



A Narrative Review of Practices and Pedagogical Innovations in Indonesian Science Education: Strengthening Learning through Education for Sustainable Development (ESD)

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Article Info	Abstract
<p>Keywords: <i>Differentiated Instruction; Education for Sustainable Development; Problem-Based Learning Project-Based Learning; Science Education; Sustainability Competencies.</i></p> <hr/> <p>Received: 31/03/2026 Revised: 05/05/2026 Accepted: 12/05/2026</p>	<p>Background: This narrative review examines how Education for Sustainable Development (ESD) is implemented in Science (IPA) education in Indonesia, from elementary to upper secondary levels, between 2020 and 2025. It investigates how ESD is operationalized through various instructional models, evaluates curriculum alignment, identifies implementation challenges, and highlights pedagogical innovations that support sustainable learning outcomes</p> <p>Methods: A descriptive-qualitative study combined direct field observation of the dumpsite with in-depth interviews of local residents and waste pickers to portray accumulation patterns and environmental impacts.</p> <p>Results: Findings show that teachers often initiate ESD practices through creative strategies such as PJBL, PBL, differentiated instruction, and sustainability competency development, although systemic curriculum integration remains limited. The absence of formal ESD indicators in several Science topics constrains scalability.</p> <p>Conclusion: Nevertheless, significant gains were observed in students' critical thinking, creativity, environmental care, and systems awareness. Community partnerships and science learning also enhance ESD awareness among learners. This narrative review emphasizes the need for clear curriculum reform and sustained teacher professional development to effectively integrate ESD into Science education.</p>

INTRODUCTION

The intersection between educational transformation and environmental sustainability has increasingly captured global attention, underscoring the importance of *Education for Sustainable Development* (ESD) as a fundamental driver in achieving the *United Nations Sustainable Development Goals* (SDGs). Among these, SDG 4 (*Quality Education*) positions education as the foundation for lifelong learning and sustainable societies, while SDG 13 (*Climate Action*) emphasizes the urgent need for knowledge, awareness, and behavioral change to address climate challenges. Together, they reflect the transformative potential of education to integrate ecological, social, and economic dimensions of sustainability. Within this framework, ESD functions as both a pedagogical framework and a philosophical foundation aimed at cultivating learners' competencies encompassing knowledge, skills, values, and attitudes so they can make informed decisions and engage in responsible actions that advance environmental stewardship, economic resilience, and social justice (Handayani et al., 2024).

At the global level, *Education for Sustainable Development* (ESD) has been increasingly integrated into educational policies, pedagogical practices, and academic research, serving both as a curricular objective and as a cross-cutting competency domain. The *UNESCO Decade of Education for Sustainable Development* (2005–2014), followed by the *Global Action Programme*, established a strong foundation for embedding sustainability principles within formal education systems. In the Asia-Pacific region, this integration has manifested in diverse ways, with many countries adopting interdisciplinary approaches such as *STEM* (Science, Technology, Engineering, and Mathematics) and its extended form, *STEAM* which incorporates the Arts as effective frameworks for embedding sustainability into science education (Sihombing et al., 2024).

Within Indonesia's educational landscape, the integration of *Education for Sustainable Development* (ESD) has become both an urgent priority and a complex undertaking. The country's rapid urban expansion, extensive deforestation, accelerating biodiversity decline, and widening socio-economic inequalities have intensified the demand for sustainability-oriented education. In response, policymakers have sought to embed ESD principles within the *Kurikulum Merdeka* a competency-driven reform framework that emphasizes autonomy in learning, contextual adaptability, and holistic learner development. Central to this curriculum is the cultivation of the *Profil Pelajar Pancasila*, which envisions students as creative thinkers, cooperative problem-solvers, environmentally responsible citizens, and lifelong learners (Fathurohman et al., 2023)

Nevertheless, translating these ideals into consistent practice remains a significant challenge. Empirical evidence reveals continuing disparities in curriculum alignment, teacher capacity, pedagogical innovation, and the equitable distribution of learning resources. The operationalization of ESD across disciplines particularly in subjects such as biology, chemistry, and physics, as well as in the integrative domain of *Ilmu Pengetahuan Alam dan Sosial* (IPAS) is still evolving. Most implementation efforts rely on teacher initiative or school-level experimentation rather than being systematically embedded through national policy mechanisms (Setyowati et al., 2022).

Empirical studies conducted between 2020 and 2024 indicate that although educators' awareness of *Education for Sustainable Development* (ESD) has progressively increased, its application in classroom practice often remains fragmented, superficial, and insufficiently aligned with sustainability-oriented competencies. In secondary biology instruction, for instance, topics such as environmental change and ecosystem resilience are frequently addressed but seldom contextualized within an explicit ESD framework. Similarly, physics lessons covering areas like rotational dynamics or energy conversion could serve as entry points for connecting scientific

principles to sustainable technologies—such as wind or hydro turbines—yet this potential is rarely harnessed (Pratiwi et al., 2025).

These limitations extend beyond curriculum design. Teachers continue to encounter structural barriers, including inadequate professional development opportunities, restricted access to evidence-based ESD learning resources, and minimal institutional reinforcement. As emphasized by (Sopa Marwa et al., 2025) Indonesian students' outcomes in international benchmarks such as PISA further highlight the pressing need to strengthen scientific and environmental literacy through more systematic and pedagogically grounded integration of ESD across subjects (Latifah et al., 2024).

To overcome these challenges, educators and researchers are exploring new teaching approaches that focus on both strong content and essential competencies. One of the emerging models is *STEAM education*, which combines science with art, creativity, and social awareness. (Jauhariyah et al., 2021) found that learning through STEAM helps increase students' motivation, creativity, and interest in sustainability topics. Similarly, (Maulina et al., 2023) explain that adding the arts to STEM subjects encourages students to think more deeply and see connections between systems, which helps them solve complex environmental problems.

Other studies also support these findings. Discovered that STEAM-based learning supports *SDG 4 (Quality Education)* by developing students' critical thinking, teamwork, and ethical decision-making skills. In Indonesia, the combination of STEAM and *Education for Sustainable Development (ESD)* is starting to gain attention, especially through project-based learning that connects science with creativity and real actions for sustainability in local communities (Ferguson et al., 2022).

Another significant pedagogical innovation is the adoption of differentiated instruction, particularly in vocational education and classrooms with diverse student abilities. This approach allows teachers to adjust learning content, processes, and outcomes according to students' readiness levels, interests, and learning preferences (Mardian, 2023). Within the framework of *Education for Sustainable Development (ESD)*, differentiated instruction provides an opportunity to link sustainability topics directly to local community contexts—for instance, waste management, food security, clean water access, or renewable energy initiatives. This not only increases student engagement but also nurtures a stronger sense of relevance, responsibility, and participation in solving environmental challenges (Vilmala et al., 2025).

