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Bridging Sustainability and Pedagogy: A Narrative Review of Education for Sustainable Development (ESD) Implementation in Indonesian Science Education

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Abstract

This narrative review explores the integration of Education for Sustainable Development (ESD) within Indonesian science education, focusing on elementary to upper secondary levels between 2020 and 2024. The study aims to analyze how ESD has been operationalized across science subjects—particularly in physics, biology, and interdisciplinary IPAS—through various instructional models. It further evaluates curriculum alignment, identifies implementation challenges, and highlights pedagogical innovations that support sustainable learning outcomes. Using a narrative synthesis approach, ten empirical studies were examined based on inclusion criteria emphasizing Indonesian science contexts, ESD orientation, and modular or project-based designs. Data were organized into six thematic categories: STEAM integration, differentiated instruction, project-based learning, ecoliteracy, digital media, and curriculum-policy gaps. Tabled analyses captured subject focus, instructional tools, ESD competencies addressed, and reported outcomes. The review finds that while teachers frequently initiate ESD-based practices through creative instructional strategies—such as ProBLES, PJBL, and ecoliteracy modules—systemic curriculum integration remains limited. Notably, the absence of formal ESD indicators in core topics like rotational dynamics constrains scalability. Nonetheless, significant cognitive and affective gains were observed, including increases in critical thinking, creativity, environmental care, and systems awareness. Community partnerships and digital media tools also show potential to amplify ESD awareness among young learners. These findings suggest a pressing need for structured curriculum reform and professional development to institutionalize ESD in science education. The review contributes a nuanced understanding of localized ESD practice and offers a roadmap for aligning policy, pedagogy, and sustainability competencies.

Keywords: Education for Sustainable Development; Indonesian science education; STEAM learning; differentiated instruction; curriculum reform; sustainability pedagogy; ecoliteracy

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INTRODUCTION

The convergence of educational reform and environmental sustainability has catalyzed global attention toward Education for Sustainable Development (ESD), particularly as a key enabler of the United Nations Sustainable Development Goals (SDGs). Among the seventeen SDGs, SDG 4 (Quality Education) and SDG 13 (Climate Action) specifically emphasize the transformative role of education in addressing ecological, social, and economic sustainability. Within this framework, ESD represents a pedagogical and philosophical approach that aims to equip learners with the knowledge, skills, values, and attitudes necessary to make informed decisions and act responsibly for environmental integrity, economic viability, and a just society (Handayani et al., 2024; Akanbi & Adesina, 2024).

Globally, ESD is increasingly embedded in educational policy, practice, and research, serving as both a curricular objective and a cross-cutting competency domain. The UNESCO Decade of Education for Sustainable Development (2005–2014) and its subsequent Global Action Programme laid the groundwork for integrating sustainability principles into formal education. In the Asia-Pacific region, this integration has taken on various forms, with countries exploring multi-disciplinary approaches such as STEM (Science, Technology, Engineering, and Mathematics) and its extension to STEAM (including the Arts) as vehicles for embedding sustainability into science education (Fathurohman et al., 2023; Nguyen et al., 2020).

In the Indonesian context, ESD has emerged as both a necessity and a challenge. As a country grappling with rapid urbanization, deforestation, biodiversity loss, and socio-economic disparities, Indonesia faces urgent imperatives to strengthen environmental education across all levels of schooling. This has led to a growing emphasis on embedding ESD within the Kurikulum Merdeka, a competency-based national curriculum designed to promote independent learning and holistic development through flexible, locally contextualized content. The curriculum aims to cultivate learners who exemplify the "Profil Pelajar Pancasila"—students who are creative, collaborative, environmentally aware, and committed to lifelong learning (Novi et al., 2024; Vioreza et al., 2023).

Despite its aspirations, however, the practical integration of ESD within Indonesian education remains uneven. Studies highlight persistent gaps in curriculum design, teacher preparedness, instructional strategies, and resource availability (Handayani et al., 2024; Sihombing et al., 2024). The incorporation of ESD within science subjects such as physics, biology, and chemistry—as well as interdisciplinary areas like Ilmu Pengetahuan Alam dan Sosial (IPAS)—is still at a developmental stage, with many educators relying on ad hoc or teacher-initiated practices rather than systemic mandates.

Several empirical investigations between 2020 and 2024 have revealed that while awareness of ESD among educators is increasing, its classroom implementation often lacks coherence, depth, and alignment with sustainability competencies (Sari et al., 2024; Farahiba et al., 2024). For instance, in high school biology modules, concepts such as environmental change and ecosystem resilience are commonly taught, yet seldom explicitly framed within an ESD-oriented paradigm. Likewise, in physics, topics like rotational dynamics or energy transformation hold potential for linking scientific knowledge to sustainable technologies (e.g., wind turbines) but are rarely utilized for this purpose (Rohmawati et al., 2021).

