (Sass et al., 2021). It is imperative that this recognition translates into widespread educational practices for sustainable development (AlAli et al., 2023).

Current research in ESD highlights that comprehensive, inclusive approaches, rather than limited STEM-focused ones, present the most promising avenues for effective and widespread ESD implementation (Bosevska & Kriewaldt, 2020; Agirreazkuenaga & Martinez, 2021; Zelenika et al., 2018). These holistic approaches promote inclusivity and collaboration and emphasize ESD as a collective responsibility. Moreover, they acknowledge the fundamental notion that unsustainable development stems from socially constructed behaviors, necessitating solutions derived from social critique and collective actions aimed at the common good (Bosevska & Kriewaldt, 2020; Aswirna et al., 2022a; Repanovici et al., 2021; Solihah et al., 2024a).

Integrating social sciences with STEM (Science, Technology, Engineering, and Mathematics) education can enhance learning activities by fostering a more holistic understanding of complex real-world problems. For example, project-based learning can be utilized to address local environmental issues, such as water pollution. Students can conduct scientific investigations to understand the chemical properties of pollutants while also engaging in social research to gather community perspectives on the impact of pollution on local health and livelihoods. This integration encourages students to analyze scientific data and social implications, fostering critical thinking and problem-solving skills.

Current research in Education for Sustainable Development (ESD) highlights that comprehensive and inclusive approaches, rather than narrow STEM-focused strategies, are essential for effective implementation (Bosevska & Kriewaldt, 2020; Agirreazkuenaga & Martinez, 2021; Zelenika et al., 2018). These holistic methods foster collaboration and frame ESD as a collective responsibility, recognizing that unsustainable development stems from socially constructed behaviors (Bosevska & Kriewaldt, 2020; Aswirna et al., 2022b).

Integrating social sciences with STEM education enhances learning by addressing complex real-world problems. For instance, project-based learning can engage students in local environmental issues like water pollution, combining scientific investigations of pollutants with social research on community impacts. This fosters critical thinking and problem-solving skills (Marcone, 2022). Additionally, using the Sustainable Development Goals (SDGs) as a framework for projects—such as designing sustainable urban spaces for SDG 11—encourages students to consider urban development's historical, cultural, and ethical dimensions (Sharma et al., 2023). Such interdisciplinary approaches empower students to view sustainability as a shared responsibility that requires insights from diverse fields.

4. CONCLUSION

The research findings show that integrating STEM-ESD in Indonesia can enhance sustainability awareness and critical thinking among students; however, it needs to be improved in areas such as the dominance of scientific perspectives, variability in implementation across regions, and resource constraints, including inadequate educator training. These challenges highlight the need for a more interdisciplinary approach that includes social sciences and the importance of collaboration among government, educational institutions, and communities to support STEM-ESD initiatives.

Future research should focus on conducting longitudinal studies to assess the lasting impact of STEM-ESD, exploring its implementation in diverse contexts, and investigating the effective integration of social science perspectives. Additionally, examining the effectiveness of educator training programs and studying the specific outcomes of different STEM-ESD approaches on students' attitudes and behaviors related to sustainability will be crucial. Addressing these aspects can enhance the effectiveness of STEM-ESD in Indonesia, fostering a generation equipped to contribute to sustainable development.

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