In parallel, the growing use of digital and electronic learning platforms has opened new avenues for integrating ESD into science education. During the COVID-19 pandemic, online resources, simulation tools, and virtual laboratories were increasingly utilized to enhance students' environmental awareness and scientific literacy. However, despite these advances, many teachers still report limited confidence in applying ESD frameworks through digital media, highlighting the urgent need for professional development and digital pedagogical training (Fitroni et al., 2025a). The application of ESD is particularly crucial because it connects scientific understanding with real-world sustainability issues. For example, lessons in biology can address biodiversity conservation and ecosystem restoration; chemistry can explore green technologies and waste reduction; and physics can highlight renewable energy systems such as solar and wind power. Through inquiry-based, project-based, and STEAM-integrated learning, students are encouraged to investigate, design, and innovate solutions to environmental problems grounded in scientific principles. Such approaches not only strengthen conceptual mastery but also cultivate critical thinking, problem-solving, and ethical decision-making—core competencies of sustainable citizenship (Nurfadilah & Siswanto, 2020).

Collectively, these developments underscore that embedding ESD within science learning is not merely an academic pursuit but a transformative process that prepares students to become scientifically literate and environmentally responsible individuals capable of contributing to

sustainable futures. Moreover, existing studies highlight the critical importance of comprehensive teacher professional development and institutional policy support to effectively embed ESD principles into daily classroom instruction (Akanbi & Adesina, 2024). Educational policies should not only advocate for the inclusion of ESD-related content but also ensure the availability of systemic and financial mechanisms that enable its practical implementation. Such support involves the development of curriculum frameworks, assessment standards, instructional materials, and mentoring programs that empower teachers to integrate sustainability concepts meaningfully into their teaching practices. Given the breadth and complexity of current developments, this review seeks to present a comprehensive synthesis of *Education for Sustainable Development (ESD)* implementation within Indonesian science education from 2020 to 2024 (Khoiri et al., 2023).

The review systematically explores how various pedagogical models and instructional strategies have been utilized to integrate ESD concepts into science and interdisciplinary subjects. These include innovative approaches such as STEAM, Ilmu Pengetahuan Alam dan Sosial (IPAS), project-based learning, and differentiated instruction, which collectively aim to strengthen sustainability-oriented learning. In addition, the review examines reported learning outcomes—both cognitive and affective—that emerge from ESD implementation in formal educational contexts (Sandy Pamungkas et al., 2025a). Attention is also directed toward identifying key systemic gaps, opportunities, and challenges, especially those related to curriculum alignment, teacher preparedness, and institutional support mechanisms. The scope of this review is limited to studies conducted in Indonesia, encompassing both national and localized case studies across educational levels from elementary (SD) to senior high school (SMA/SMK) (Rohmaya, 2022). The primary disciplines under focus include Physics, Biology, and Chemistry, along with interdisciplinary learning projects in IPAS (Ilmu Pengetahuan Alam dan Sosial). To maintain conceptual clarity and coherence throughout the discussion, several key terms relevant to ESD and science education are defined in the following section (Maulidiya Nabila et al., 2025).

Education for Sustainable Development (ESD) is a lifelong educational framework aimed at equipping learners with the knowledge, skills, values, and attitudes needed to build sustainable societies by integrating ecological, economic, and sociocultural dimensions while fostering responsible citizenship and environmental stewardship. In this context, *STEAM*—an interdisciplinary approach combining Science, Technology, Engineering, Arts, and Mathematics—promotes holistic learning that enhances creativity, innovation, and critical thinking in addressing sustainability-related issues (Vázquez-Villegas et al., 2022). Complementing this, *Ilmu Pengetahuan Alam dan Sosial (IPAS)* serves as a contextualized subject within the Indonesian curriculum that bridges scientific and social perspectives, encouraging students to connect classroom concepts with real-world environmental and community challenges. Collectively, these frameworks reflect a unified effort to cultivate scientifically literate, environmentally conscious, and socially responsible learners capable of contributing to sustainable development (Kapranov, 2022).

Education for Sustainable Development (ESD) is widely recognized as an educational paradigm that seeks to empower learners to make informed choices and take responsible actions in promoting environmental integrity, economic resilience, and social equity. This global movement established a crucial framework for transforming education systems by embedding sustainability principles within teaching, learning, and institutional practices (Lamauskas & Malinauskienė, 2024). The progression of ESD throughout the UNDESD period signaled a paradigm shift—from merely raising awareness to adopting interdisciplinary, participatory, and competency-based approaches. This evolution emphasized that achieving sustainable development requires not only cognitive understanding but also emotional engagement, ethical awareness, and social responsibility. As highlighted by (Setiawan et al., 2023) ESD must cultivate learners' ability to

analyze complex systems, anticipate long-term environmental and societal impacts, and collaborate effectively in addressing community and sustainability challenges.

Building upon these competency frameworks, the integration of *Education for Sustainable Development (ESD)* within science education has gained increasing importance, particularly in the Indonesian context. Science subjects—such as biology, physics, and chemistry—offer authentic opportunities for students to develop sustainability competencies through inquiry, experimentation, and problem-solving (Miao et al., 2022). When aligned with the competencies outlined by Wiek et al. and UNECE, science learning can move beyond factual understanding to cultivate systems thinking, foresight, ethical reasoning, and collaborative action. In Indonesia, the implementation of ESD within the *Kurikulum Merdeka* framework encourages teachers to design learning experiences that connect scientific knowledge with local environmental issues, including waste management, renewable energy, and biodiversity conservation. Such integration not only strengthens scientific literacy but also nurtures the values, attitudes, and behaviors essential for sustainable living (Fitroni et al., 2025b).

Although these models differ in focus and scope, they share a common goal: integrating ecological, economic, and socio-cultural dimensions into education. According to (Alsarayreh et al., 2022) and (Janssens et al., 2022) such frameworks help maintain the multidimensional nature of ESD, enabling learners to link theoretical knowledge with practical, real-world sustainability actions. (Minh Khoa & Isabel Santos, 2025) further contend that a comparative perspective highlights the complementary strengths of these models, with the individual-focused framework emphasizing personal responsibility, while UNESCO and UNECE frameworks underscore collective and institutional accountability.