This shortfall is not solely attributable to curriculum gaps. Teachers often face systemic constraints, including insufficient training, limited access to validated ESD-based learning materials, and lack of institutional support (Nguyen et al., 2020; Vioreza et al., 2023). As noted by Murdiyana and Ayu et al. (2025), Indonesian students' performance in international assessments such as PISA also underscores the urgency of enhancing scientific and environmental literacy through more robust ESD integration.

To address these challenges, scholars and educators have begun exploring alternative pedagogical frameworks that are both content-rich and competency-driven. STEAM education, for example, integrates scientific reasoning with creativity, aesthetics, and social responsibility. According to Hsiao and Su (2021), STEAM-based instruction significantly improves student motivation, innovation, and engagement with sustainability issues. Similarly, Nurfadilah and Siswanto (2020) argue that the infusion of the arts into STEM disciplines promotes deeper cognitive processing and systems thinking, thereby enhancing learners' capacity to address complex environmental problems.

These claims are further corroborated by Akanbi and Adesina (2024), who found that STEAM-oriented education effectively supports SDG 4 by embedding critical thinking, collaboration, and ethical decision-making into classroom practices. In Indonesia, the intersection of STEAM and ESD is gaining traction, particularly in project-based learning

(PBL) models where students engage with real-world environmental problems through hands-on experimentation and community-oriented initiatives (Indahwati et al., 2023; Sihombing et al., 2024).

A related pedagogical advancement is the adoption of differentiated instruction, especially in vocational schools and heterogeneous classrooms. Differentiated instruction accommodates diverse learner profiles by varying content, process, and product based on students' readiness, interests, and learning preferences. In the context of ESD, differentiation enables the customization of sustainability topics to local community issues, such as waste management, food security, or renewable energy. This not only enhances student engagement but also fosters a sense of relevance and agency (Novi et al., 2024; Vioreza et al., 2023).

In addition to pedagogical approaches, emerging digital and electronic platforms are being utilized to disseminate ESD content and foster eco-literacy among younger learners. While such technologies have been adopted widely during the COVID-19 pandemic, their integration into sustainability education has yet to reach optimal levels. Teachers report limited familiarity with ESD frameworks and express the need for professional development to navigate digital tools effectively (Salam & Hamdu, 2022).

Furthermore, the literature underscores the need for robust teacher training and institutional policies that explicitly support the incorporation of ESD principles into everyday classroom practice. Policy frameworks must not only mandate ESD content but also provide the structural and financial support necessary for its execution. This includes curriculum guidelines, assessment rubrics, instructional resources, and teacher mentoring systems (Nguyen et al., 2020; Sari et al., 2024).

Given the breadth and complexity of these developments, this review aims to provide a systematic synthesis of ESD implementation in Indonesian science education between 2020 and 2024. Specifically, the review seeks to:

1. Map the diverse models and instructional strategies used to incorporate ESD within science and interdisciplinary subjects, including STEAM, IPAS, project-based learning, and differentiated instruction.
2. Analyze reported learning outcomes, both cognitive and affective, associated with ESD implementation in formal school settings.
3. Identify systemic gaps, opportunities, and challenges, particularly in relation to curriculum alignment, teacher readiness, and institutional support.

This review focuses on studies conducted in Indonesia, encompassing both national and localized case studies across educational levels ranging from elementary (SD) to senior high school (SMA/SMK). The primary subject areas under investigation include Physics, Biology, Chemistry, as well as interdisciplinary projects in Ilmu Pengetahuan Alam dan Sosial (IPAS). To ensure conceptual clarity and coherence throughout this review, several key terms are briefly defined.

Education for Sustainable Development (ESD) refers to a lifelong educational framework designed to empower learners with the knowledge, skills, values, and attitudes needed to contribute to sustainable societies. It integrates ecological, economic, and socio-cultural dimensions and promotes responsible citizenship and environmental stewardship. STEAM is an interdisciplinary instructional approach that combines Science, Technology, Engineering, Arts, and Mathematics to foster holistic learning and enhance students' creative and analytical competencies. The IPAS subject, or Ilmu Pengetahuan Alam dan Sosial, is a thematically integrated discipline introduced in Indonesian curricula to bridge scientific and social domains in a contextualized manner, encouraging students to connect classroom knowledge with real-world issues.

Differentiated Instruction is a pedagogical model that adapts teaching strategies, content, and assessments to accommodate the diverse needs, interests, and readiness levels of students. This approach is particularly relevant for ESD as it allows the customization of learning

experiences to align with local environmental and community contexts. Finally, Kurikulum Merdeka is Indonesia's recently implemented competency-based national curriculum that emphasizes student autonomy, flexibility in content delivery, and the cultivation of the "Profil Pelajar Pancasila"—students who embody the values of creativity, collaboration, and ecological responsibility.

Theoretical Framework/Background

Understanding ESD

Education for Sustainable Development (ESD) is a globally recognized educational framework aimed at empowering learners to make informed decisions and take responsible actions that support environmental integrity, economic viability, and social justice. The development of ESD as a conceptual and policy-driven movement can be traced to the United Nations Decade of Education for Sustainable Development (UNDESD), launched by UNESCO for the period 2005 to 2014. This initiative laid the groundwork for transforming educational systems worldwide to integrate sustainability principles into learning and teaching processes (McKeown & Down, 2022; Hidayati, 2021).