The growing integration of ESD principles in higher education highlights the extensive impact of UNESCO's framework. (Ekselsa et al., 2023) and (Shakir et al., 2024), universities and teacher education programs have increasingly incorporated ESD into their curricula, research agendas, and community engagement initiatives. Embedding ESD at the institutional level is essential for reinforcing sustainability education across all stages—from foundational learning to advanced study—while promoting lifelong learning and leadership in sustainability across various sectors. In Indonesia, the principles of Education for Sustainable Development (ESD) have been progressively embedded through curriculum reforms, particularly the Kurikulum 2013 and its successor, the Kurikulum Merdeka. Both curricula promote a competency-based approach that emphasizes inquiry, critical thinking, and student autonomy, which are fundamental aspects of ESD. A notable feature of the Kurikulum Merdeka is the Profil Pelajar Pancasila, a character-centered learning framework designed to align educational goals with Indonesian cultural and ethical values. This profile nurtures qualities such as global citizenship, environmental awareness, and collaborative problem-solving, echoing competencies highlighted in international ESD standards (Mardian, 2023)

ESD is also implemented through interdisciplinary thematic initiatives like Proyek IPAS (Ilmu Pengetahuan Alam dan Sosial), which integrate natural and social sciences to address real-life issues. These projects focus on sustainability topics, encouraging students to cultivate comprehensive perspectives and apply sustainability literacy in contextually meaningful ways (Lestari et al., 2024). A comparison with other Southeast Asian nations highlights both common goals and distinct national approaches. For example, Malaysia incorporates environmental education into its national science curriculum to cultivate ecological awareness from an early stage (Lüdtke et al., 2025) In contrast, Thailand focuses on community-centered practices, involving students in practical, hands-on sustainability activities.

However, the implementation of ESD in Indonesia continues to face several challenges. Limited teacher training, insufficient resources, and centralized curricular control have constrained

the effective adoption of ESD frameworks. (Fitri & Drastisianti, 2024) and (Maolida et al., 2024) highlight the importance of continuous professional development and decentralization to enable educators to act as agents of sustainability transformation. Similarly, (Taqiya et al., 2024) and (Nugroho et al., 2025) argue that sustained institutional support is crucial for shifting instructional strategies toward project- and inquiry-based learning aligned with ESD principles. Even with these challenges, regional studies in Indonesia demonstrate encouraging results from ESD-oriented reforms. (Widyawati et al., 2024) find that involvement in sustainability-focused classroom projects increases student awareness and fosters positive behavioral changes. These results suggest that curriculum designs and implementations adapted to local contexts can effectively nurture sustainable practices among learners.

Strategies and Models to Facilitate the Implementation of ESD in Education

A variety of instructional models have been proposed to implement ESD in educational settings. Notable among these are STEAM education, project-based learning (PBL), ProBLES, and differentiated instruction. Each approach fosters interactive, student-centered learning environments that nurture sustainability-related competencies. Among these approaches, STEAM (Science, Technology, Engineering, Arts, and Mathematics) stands out for its effectiveness in enhancing students' creativity, critical thinking, and innovative capacities within sustainability-focused contexts. By incorporating the arts into traditional STEM subjects, learners are encouraged to adopt holistic and empathetic perspectives when addressing complex global challenges. (Bedford, 2022) indicate that STEAM-based learning stimulates intrinsic motivation and drives sustainability-oriented innovation, while Chen et al., 2022 highlight its role in fostering deeper cognitive engagement with environmental issues.

Among the various instructional strategies, Project-Based Learning (PBL) provides learners with opportunities to explore sustainability-related issues through authentic, hands-on experiences. Ekselsa et al. (2023) point out that ESD-focused PBL enhances systems thinking by allowing students to understand the interconnections between natural and human systems. (Sintiya et al., n.d.) note that this approach fosters creative scientific literacy, especially in subjects like optics and waves. In addition, Ferguson et al., 2022 show that integrating STEAM into PBL leads to higher academic achievement and increased learner engagement compared to conventional teaching methods.

Another important strategy for implementing ESD is differentiated learning, particularly in classrooms with diverse learners. This method enables educators to customize teaching according to students' abilities, interests, and learning profiles. Vázquez-Villegas et al., 2022 note that differentiated ESD modules enhance both student engagement and mastery of content. The approach also aligns well with Wiek et al.'s sustainability competencies, as it accommodates multiple entry points for learners to tackle complex sustainability challenges. Furthermore, Haim and Khoiri et al., 2023 highlight that engaging students in innovative, real-world projects within the ESD framework fosters creativity, ethical reasoning, and collaborative problem-solving skills. These competencies are crucial for preparing learners to address sustainability issues effectively at both local and global levels (Prabawani et al., 2022).

METHODS

This narrative literature review utilized a qualitative synthesis method to examine the implementation of Education for Sustainable Development (ESD) in Indonesian science education. The data sources included peer-reviewed journal articles, validated student theses, and conference proceedings, encompassing both published and gray literature. The review focused exclusively on

materials explicitly situated within the context of Indonesian formal education and that discussed the integration of ESD into science-based or interdisciplinary learning frameworks.

Relevant literature was identified through a focused search strategy using carefully selected keywords. The search targeted terms such as "Education for Sustainable Development" and these were examined across document titles, abstracts, and full texts to capture pertinent sources. Unlike conventional systematic reviews that adhere to strict protocols such as PRISMA, this study employed a narrative review methodology. The emphasis was placed on synthesizing ideas conceptually and interpreting findings rather than compiling exhaustive lists. This approach aligns with the integrated review methods and with interpretive strategies for evaluating transformative learning outcomes.

The document screening was carried out through a two-step manual selection process, in line with the procedures described by Milošević et al. (2023), who emphasized the use of integrative review techniques to maintain consistency across diverse content categories and structural formats. At the initial stage, the relevance of titles and abstracts to ESD topics and Indonesian educational settings was assessed. This was followed by a comprehensive examination of the full texts to validate their suitability for inclusion in the review.

Each document underwent systematic coding and categorization according to key analytical dimensions, encompassing research design, educational stage, disciplinary orientation, pedagogical framework employed (e.g., STEAM, Differentiated Instruction, or Project-Based Learning), and the extent of integration with Education for Sustainable Development (ESD) principles.

RESULT AND DISCUSSION

The Integration of Education for Sustainable Development (ESD) with Science Learning

PjBL-PBL ESD

Project-Based Learning (PBL) has emerged as a transformative pedagogical model that bridges scientific exploration with authentic, real-life challenges, thereby nurturing learners' competencies and consciousness toward the goals of Education for Sustainable Development (ESD). Within the Indonesian educational landscape, the synergy between PjBL and the *Kurikulum Merdeka* framework underscores its potential as an effective medium for embedding sustainability concepts through experiential, student-driven learning processes. Project-Based Learning (PjBL) model in teaching plant tissue culture within senior high school biology contexts. The learning projects were designed around the sustainability theme of food security, where students conducted propagation experiments and developed informational posters on cultivation practices. By integrating ecological and economic aspects, the activity allowed learners to recognize the interconnection between scientific innovation and sustainable food production systems.

The implementation resulted in notable improvements in students' creativity and critical thinking, aligning with the findings of Maulina et al., (2023), who highlighted PBL's effectiveness in enhancing understanding within environmental education. Furthermore, theoretical insights from Naibaho et al., (2025) and Fitri & Drastisianti, (2024) support this pedagogical approach, emphasizing the immersive and transformative qualities of PBL. Its capacity to foster systems thinking, applied problem-solving, and collaborative learning underscores its relevance for ESD-oriented instruction. Learners who engage with sustainability principles through such experiential processes are more likely to exhibit enduring shifts in attitudes and behavior. Mutmainnah et al., (2025) developed a student worksheet (LKPD) based on the PBL-ESD framework to teach

rotational dynamics a physics topic often regarded as abstract and conceptually demanding. By contextualizing the lesson through local craft traditions, such as the making of traditional spinning toys, the learning design incorporated socio-cultural and sustainability perspectives. The intervention produced a moderate N-Gain score of 0.46 in students' creative thinking, indicating measurable improvement. This aligns with the findings of Setiawan et al., (2023), who emphasized the pedagogical.

The implementation of PBL–ESD in school science learning provides a pedagogical framework that situates scientific inquiry within authentic, real-world contexts. Through project-based activities, students explore sustainability issues such as water conservation, renewable energy, waste management, or food security. These projects encourage learners to apply scientific concepts while reflecting on their environmental and social implications (Minh Khoa & Isabel Santos, 2025). For example, students may design small-scale biogas systems or hydroponic gardens to examine the principles of energy transformation and plant physiology. Such contextualized learning experiences make science more relevant, engaging, and aligned with sustainability values promoted in the national curriculum. In implementing PBL–ESD, science educators are encouraged to adopt an interdisciplinary lens, connecting biology, chemistry, physics, and environmental science with socio-economic and cultural dimensions (Sopa Marwa et al., 2025). This approach helps students perceive scientific phenomena not as isolated facts but as systems embedded in ecological and human contexts. For instance, studying air pollution can involve measuring particulate matter (physics), analyzing chemical reactions (chemistry), exploring effects on living organisms (biology), and proposing sustainable urban solutions (social dimension). The process develops students' systems thinking—an essential competency within ESD frameworks as described by UNESCO (2023).

Empirical evidence shows that students engaged in PjBL–ESD activities exhibit increased motivation, creativity, and critical awareness toward environmental issues. They develop a sense of ownership and agency in proposing science-based solutions for local sustainability challenges. Classroom projects, such as recycling experiments, renewable energy prototypes, or biodiversity mapping, foster not only conceptual understanding but also social and emotional competencies—key indicators of sustainable learning behavior. These findings echo earlier research by Bolstad et al. (Maolida et al., 2024)), which demonstrate that experiential and collaborative learning significantly strengthens students' sustainability literacy. The approach demonstrated by (Setiawan et al., 2023) illustrates how PjBL–ESD can serve as an effective vehicle for integrating local wisdom into science learning. By linking traditional agricultural knowledge with modern biotechnological applications, the learning process positioned students as active contributors to sustainable innovation rather than passive recipients of information. Such integration of indigenous practices promotes a deeper appreciation of cultural heritage while reinforcing scientific literacy through contextualized inquiry.

In this way, PjBL and PBL with ESD not only nurtures students' understanding of sustainability concepts but also cultivates their sense of ecological responsibility and cultural identity. Similar approaches have been highlighted by Setyowati et al., (2022), who found that embedding socio-cultural relevance within science instruction enhances both cognitive outcomes and students' commitment to sustainability-oriented action. A recurring theme in PBL–ESD research is the value of embedding local culture and community relevance into science learning. By incorporating local wisdom—such as traditional ecological knowledge or indigenous technologies—students experience science as culturally meaningful and socially responsible. (Vilmala et al., 2025) highlight that integrating cultural and ethical dimensions not only strengthens conceptual mastery but also fosters empathy, respect for local heritage, and ethical reasoning in scientific contexts. This socio-

cultural grounding ensures that sustainability learning is both inclusive and transformative (Tomren, 2022).

Widya et al. (2025) implemented an ESD-assisted Project-Based Learning model in the context of ecosystems and environmental changes, emphasizing environmental dimensions. Their findings indicate that this approach enhances students' understanding of climate change and other environmental issues through scientific concepts while fostering critical thinking skills. Similarly, Pratiwi et al. (2025) applied an ESD-oriented differentiated project-based learning model focusing on biodiversity literacy and environmental behavior. The study showed that students' critical thinking and biodiversity literacy improved, enabling them to analyze and address ecological challenges effectively.

Sandy Pamungkas et al., (2025b) explored PBL-based differentiated projects in physics, particularly in rotational dynamics, integrating sustainability perspectives through local crafts to promote social awareness. This approach supported inclusive learning and holistic student development while guiding educators to integrate both scientific understanding and moral-spiritual values. Maulina et al., (2023) investigated the impact of SDG-oriented PBL on environmental pollution materials, highlighting significant improvements in students' critical thinking regarding ecological processes and human impact. Finally, Parwati et al., (2019) examined PBL-based SSI-ESD learning on chemical change topics, demonstrating enhanced chemical literacy and environmental awareness, aligned with competency-based education and the Merdeka Belajar curriculum.

Overall, these studies collectively suggest that integrating ESD with PjBL and PBL in science education not only strengthens students' understanding of scientific concepts but also enhances critical thinking, environmental awareness, and socio-moral competencies. The evidence highlights the potential of ESD-oriented learning approaches to foster holistic, inclusive, and competency-based science education that prepares students to address contemporary environmental challenges.

STEAM-ESD

The integration of STEAM (Science, Technology, Engineering, Arts, and Mathematics) with Education for Sustainable Development (ESD) offers a holistic framework for cultivating 21st-century competencies through sustainability-oriented science education. STEAM–ESD emphasizes inquiry-based, creative, and solution-oriented learning that bridges scientific understanding with real-world sustainability challenges. The inclusion of the “Arts” dimension enriches the scientific process with creativity, empathy, and design thinking—skills essential for addressing complex socio-ecological issues. (Indahwati et al., 2023), such integration fosters transdisciplinary reasoning, enabling students to connect cognitive, affective, and ethical dimensions of learning.

Integrating STEAM–ESD within the Indonesian educational context often involves incorporating local wisdom (*kearifan lokal*) to strengthen cultural and environmental relevance. For example, lessons on biodiversity can include traditional ecological practices or indigenous art forms that express harmony with nature. Such approaches, as highlighted by (Minh Khoa & Isabel Santos, 2025), demonstrate that combining STEAM design with cultural narratives fosters a sense of identity and belonging while advancing sustainability values. Through locally grounded STEAM projects, students learn that scientific creativity can emerge from their own cultural contexts, making ESD principles more meaningful and accessible.