The evolution of ESD during the UNDESD marked a paradigm shift: from focusing primarily on awareness-raising to embracing interdisciplinary teaching, participatory learning, and competency-based approaches. This transformation recognized that sustainable development requires not only cognitive understanding but also emotional engagement and ethical commitment. Stanciu and Condrea (2023) underscore that ESD must facilitate learners' capacity to analyze complex systems, anticipate long-term consequences, and engage collaboratively with community and environmental challenges.

Various frameworks have emerged to delineate the competencies required for effective ESD implementation. One of the most influential is Wiek et al.'s framework, which identifies core sustainability competencies such as systems thinking, anticipatory skills, normative competency, strategic competency, and interpersonal skills (Chen et al., 2022). These are essential for empowering learners to address and resolve sustainability problems proactively. Complementing this, the UNECE (United Nations Economic Commission for Europe) framework adapts these competencies to regional contexts, emphasizing social and cultural specificity in the application of ESD (Nurhayati, 2022).

Each of these models, while varying in scope and emphasis, shares a common objective: to integrate ecological, economic, and socio-cultural dimensions into education. Barak and Avcı (2022) and Álvarez et al. (2024) note that these frameworks help ensure ESD content remains multidimensional, allowing learners to connect theoretical knowledge with real-world sustainable practices. Wynn and Jones (2020) further argue that a comparative approach reveals the complementary strengths of these frameworks—where Wiek emphasizes individual action, UNESCO and UNECE frameworks promote collective and institutional responsibility.

The importance of ESD was reaffirmed in UNESCO's seminal report, "Shaping the Future We Want" (2014), which emphasized the role of education in achieving the Sustainable Development Goals (SDGs) adopted in 2015. Rundgren and Yamada (2023) and Vilbar (2021) highlight how ESD's competencies align directly with SDG 4 (Quality Education) and SDG 13 (Climate Action), embedding ESD as both a goal and a method for achieving broader sustainability targets.

The increasing adoption of ESD principles in higher education institutions illustrates the widespread influence of UNESCO's framework. As noted by Keryan et al. (2020) and Brunold & Ohlmeier (2022), universities and teacher training programs have begun embedding ESD into their curricula, research, and community engagement missions. This institutionalization is crucial for reinforcing ESD from foundational to advanced levels of education, supporting lifelong learning and cross-sectoral sustainability leadership (Galleli et al., 2022; Yang et al., 2023; Marujo & Casais, 2021).

ESD in the Indonesian Curriculum

In the Indonesian context, the adoption of ESD principles has been articulated through successive curriculum reforms, most notably in the Kurikulum 2013 and its successor, the Kurikulum Merdeka. Both frameworks aim to promote a competency-based learning approach that emphasizes inquiry, critical thinking, and student autonomy—core principles of ESD (Sofiana et al., 2022; Susanti et al., 2023).

A central innovation in the Kurikulum Merdeka is the introduction of the Profil Pelajar Pancasila, a character-based learning profile designed to align educational objectives with Indonesia's cultural and ethical values. This profile fosters traits such as global citizenship, ecological awareness, and collaborative problem-solving—mirroring the competencies outlined in global ESD frameworks (Indriani & Marno, 2024; Rahmadhani et al., 2022).

Additionally, ESD integration occurs through interdisciplinary thematic projects such as Proyek IPAS (Ilmu Pengetahuan Alam dan Sosial), which combine natural and social sciences to tackle real-world issues. These projects are aligned with sustainability themes, thereby encouraging students to develop holistic perspectives and practice sustainability literacy in a contextualized setting.

A comparison with other Southeast Asian countries reveals both shared ambitions and unique national adaptations. Malaysia, for instance, integrates environmental education within its national science curriculum, aiming to foster ecological consciousness from an early age (Shah & Brett, 2021). Thailand emphasizes community-based practices, engaging students in hands-on sustainability initiatives (Terzano et al., 2022).

Nevertheless, implementation challenges persist. In Indonesia, limited teacher training, inadequate resources, and centralized curricular control hinder optimal adoption of ESD frameworks. Hoque et al. (2022) and Waton (2023) emphasize the need for continuous professional development and decentralization to empower educators as agents of sustainability transformation. Swalih et al. (2024) and Álvarez et al. (2024) argue that ongoing institutional support is essential to shift instructional strategies toward project- and inquiry-based learning embedded in ESD.

Indonesian regional studies affirm the positive impact of ESD-oriented reforms. Susanti et al. (2023) document increased student awareness and behavioral change as a result of participating in sustainability-driven classroom projects. These practices support the hypothesis that context-sensitive curriculum design and implementation can foster sustainable behavior among learners.