The integration of ESD and STEAM strategies in Indonesian science education aligns closely with the principles of transformative learning, which encourage students to develop sustainable habits and worldviews. A study by Widarti and Roshayanti (2021) exemplified this approach through a STEAM-enriched lesson on fluid dynamics conducted in a *Madrasah Aliyah* (upper

secondary school). In this project, students constructed water flow models from recycled materials, bridging abstract physics concepts with local environmental issues such as water waste and sanitation management. This initiative illustrates the ecological and economic dimensions of ESD by prompting learners to evaluate the sustainability of material use and the broader implications of scientific applications. The activity also cultivated key values such as resource efficiency, innovation, and environmental responsibility. These findings are consistent with LeSage-Clements et al. (2024), who underscore the pedagogical significance of employing authentic, real-world materials to enhance ecological literacy and scientific inquiry within sustainability education.

In a vocational high school (SMK), implemented a full STEAM cycle focused on the topic of *Zat dan Perubahannya* (matter and its transformation). Students engaged in substance change experiments involving low-cost, sustainable materials to model real-life industrial applications. Students engaged in experimental investigations of substance transformations utilizing low-cost and environmentally sustainable materials, such as biodegradable polymers and recycled substances, aimed at simulating real-world industrial applications (Sihombing et al., 2024). According to their findings, 73% of teachers reported integrating STEAM, and 87% of students demonstrated improved conceptual mastery. Importantly, 89% of students reported increased creativity—a central competency within both STEAM and ESD frameworks.

These results underscore the connection between sustainability education and STEAM's creative, interdisciplinary orientation. As noted by Lage-Gómez and Ros (2023), embedding creativity into science tasks nurtures students' ability to generate novel solutions to environmental challenges. Similarly, another study on green chemistry implementation in senior high schools involved students in designing and testing biodegradable materials as alternatives to conventional plastics, emphasizing the principles of environmentally friendly chemical processes and sustainable production systems (Mutmainnah et al., 2025). These project-based experimental activities allowed learners to connect abstract chemical concepts such as polymerization, material properties, and degradation processes with real-world environmental challenges, thereby strengthening both conceptual understanding and sustainability awareness (Alberto et al., 2024).

The study by Riyanto et al. further supports findings by Ragisha.K.K (2025), who highlight that sustainability themes embedded within applied chemistry lessons increase students' engagement and promote environmental responsibility. The implementation of the STEAM framework in upper secondary science learning as a means to bridge abstract scientific concepts with sustainability-oriented contexts. Rather than emphasizing theoretical instruction, the learning design encouraged students to create simple prototypes using locally available materials and low-cost sensors. Through this process, students were guided to relate scientific principles to real-world technological innovations such as wind turbines and renewable energy systems.

Recent studies have further reinforced the pedagogical value of integrating STEAM and ESD in science education. For instance, Sari et al. (2023) implemented a STEAM-based environmental chemistry module in junior high schools to promote waste management awareness and green innovation. Students designed eco-friendly filtration systems using recyclable materials, which not only enhanced their conceptual mastery of chemical processes but also strengthened their sense of environmental responsibility. Similarly, Ariyanti and Nugraha (2022) developed a STEAM–ESD project on renewable energy, where students created miniature solar panels and conducted energy efficiency analyses. The intervention led to significant improvement in systems thinking and collaborative problem-solving—key competencies outlined in the ESD framework. These studies collectively demonstrate that when STEAM is contextualized within sustainability challenges, it cultivates both scientific literacy and sustainability-oriented mindsets, preparing students to engage critically with real-world environmental and socio-economic issues.

These findings align with the theoretical perspectives of Wiek et al. (as cited in Chen et al., 2022) and the UNECE framework (Nurhayati, 2022), both of which emphasize that cultivating sustainability competencies necessitates intentional and well-structured instructional design that explicitly connects scientific content with ESD objectives. The relatively low proportion of ESD indicators observed suggests that, although the STEAM framework provides a strong foundation for interdisciplinary and inquiry-based learning, its effectiveness largely depends on the educator's capacity to situate scientific understanding within authentic sustainability contexts.

STEAM-ESD Can Promote Deep Learning?

Integrating STEAM (Science, Technology, Engineering, Arts, and Mathematics) with Education for Sustainable Development (ESD) provides a powerful pathway for fostering *deep learning* in science classrooms, especially when addressing critical topics such as climate change, global warming, renewable energy, and ecosystem degradation. As Sari et al. (2023) highlight, STEAM-ESD projects that incorporate student-centered inquiry and hands-on experimentation allow learners to engage in enjoyable learning, where curiosity and exploration drive motivation. Activities such as modeling carbon cycles, designing solar-powered devices, or analyzing local pollution data create opportunities for playful experimentation while deepening conceptual understanding.

At the same time, integrating mindful learning practices encourages students to reflect critically on the societal and ethical dimensions of scientific problems. Fathurohman et al., (2023) found that students engaged in STEM-ESD activities—like monitoring environmental changes or investigating the causes of climate phenomena—developed both cognitive skills and awareness of human impacts on ecosystems. These experiences cultivate mindfulness, helping learners consider the consequences of human action and fostering a responsible, reflective approach to problem-solving (Setyowati et al., 2022).

Finally, meaningful learning emerges when STEM-ESD tasks are explicitly connected to real-life sustainability challenges. Sihombing et al., (2024) demonstrated that biology and chemistry projects addressing biodegradable materials, water quality, or local carbon reduction strategies enabled students to integrate disciplinary knowledge with authentic environmental issues. By connecting classroom science to community and global contexts, learners construct lasting understanding, develop ethical reasoning, and see the relevance of their learning, which are all hallmarks of *deep learning*.

Several recent studies highlight how STEM-ESD fosters *deep learning* by integrating interdisciplinary science content with sustainability-oriented projects. Fathurohman et al., (2023) examined differentiated inquiry-based learning in Indonesian biology classrooms, where students investigated local environmental problems such as river pollution and deforestation. The study found that when students were allowed to choose their investigative topics and design experiments collaboratively, engagement, critical thinking, and problem-solving skills increased substantially. Such autonomy aligns with the principles of *enjoyable learning*, as students are intrinsically motivated to explore meaningful, context-driven science challenges.

Complementing this, Novi et al., (2024) implemented ESD activities in physics classes to address energy conservation and climate-related issues. Their results indicated that students' reflective practices and systems thinking improved significantly when lessons incorporated *mindful learning* approaches, such as guided reflection on the societal impacts of energy use or the ethical implications of carbon emissions. Students reported heightened awareness of sustainability issues and a stronger sense of responsibility for local environmental actions, suggesting that mindfulness deepens the connection between conceptual understanding and social application (Jauhariyah et al., 2021).