Models Supporting ESD Integration

Numerous pedagogical models have emerged to operationalize ESD in classroom practice. Among the most prominent are STEAM education, project-based learning (PBL), ProBLES, and differentiated instruction. Each of these approaches promotes active, learner-centered environments that support the development of sustainability competencies.

STEAM (Science, Technology, Engineering, Arts, and Mathematics) has proven particularly effective in enhancing students' creativity, problem-solving, and innovation skills in sustainability contexts. By integrating the arts into STEM disciplines, learners are encouraged to think holistically and empathetically about complex global issues. Hsiao and Su (2021) demonstrate that STEAM-based learning fosters intrinsic motivation and sustainability-oriented innovation. Similarly, Nurfadilah and Siswanto (2020) argue that STEAM cultivates deeper cognitive engagement with environmental challenges.

Project-Based Learning (PBL) allows students to engage with sustainability challenges through authentic, hands-on experiences. According to Ekselsa et al. (2023), ESD-linked PBL supports systems thinking by allowing students to visualize interconnections within natural and human systems. Ardiansyah et al. (2024) confirm that PBL enhances creative scientific literacy, especially in topics like optics and waves. Karimah and Wulandari (2023) further report that

STEAM-integrated PBL yields higher academic achievement and learner engagement compared to traditional methods.

ProBLES (Project-Based Learning Embedded with Sustainability) extends the benefits of PBL by anchoring learning directly in local sustainability issues. These models emphasize inquiry, collaboration, and civic responsibility. Through ProBLES, students not only develop academic understanding but also engage in community-based environmental action.

Differentiated Instruction is another essential strategy for ESD implementation, especially in diverse classrooms. It allows educators to tailor instruction to students' needs, interests, and learning profiles. Zulfarina et al. (2023) highlight that differentiated ESD modules increase student participation and content mastery. Wiek et al.'s sustainability competencies also align well with this model, as differentiation supports various learner entry points into complex issues (Chen et al., 2022).

Haim and Aschauer (2024) emphasize that innovative, real-world projects under the ESD framework help develop learners' creativity, ethical reasoning, and collaborative problem-solving. These features are essential for building the capacities needed to address sustainability in local and global contexts.

Table 1. Core ESD Dimensions and Their Educational Translations

ESD Dimension	Educational Manifestation	Relevant Learning Models	Indicators of Success	Example Studies
Ecological	Waste management, biodiversity projects	STEAM, PBL, ProBLES	Systems thinking, environmental ethics	Ekselsa et al., 2023; Haim & Aschauer, 2024
Economic	Circular economy simulations, local industry mapping	STEAM, IPAS, Differentiated	Innovation, responsible consumption	Karimah & Wulandari, 2023; Zulfarina et al., 2023
Socio-Cultural	Cultural heritage, community resilience projects	PBL, ProBLES	Empathy, civic responsibility	Rahmadhani et al., 2022; Susanti et al., 2023

Together, these models and frameworks form the backbone of pedagogical innovation for sustainability education in Indonesia and beyond. Their successful integration requires systemic curriculum alignment, continuous teacher development, and strong institutional commitment to the principles of ESD.

METHOD

Search Strategy

This narrative literature review employed a qualitative synthesis approach to explore the implementation of Education for Sustainable Development (ESD) in Indonesian science education. Data sources comprised academic peer-reviewed journal articles, validated student theses, and conference proceedings—all of which were provided as uploaded gray and published literature. The review was limited to documents that were explicitly contextualized within Indonesian formal education and addressed the integration of ESD within science-based or interdisciplinary learning frameworks.

To identify relevant literature, keyword-based string searches were conducted. Keywords and Boolean combinations were formulated using best practices in query optimization as recommended by Joo (2024), who emphasized the importance of precision and breadth in keyword design to enhance the relevance of interdisciplinary literature retrieval. The

following keyword groups were used: "Education for Sustainable Development", "ESD Indonesia", "STEAM and ESD", "Differentiated Learning", "IPAS Project", and "Eco-literacy". These search terms were applied manually across document metadata, titles, and content to facilitate inclusion.

Unlike systematic reviews that rely on rigid procedural frameworks such as PRISMA, this review adopted a narrative approach. It emphasizes interpretive synthesis and conceptual mapping over exhaustive enumeration, following the precedent of integrated review methods highlighted by Milošević et al. (2023) and interpretive appraisal strategies aligned with transformative learning evaluation (Janssens et al., 2022).

Inclusion and Exclusion Criteria

To ensure methodological consistency and contextual relevance, the criteria in Table 2 were applied. This filtering allowed for the selection of documents that directly engaged with the scope of this narrative review while excluding those that could potentially dilute the thematic relevance of the findings.