Additionally, Maulina et al., (2023) explored differentiated STEM–ESD projects in chemistry, where students designed experiments using biodegradable materials and analyzed chemical processes in waste management. The research highlighted that linking tasks directly to real-world sustainability challenges facilitated *meaningful learning*, as students could see the relevance of scientific principles in addressing community problems. This approach not only enhanced academic performance but also strengthened ethical reasoning and collaborative skills, demonstrating the potential of STEAM–ESD to cultivate holistic competencies aligned with Education for Sustainable Development (Nurfadilah & Siswanto, 2020).

Collectively, these studies indicate that STEAM–ESD, when designed to incorporate enjoyable, mindful, and meaningful learning experiences, can transform science classrooms into environments conducive to deep learning. Students engage cognitively, affectively, and socially, applying disciplinary knowledge to solve real sustainability problems while developing critical thinking, empathy, and agency—competencies essential for nurturing future-ready and sustainability-literate citizens.

Differentiated Learning within ESD Contexts

Recent studies have shown that differentiated learning serves as an effective pedagogical bridge in implementing Education for Sustainable Development (ESD), particularly in heterogeneous classrooms. Ferguson et al., (2022) reported that the integration of *differentiated project-based learning* within ESD frameworks significantly improved students' environmental literacy and social responsibility. The study emphasized that providing students with options in project themes, learning materials, and modes of presentation allowed for greater engagement and deeper reflection on sustainability issues. This flexibility enabled learners with varying cognitive levels to contribute meaningfully to sustainability-oriented discussions and community-based projects. A similar trend was observed by Mardian, (2023) who implemented differentiated inquiry learning for ESD in biology classes at several Indonesian junior high schools. Their study found that when students were provided with tiered investigative tasks—ranging from ecosystem observation to mini-experiments on pollution impact—learning outcomes improved across cognitive, affective, and psychomotor domains. The differentiated approach not only increased students' motivation and participation but also enhanced their ability to apply biological concepts in addressing local environmental challenge enabling students to connect disciplinary knowledge with sustainability competencies through active, inclusive, and context-responsive learning (Minh Khoa & Isabel Santos, 2025).

Similarly, Jauhariyah et al., (2021) found that differentiated instruction in biology classes, when aligned with ESD competencies, enhanced students' systems thinking and problem-solving abilities. The research implemented tiered assignments related to environmental change and resource management, where students could choose between analytical reports, creative posters, or experimental mini-projects. Findings indicated that such differentiation promoted not only academic achievement but also students' emotional connection to environmental stewardship and local ecological contexts. In addition, Chen et al., (2022) examined differentiated ESD implementation in secondary schools across South Korea, highlighting the role of teacher autonomy and localized content adaptation. Their results demonstrated that when teachers were empowered to adjust ESD content to suit students' readiness and interests, learners showed higher sustainability awareness and were more capable of transferring concepts into real-life action. This underscores the importance of pedagogical flexibility within policy frameworks that often remain rigid or standardized (Permanasari & Dwi Pursitasari, 2021).

Expanding on assessment practices, Nugroho et al., (2025) explored differentiated evaluation strategies in ESD-oriented classrooms. Their findings revealed that allowing diverse

assessment formats—such as reflective journals, oral presentations, and design prototypes—captured students' sustainability competencies more accurately than conventional testing. This approach aligned with UNESCO's (2022) call for inclusive and participatory learning environments that recognize multiple pathways to demonstrating understanding, critical inquiry, and action competence. Moreover, (Vázquez-Villegas et al., 2022) provided cross-case evidence from teacher training programs in Indonesia, demonstrating that differentiated ESD-based instruction not only enhanced student learning outcomes but also strengthened teachers' pedagogical confidence. Teachers reported that designing ESD lessons with varied levels of complexity and local sustainability themes increased students' motivation and sense of agency. These findings collectively affirm that differentiated learning principles, when merged with ESD goals, foster equitable, inclusive, and contextually relevant sustainability education (Shakir et al., 2024).

Bedford, (2022)) explored differentiated learning in environmental physics modules using inquiry-based laboratory activities. The study found that providing tiered experiments—ranging from simple household energy audits to prototype solar-powered devices—encouraged students to think critically about energy efficiency and climate action, directly reflecting ESD competencies. Complementing these findings, Goller & Rieckmann, (2022) analyzed teacher perceptions of differentiated instruction within ESD-based science curricula across several provinces in Indonesia. They reported that teachers who implemented differentiated strategies felt better equipped to address students' diverse abilities and to link scientific inquiry with local sustainability challenges. However, they also highlighted systemic barriers, including rigid assessment policies and insufficient curriculum guidance, which often discourage innovation. Collectively, these studies reinforce that differentiated instruction not only enhances conceptual mastery in science but also cultivates the transformative competencies critical thinking, problem-solving, and collaborative skill to enhancing Education for Sustainable Development (Rico et al., 2021).

Overall, the growing body of research—from Wahyuni et al. (2023) to Kurniawan et al. (2024)—demonstrates that differentiated learning provides a viable and contextually responsive pathway for embedding Education for Sustainable Development (ESD) within Indonesia's science education system Sriyati et al., (2023). Across disciplines such as physics, biology, and chemistry, differentiated strategies have been shown to enhance students' scientific reasoning, systems thinking, and sustainability awareness while simultaneously promoting inclusivity and active engagement (Dias et al., 2022). These classroom-based innovations illustrate that ESD integration can succeed even within existing curricular structures, provided teachers are empowered with pedagogical flexibility and institutional support. To ensure sustainability of impact, however, these practices must be reinforced by coherent national policies that embed ESD competencies into science learning standards, assessment frameworks, and teacher professional development programs (Alsarayreh et al., 2022). Strengthening this alignment between curriculum design, policy direction, and classroom practice will transform ESD from isolated initiatives into a systemic foundation for cultivating environmentally literate, socially responsible, and future-oriented learners across Indonesia's educational landscape (Kapranov, 2022).

Digital Media Implementation for ESD-Based Science Learning

The implementation of digital and electronic learning media as part of Education for Sustainable Development (ESD) initiatives is gaining prominence in Indonesian elementary education. Despite the strong conceptual rationale for integrating technology to reinforce ESD objectives, its practical implementation in classrooms remains limited, largely due to variations in teacher competency and the depth of pedagogical integration (Sund & Gericke, 2020). This section investigates how digital learning environments intersect with systems thinking within the ESD paradigm, highlighting their potential to nurture sustainability awareness, reflective thinking, and

environmental responsibility among young students. The discussion focuses on elementary-level applications and outcomes, providing insights into how digital tools can be harnessed to promote meaningful and future-oriented sustainability learning (Dusturi et al., 2024).