Table 2. Inclusion and Exclusion Criteria for Study Selection

Category	Criterion Description
Inclusion	Publications dated between 2020 and 2024 Empirical research studies, intervention validations, or case-based classroom practices Focus on formal educational settings (elementary to high school) Studies conducted in Indonesia, explicitly referencing ESD-related interventions or competencies
Exclusion	Theoretical or conceptual papers lacking empirical application Studies situated outside the Indonesian context Research limited to higher education unless directly relevant to K–12 pedagogy Non-formal educational models such as community outreach or NGO training programs

Screening and Selection Process

The screening process followed a two-stage manual filtering method, aligning with strategies observed in Milošević et al. (2023), where integrated review methods were adopted to ensure convergence across content types and document structures. Initially, titles and abstracts were reviewed for relevance to ESD themes and Indonesian school contexts. Documents were then subjected to full-text analysis to confirm inclusion.

A total of 10 documents were selected for final synthesis. These consisted of:

- 6 peer-reviewed journal articles,
- 2 validated conference papers,
- 2 academic theses deemed equivalent in rigor based on descriptive clarity, sample coherence, and intervention documentation.

Each document was coded and tabulated based on the following attributes: study design, educational level, subject domain, intervention model (e.g., STEAM, Differentiated Learning, PJBL), and ESD dimension addressed (ecological, economic, socio-cultural).

RESULTS AND DISCUSSION

ESD–STEAM Integration in Science Learning

The integration of Education for Sustainable Development (ESD) with Science, Technology, Engineering, Arts, and Mathematics (STEAM) frameworks has emerged as a transformative pedagogical strategy in science education. This sub-section critically reviews how STEAM-based instruction supports ESD objectives by enhancing students' competencies in problem-solving, creativity, and systems thinking. Drawing upon three empirical studies

(Table 3), we examine how STEAM-oriented approaches contribute to sustainability learning through contextualized, project-based science education.

STEAM education, when paired with project-based learning (PBL), promotes interdisciplinary problem-solving by allowing students to address complex environmental issues through real-world applications. According to Miao et al. (2022), STEAM-PBL serves as an effective medium for environmental education, offering hands-on experiences that connect learners with sustainability challenges in their communities. Such engagement encourages transformative learning, in which students reflect on their actions and experiences to develop sustainable habits and worldviews (Koirala, 2023).

The implementation of ESD-STEAM strategies in Indonesian schools reflects this transformative learning approach. Widarti and Roshayanti (2021) investigated a STEAM-infused lesson on fluid dynamics in a Madrasah Aliyah (upper secondary school) context. Students designed water flow models using recycled materials, thereby linking abstract physics principles to local environmental problems such as water waste and sanitation. As shown in Table 3, 52% of participating teachers were already implementing STEAM elements, and students exhibited significant gains in creative problem-solving.

This project exemplifies the integration of ecological and economic dimensions of ESD, demonstrating how STEAM-based tasks enable students to consider the resource implications of scientific phenomena. The activity also reinforced key sustainability values such as resource conservation and innovation. The findings resonate with LeSage-Clements et al. (2024), who emphasize the importance of using real-life materials to support ecological literacy and scientific inquiry.

In a vocational high school (SMK), Riyanto et al. (2024) 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. According to their findings (Table 3), 68% of teachers reported integrating STEAM, and 97% of students demonstrated improved conceptual mastery. Importantly, 91% 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. 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 third study by Rohmawati and Roshayanti (2021) addressed the application of STEAM in the topic of rotational dynamics (*Dinamika Rotasi*) at the upper secondary level. While the national curriculum did not explicitly include ESD competencies in this topic, the researchers introduced prototype STEAM tasks using rotation toys and low-cost sensors to explore torque, angular momentum, and real-world applications such as wind turbines. The ESD dimensions highlighted included socio-cultural and economic aspects. As shown in Table 3, ESD indicators surfaced in only 33% of the activities, pointing to gaps in systemic integration yet illustrating the feasibility of embedding ESD through creative instructional design.

This finding supports theoretical insights from Wiek et al. (Chen et al., 2022) and the UNECE framework (Nurhayati, 2022), which argue that developing sustainability competencies requires deliberate instructional planning that aligns content with ESD goals. The low percentage of ESD indicators detected indicates that while the STEAM platform is promising, its success depends on the educator's ability to contextualize scientific knowledge within sustainability challenges.

Notably, all three case studies emphasize the ecological and economic aspects of ESD, with fewer direct applications of the socio-cultural domain. This suggests an opportunity for future curriculum design to more deliberately integrate cultural values, community knowledge, and indigenous practices—components central to a holistic interpretation of ESD (Stanciu & Condrea, 2023; Susanti et al., 2023).

The role of teachers in facilitating these STEAM-based ESD projects is crucial. As noted in studies by Bastian et al. (2023) and Koirala & Neupane (2023), teacher preparedness and professional development determine how effectively ESD principles are integrated into STEAM frameworks. In all three reviewed cases, success was linked to educators' initiative and familiarity with ESD, rather than structural curricular mandates. This aligns with the findings of Efiariza et al. (2021), who underscore that effective facilitation enhances student engagement and fosters sustainable thinking.

Table 3 provides a synthesis of these empirical studies, capturing the variation in STEAM component usage, ESD dimension integration, and student outcomes. It illustrates the potential of STEAM education to contextualize science learning in sustainability-oriented frameworks while revealing areas for pedagogical enhancement.

Table 3. ESD–STEAM Integration in Science Learning

Study (Author & Year)	Topic & School Level	STEAM Component(s) Emphasised	ESD Dimension(s) Addressed	Key Learning Outcomes
Widarti & Roshayanti (2021)	Fluida – MA (upper secondary)	S, T, E, A, M via project design using recycled materials	Ecology & Economy	52% teachers already implement STEAM; activities link fluid laws to water management; ↑ student problem-solving & creativity
Riyanto et al. (2024)	"Zat & Perubahannya" – SMK (vocational)	Full STEAM sequence in substance change experiments	All three (Eco, Socio, Econ)	68% teachers implement; 97% note better concept mastery; 91% report ↑ creativity
Rohmawati & Roshayanti (2021)	Dinamika Rotasi – MAN (upper secondary)	Prototype STEAM tasks (rotation toys, low-cost sensors)	Socio-cultural & Economy	ESD indicators surfaced only 33%; highlights curriculum gap but shows feasibility of STEAM infusion

The data in Table 3 reinforce broader insights from international literature. Miao et al. (2022) emphasize that student-centered, interdisciplinary learning cultivates long-term pro-environmental behaviors. Šorytė & Pakalniškienė (2021) and Rizaq et al. (2025) found that working with recycled materials enhances ecological responsibility, while Zhan et al. (2022) connect these practices to creativity and systems thinking.

In terms of theoretical alignment, these findings clearly resonate with the sustainability competencies described, particularly systems thinking, anticipatory competency, and normative values (Chen et al., 2022). Furthermore, they demonstrate how models like STEAM can actualize these competencies when supported by appropriate instructional design and professional development.

Differentiated and Modular ESD-Based Instruction for Diverse Learners

The integration of Education for Sustainable Development (ESD) through differentiated instruction and modular learning has gained momentum as an inclusive pedagogical strategy for engaging diverse student populations in science education. This section reviews two empirical studies (Table 4) that illustrate how differentiated instructional models and validated learning modules contribute to cognitive and affective gains among Indonesian high school learners, especially in the context of environmental and sustainability education.

Differentiated instruction refers to tailoring teaching practices based on learners' readiness, interests, and learning profiles. Within the framework of ESD, such strategies enable educators to provide meaningful and personalized experiences that promote the acquisition of sustainability competencies. Kusumaningrum et al. (2022) and Latifah et al. (2023) provide evidence that modular and differentiated approaches help students engage with real-world environmental issues while advancing their scientific understanding and civic responsibility (Table 4).

The study by Kusumaningrum et al. (2022) focused on the development and validation of a biology module designed around environmental change. The module was aligned with the six cognitive levels of Bloom's taxonomy (C1–C6) and embedded with all 15 core ESD indicators, including critical thinking, ethical decision-making, and systems thinking. Conducted at the senior high school level (SMA), the study found that the module achieved an 85.6% validity rating from subject matter experts and a 93% rating from practitioner assessments. These metrics affirm the module's pedagogical soundness and its potential to enhance higher-order thinking—a critical goal in ESD-oriented science education.

This research aligns with theoretical frameworks discussed, particularly Wiek et al.'s sustainability competencies and the UNECE's regional application models. By structuring the module around real-world environmental scenarios and using differentiated tasks across cognitive levels, the instructional design allowed students to explore complex sustainability topics in an accessible and structured format (Chen et al., 2022; Nurhayati, 2022).

Similarly, Latifah et al. (2023) employed differentiated instruction strategies in an interdisciplinary IPAS class at the vocational high school level (SMK). Differentiation was implemented along two axes: readiness and interest. Students were grouped accordingly and engaged in project-based learning activities focused on transforming waste materials into usable resources—a theme with both ecological and economic dimensions. The results indicated that 88% of teachers believed the differentiated ESD model increased student engagement, while 96% of students reported actively reusing waste in their projects (Table 4).

These findings resonate with broader literature emphasizing the benefits of differentiated learning environments in mixed-ability classrooms. Liou et al. (2023) and Bernardo et al. (2023) note that differentiated instruction supports engagement and comprehension by recognizing students' diverse strengths and learning preferences. Moreover, integrating ESD into this model enhances its relevance by framing science instruction around real-world, community-based challenges, thus fostering both academic growth and environmental literacy.

In terms of pedagogical design, both studies exemplify the role of modular resources and tailored instruction in promoting student-centered learning. Lunar et al. (2023) and Sepian et al. (2023) argue that adaptive resources—such as student worksheets (LKPD) and differentiated assignments—support deeper understanding and sustained interest in science. These tools also facilitate inclusive participation, allowing students with varying competencies to contribute meaningfully to sustainability-themed tasks.

Project-based learning (PBL), as employed in the Latifah et al. study, plays a pivotal role in contextualizing sustainability education. According to Suprianti et al. (2021) and Pratiwi (2021), PBL enables students to apply scientific knowledge to real-life issues, such as waste

management or energy conservation. This bridges the gap between theoretical content and practical implementation, fostering critical thinking, creativity, and collaboration—core competencies outlined in both the Wiek and UNECE frameworks.