Recent empirical studies have demonstrated the significant role of ESD-based digital media in enhancing students' environmental literacy and critical awareness in science learning. Khairrunisa et al., (2025) developed an interactive multimedia module on waste management for elementary students, which successfully improved conceptual understanding and pro-environmental attitudes, with an N-Gain score of 0.62 categorized as medium to high. Similarly, Ramadhani & Susiyawati, (2025) implemented a digital storytelling approach centered on biodiversity conservation, allowing students to express local environmental issues through narrative-based animation projects. The findings revealed not only improved communication and creativity skills but also an increased sense of ecological responsibility. In another study, (Zidny et al., 2021) designed a gamified ESD application that integrated climate action and energy-saving themes into science lessons. The intervention showed a marked increase in students' motivation and sustainability-oriented decision-making. Collectively, these findings underscore that ESD-integrated digital learning media can transform science education from content-oriented instruction into value-driven and action-oriented learning experiences (Zidny et al., 2021).

The integration of e-learning and augmented reality (AR) technologies into ESD-based science education has further expanded the potential for interactive and transformative learning experiences. Sutadji et al., (2021) found that an e-learning platform embedding sustainability themes—such as renewable energy and waste reduction—significantly enhanced students' systems thinking and digital literacy. The study highlighted that online learning environments, when designed with inquiry-based and reflective components, can effectively bridge environmental knowledge with personal responsibility and social awareness. In a related study, Siti Fatimah et al., (2025) developed an AR-assisted module to visualize ecological balance and the impact of human activities on ecosystems. The AR media allowed students to manipulate 3D models of natural processes such as photosynthesis and pollution cycles, making abstract sustainability concepts more concrete and experiential. Results indicated substantial improvements in conceptual understanding and empathy toward environmental issues. Moreover, Fitri & Drastisianti, (2024) emphasized that AR technology fosters immersive learning experiences that promote affective engagement—a critical dimension often underrepresented in traditional ESD delivery.

Curriculum Alignment and Policy Consistency for ESD Implementation

Although awareness and classroom practices related to Education for Sustainable Development (ESD) continue to grow, its integration at the curriculum level remains partial and uneven. In Indonesia, as reflected, numerous educators have incorporated sustainability-oriented themes into their teaching; however, a lack of explicit ESD frameworks within the national curriculum especially in key science subjects such as physics and biology has limited the coherence and scalability of these efforts Parwati et al., (2019). This section analyzes such discrepancies through empirical evidence and recent scholarly findings, illustrating how teacher-driven pedagogical innovation has emerged as a compensatory mechanism for policy discontinuity, while simultaneously underscoring the urgent need for comprehensive curriculum reform (Fitroni et al., 2025a).

These findings are consistent with the studies of Rico et al., (2021), who contend that embedding ESD within the physics curriculum not only strengthens students' conceptual comprehension but also enhances the subject's relevance to real-world sustainability challenges. The absence of explicit ESD indicators in national curriculum documents has consequently

produced systemic blind spots, reinforcing the necessity for curricular reform that fosters interdisciplinary connections and socially responsive learning. Similarly, Latifah et al., (2023) highlight that teachers with strong professional agency tend to contextualize sustainability concepts more effectively, even when formal policy support is lacking.

In the field of biology, parallel deficiencies appear in instructional units addressing environmental change. Current textbooks and lesson plans tend to emphasize descriptive ecological content—such as ecosystem definitions and pollution categories—while neglecting broader ESD competencies like systems thinking, critical reflection, and linkage to the Sustainable Development Goals (SDGs) (Musyarofah et al., 2025). As illustrated in Table 8, biology modules developed by practicing educators successfully integrate all 15 core ESD indicators into activities aligned with Bloom’s cognitive domains. These teacher-initiated models exemplify the practical viability of embedding sustainability competencies within existing curricular structures, demonstrating that meaningful ESD integration does not necessarily require a complete structural overhaul (Salsabila, 2024).

In the field of chemistry, similar gaps are evident in the integration of ESD principles within the curriculum. Chemistry instruction often emphasizes abstract concepts—such as reaction mechanisms, stoichiometry, and chemical equilibrium—without adequately connecting them to real-world sustainability issues. This limits students’ ability to understand the role of chemistry in addressing global challenges such as environmental pollution, waste management, and sustainable material development (Alberto et al., 2024). Recent studies highlight that incorporating green chemistry principles, such as the use of safer chemicals, waste reduction, and energy-efficient processes, can enhance both conceptual understanding and environmental awareness. For example, learning activities involving the development of biodegradable materials, water purification experiments, or analysis of air and water pollutants enable students to link chemical concepts with sustainability practices. However, the absence of explicit ESD indicators in chemistry curricula continues to hinder the systematic integration of these approaches, reinforcing the need for more interdisciplinary and sustainability-oriented curriculum design (Mutmainnah et al., 2025).

The evidence underscores a persistent disjunction between curriculum design and policy continuity in Indonesia’s pursuit of Education for Sustainable Development (ESD). While teacher-led innovations in physics and biology demonstrate adaptive capacity and pedagogical creativity, their fragmented implementation reveals the absence of a coherent policy framework to sustain and scale such practices (Putri et al., 2025). This misalignment suggests that ESD remains positioned more as an instructional initiative than as a systemic educational commitment. Strengthening curriculum alignment therefore requires embedding ESD competencies explicitly within national learning outcomes, accompanied by consistent policy support, professional development mechanisms, and resource provision. Only through this structural coherence can ESD move beyond isolated classroom practices toward a transformative model that cultivates sustainability-oriented thinking across disciplines and educational levels (Vilmala et al., 2025).

Challenges in Implementing ESD in Science Education

The implementation of Education for Sustainable Development (ESD) in Indonesian science education faces several persistent challenges at both structural and pedagogical levels. One of the primary issues is the lack of explicit integration of ESD indicators within the national science curriculum. Although sustainability concepts are implicitly embedded in topics across physics, biology, and chemistry, they are not systematically structured to develop core ESD competencies such as systems thinking, critical reflection, and sustainability-oriented decision-making (Khoiri et al., 2023). In addition, ESD implementation remains highly dependent on

individual teacher initiatives. While many educators demonstrate innovation in integrating sustainability themes, the absence of consistent policy support and clear curriculum guidelines limits the scalability and sustainability of these practices. This results in fragmented implementation across schools and regions (Latifah et al., 2024).

The implementation of Education for Sustainable Development (ESD) in Indonesian science education faces several persistent challenges at both structural and pedagogical levels. One of the primary issues is the lack of explicit integration of ESD indicators within the national science curriculum. Although sustainability concepts are implicitly embedded across subjects such as physics, biology, and chemistry, they are not systematically structured to develop core ESD competencies such as systems thinking, critical reflection, and sustainability-oriented decision-making (Setiawan et al., 2023).