The incorporation of ESD indicators into differentiated instruction requires effective formative assessment mechanisms. Laili et al. (2023) and Kamila et al. (2023) emphasize the importance of using diagnostic and ongoing assessments to evaluate the success of such pedagogical interventions. By tracking student responses to various tasks and groupings, teachers can adjust instruction to maximize conceptual understanding and sustainability awareness.

Furthermore, teacher preparedness and professional development are instrumental in the success of differentiated ESD instruction. Hayes et al. (2024) note that teacher self-efficacy is significantly enhanced when educators receive structured training on differentiation strategies and sustainability integration. In both reviewed studies, the successful implementation of differentiated ESD learning was largely dependent on teacher initiative and understanding of student learning profiles. This underscores the importance of institutional support for ongoing educator development.

From a curriculum policy perspective, the outcomes of these studies provide compelling evidence for embedding differentiated ESD strategies into national curriculum frameworks such as Kurikulum Merdeka. As discussed in the Theoretical Framework Section, the curriculum's emphasis on student autonomy, contextual learning, and interdisciplinary exploration is well-aligned with the goals of differentiated ESD instruction (Sofiana et al., 2022; Susanti et al., 2023).

Table 4. Modular & Differentiated ESD Implementation

Study	Module / Differentiation Method	Level	ESD Indicators Integrated	Reported Cognitive / Affective Gains
Kusumaningrum et al. (2022)	Validated Biology module (C1–C6 tasks on environmental change)	SMA	Full ESD matrix (15 indicators)	Module rated 85.6% valid (experts) & 93% (practitioners); projected to ↑ higher-order cognition
Latifah et al. (2023)	Differentiated IPAS learning (readiness & interest clusters)	SMK	Waste-to-resource projects (Eco/Econ)	88% teachers feel DI-ESD boosts engagement; 96% students reuse waste in projects

The data from Table 4 illustrate the utility of differentiated and modular strategies in achieving both cognitive and behavioral learning objectives within ESD contexts. The integration of full ESD indicators in validated modules and their adaptation to real-world environmental tasks illustrates a robust model of instructional design that is both inclusive and competency-driven.

Project-Based and Contextual Learning to Foster ESD Awareness

Project-Based Learning (PBL) has been widely recognized as an innovative instructional strategy that connects scientific inquiry with real-world issues, particularly in fostering students' awareness and competencies in Education for Sustainable Development (ESD). In the Indonesian context, the alignment between project-based approaches and the Kurikulum Merdeka framework positions PBL as a promising vehicle to actualize sustainability learning through contextual, student-centered experiences. As demonstrated by Table 5, the use of PBL, ProBLES (Project-Based Learning Embedded with Sustainability),

and differentiated IPAS projects has effectively promoted environmental awareness, creativity, and critical thinking.

The study by Meilani et al. (2023) implemented PJBL and ProBLES models in teaching plant tissue culture in senior high school biology classes. The projects emphasized food security as a sustainability theme, with students engaging in propagation experiments and producing informative posters on cultivation methods. The integration of ecological and economic dimensions enabled students to understand how scientific techniques intersect with sustainable food systems. The project demonstrated enhanced student creativity and critical thinking, consistent with findings by Haswan et al. (2024), who emphasized the role of PBL in environmental knowledge courses.

This is further reinforced by the theoretical perspectives discussed, where Bolstad et al. (2021) and Konrad et al. (2021) underline the immersive and transformative nature of PBL. The ability of PBL to integrate systems thinking, practical application, and collaboration makes it particularly effective for ESD instruction. Students who internalize sustainability principles through experiential learning are more likely to demonstrate long-term behavioral change.

Rohmawati et al. (2023) adapted a ProBLES-based LKPD (student worksheet) set for rotational dynamics—a topic in physics often considered abstract. By contextualizing the topic through local craft practices (e.g., traditional spinning toys), the lesson incorporated socio-cultural and sustainability perspectives. The intervention achieved a medium N-Gain score of 0.46 in students' creative thinking development, indicating measurable improvement. This approach mirrors the emphasis by Rambe et al. (2022) on the value of integrating historical and cultural contexts into sustainability education.

Furthermore, the integration of community and local relevance in science instruction resonates with Lavicza et al. (2022), who stress the need for pedagogies that bridge formal knowledge and lived experience. In this case, using indigenous materials and cultural motifs allowed students to explore the relevance of physics concepts in daily life, thus elevating the socio-cultural dimension of ESD—one often underrepresented in traditional curricula.

In the interdisciplinary IPAS context, Latifah et al. (2023) employed differentiated project-based learning focused on the 3R (reduce, reuse, recycle) framework and pollution mitigation. Conducted at the vocational high school level, the project required students to repurpose local waste into functional products. According to the study, 85% of teachers adopted local materials in their instruction, and 88% of students affirmed that the projects fostered a caring attitude toward the environment. This supports Piippo and Pongrácz (2020), who argue that waste management integration in rural education enhances sustainability literacy.