Indonesia has formally aligned with global ESD commitments, particularly through UNESCO's framework on Education for Sustainable Development and the ESD for 2030 Roadmap, which emphasizes the integration of sustainability competencies across all levels of education. These commitments are also connected to the broader agenda of the Sustainable Development Goals (SDGs), especially Goal 4.7 on quality education for sustainable development (Minh Khoa & Isabel Santos, 2025). At the national level, these global directions are reflected in policies such as Undang-Undang No. 20 Tahun 2003 tentang Sistem Pendidikan Nasional and the implementation of *Kurikulum Merdeka* under Permendikbudristek No. 12 Tahun 2024, including the P5 (Proyek Penguatan Profil Pelajar Pancasila), which incorporates sustainability-related themes. However, despite this alignment, ESD policy in Indonesia remains largely normative and programmatic. There is still a lack of specific regulatory instruments, technical guidelines, and measurable indicators that explicitly mandate the integration of ESD competencies within core science subjects (Novi et al., 2024).

Furthermore, the absence of operational standards and assessment frameworks linked to ESD limits the effective translation of policy into classroom practice. As a result, ESD implementation continues to rely heavily on individual teacher initiatives, leading to fragmented and inconsistent practices across schools and regions (Fitroni et al., 2025b). To address this gap, stronger policy coherence is needed by translating global ESD commitments into concrete national regulations, curriculum standards, and assessment systems. This includes embedding explicit ESD competencies into science subject frameworks and providing clear pedagogical and evaluative guidelines. Strengthening this policy–practice linkage is essential to ensure the scalability, consistency, and long-term sustainability of ESD implementation in Indonesian science education (Nurfadilah & Siswanto, 2020).

Another major challenge lies in limited teacher capacity and professional development opportunities. Many teachers face difficulties in translating ESD concepts into interdisciplinary and context-based learning activities, particularly in integrating approaches such as STEAM, project-based learning, and differentiated instruction (Jauhariyah et al., 2021). Furthermore, disparities in access to digital resources and technological infrastructure also hinder the effective implementation of ESD-based learning, especially in under-resourced schools. These constraints highlight the gap between the conceptual framework of ESD and its practical application in science classrooms (Ferguson et al., 2022).

Recommendations for Strengthening ESD Implementation

To address these challenges, several strategic recommendations can be proposed. First, it is essential to strengthen curriculum alignment by explicitly integrating ESD competencies and indicators into science learning outcomes across all educational levels, including physics, biology, and chemistry (Alberto et al., 2024). This will ensure a more systematic and consistent

implementation of sustainability-oriented education. Second, continuous and targeted professional development programs are needed to enhance teachers' capacity in implementing ESD. These programs should focus on practical pedagogical strategies, interdisciplinary learning design, and the integration of local sustainability issues into science instruction. Third, the development of contextualized and locally relevant teaching materials should be prioritized. Integrating local wisdom, environmental issues, and community-based projects can make ESD more meaningful and applicable to students' daily lives (Fitroni et al., 2025a).

Importantly, the success and sustainability of ESD implementation also depend on the development of students' competencies and skills. ESD should not only aim at knowledge acquisition but also at fostering key competencies such as critical thinking, systems thinking, problem-solving, collaboration, and action-oriented skills. These competencies enable students to actively engage with real-world sustainability challenges and to make informed and responsible decisions in their daily lives. By strengthening these skills, students can act as agents of change who contribute to sustainable practices within their communities and beyond. Additionally, improving access to digital technologies and learning media is crucial to support innovative and interactive ESD-based learning environments. Finally, stronger policy support and institutional commitment are required to ensure that ESD is not implemented as isolated classroom practices, but as a coherent and sustainable component of the national education system.

In practice, these competencies contribute directly to the strengthening of ESD implementation in schools. For example, through problem-based learning, students can investigate authentic environmental challenges such as waste management, energy use, or local ecological issues—and propose contextually relevant solutions, thereby linking classroom learning with community needs (Setiawan et al., 2023). Collaborative and project-based activities further support the co-construction of knowledge and foster shared responsibility for sustainability outcomes. Meanwhile, metacognitive practices, including reflection journals and self-assessment, enhance students' awareness of their learning processes and sustainability values, reinforcing deeper and more transformative learning experiences (Vioreza et al., 2023). Moreover, scientific literacy empowers students to engage with evidence-based reasoning, interpret environmental data, and make responsible decisions, which are essential for sustaining ESD practices beyond the classroom. When supported by digital technologies, these competencies can be expanded through access to real-time data, simulations, and interactive platforms, further enriching students' engagement with sustainability issues (Goller & Rieckmann, 2022).

By cultivating these competencies, students become key agents in sustaining and scaling ESD practices, contributing not only to improved learning outcomes but also to the creation of a sustainability-oriented school culture. This student-centered contribution is essential to ensure that ESD implementation is not limited to policy and curriculum design, but is continuously enacted and sustained through learners' knowledge, skills, and actions. Finally, stronger policy support and institutional commitment are required to ensure that ESD is not implemented as isolated classroom practices, but as a coherent and sustainable component of the national education system.

The development of students' competencies plays a central role in advancing quality education as outlined in Sustainable Development Goals (SDGs), particularly Goal 4 on inclusive and equitable quality education. Within the framework of Education for Sustainable Development (ESD), fostering students' skills such as metacognitive awareness, scientific literacy, critical and systems thinking, collaboration, and problem-solving—enables learners to move beyond passive knowledge acquisition toward active, meaningful engagement with real-world challenges. These competencies support students in understanding complex sustainability issues, making evidence-based decisions, and taking responsible actions in their communities. As such, students become not only recipients of education but also key contributors to the realization of quality education by promoting transformative learning processes, enhancing learning relevance, and sustaining the long-term impact of ESD practices. Consequently, strengthening these skills is essential for

achieving SDG 4, as it ensures that education equips learners with the knowledge, values, and capacities needed to support sustainable development in an increasingly complex and interconnected world.

CONCLUSION

This narrative review examined the implementation of Education for Sustainable Development (ESD) in Indonesian science education, focusing on pedagogical approaches, learning outcomes, and key challenges. The findings indicate that ESD is primarily implemented through innovative strategies such as Project-Based Learning, Problem-Based Learning, STEAM/STEM integration, differentiated instruction, and digital learning media. These approaches enhance students' critical thinking, creativity, environmental awareness, and sustainability competencies, particularly when linked to real-world contexts. However, ESD implementation remains fragmented and largely dependent on individual teacher initiatives due to limited curriculum alignment, the absence of explicit ESD indicators, and insufficient professional development. These findings highlight the need to strengthen curriculum integration and provide sustained teacher support to ensure consistent implementation. Looking forward, it is recommended that future educational practices emphasize the development of interdisciplinary, context-based, and sustainability-oriented learning frameworks supported by continuous teacher training and policy alignment. Overall, ESD has a significant impact on science learning by fostering environmentally responsible and future-ready learners. Strengthening institutional commitment and innovation in teaching practices will be essential to embed ESD more systematically within Indonesia's education system.

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