Moreover, the pedagogy aligns with the circular economy model, as emphasized in the literature by Shooshtarian et al. (2023) and Owusu-Nimo et al. (2023). Waste-to-resource projects not only reduce environmental impact but also function as learning tools that help students understand material cycles, conservation, and innovation. Such approaches directly support the development of systems thinking and strategic competencies identified in ESD frameworks like those of Wiek et al. (Chen et al., 2022).

Riyanto et al. (2024) provide additional insights into how STEAM and PBL integration can support ESD. Their study in chemistry classes involved students in creating mini factory simulations using low-cost, recycled materials. These simulations modeled the workings of a circular economy and addressed sustainability themes related to industry and resource use. The project was found to instill future orientation among 74% of teachers and significantly boosted creativity scores.

This reinforces Miao et al.'s (2022) conclusion that STEAM-PBL enhances technical learning while fostering awareness of environmental issues. It also underscores the interdisciplinary nature of sustainability education, requiring learners to navigate both scientific and socio-economic domains. As Wuni (2022) cautioned, successful circular

economy education requires context-sensitive pedagogy—an element effectively demonstrated in Riyanto et al.'s approach.

Table 5. Project-Based & Contextual ESD Approaches

Study	Project Type / Model	Subject Area	ESD Dimension Highlight	Skill / Value Outcomes
Meilani et al. (2023)	PJBL & ProBLES on plant tissue culture	Biology	Food security (Eco, Econ)	Students devise propagation posters; ↑ critical & creative thinking
Rohmawati et al. (2023)	ProBLES LKPD set	Physics – Rotational dynamics	Sustainability context via local crafts (Socio)	N-Gain 0.46 (medium) in creative thinking skills
Latifah et al. (2023)	IPAS Differentiated projects	Chemistry / IPAS	3R & pollution mitigation (Eco)	85% teachers use local waste; 88% say ESD fosters attitudes of care
Riyanto et al. (2024)	STEAM PBL mini factories	Chemistry	Circular economy focus	74% teachers: projects instil future orientation; ↑ creativity scores

The reviewed studies clearly demonstrate that PBL and contextual learning strategies play a vital role in fostering ESD competencies. Across diverse subjects—biology, physics, and chemistry—PBL has been shown to increase student engagement, creativity, and sustainability awareness. These findings align with theoretical assertions from Section 3, particularly regarding the importance of authentic, community-based learning in developing sustainability competencies (Álvarez et al., 2024; Nurhayati, 2022).

One significant implication is that curriculum planners should institutionalize project-based ESD instruction by embedding it into national policy and assessment standards. The Kurikulum Merdeka already provides a flexible structure conducive to such innovations, but clearer guidance on integrating sustainability themes in science topics is necessary. Furthermore, teacher capacity-building is essential. While the reviewed studies showcase successful implementations, they were often driven by individual initiative rather than systemic support. Professional development programs that emphasize contextual design, interdisciplinary collaboration, and sustainability pedagogy would help scale such models across schools.

Another implication is the need for structured partnerships between schools and local communities. Projects grounded in local environmental challenges and socio-cultural practices yield richer educational outcomes and foster civic responsibility. As Adewuyi (2020) and Lavicza et al. (2022) argue, community-linked projects are more likely to leave a lasting impact on students' values and behavior.

Ecoliteracy-Based Learning and Community-Oriented Sustainability

Ecoliteracy, a fundamental component of Education for Sustainable Development (ESD), emphasizes learners' capacity to understand ecological principles, develop sustainable values, and act responsibly in their environments. In the context of Indonesian education, especially in primary and secondary schools, ecoliteracy initiatives have been increasingly implemented through community-based programs and interdisciplinary classroom practices. This section examines two key studies (Table 6) that illustrate how ecoliteracy-driven strategies foster long-term behavioral change and instill sustainability awareness among students.

The study by Setyaningrum and Gunansyah (2020) documents the implementation of the Surabaya Eco School program in elementary schools (SD) across Surabaya. This initiative integrates 3R principles (reduce, reuse, recycle), school-wide waste audits, and green-flag incentives into school culture. The program is co-supported by teachers, city government, and the environmental NGO Tunas Hijau. Survey data from 63 teachers indicated that overall program implementation was rated "cukup baik" (fairly good), with observable improvements in student awareness and school environmental cleanliness.

This aligns with Zain et al. (2022) and Anisa et al. (2023), who emphasize the role of 3R initiatives in shaping students' environmental attitudes and behavior. Through repeated exposure to environmental practices and value-based reinforcement, students internalize eco-friendly habits that transcend the classroom. Moreover, Rahayu and Setiana (2024) highlight that such programs have ripple effects, influencing students' behavior in their home environments and communities. The Surabaya case exemplifies this model, showcasing a symbiosis between structured environmental programs and broader civic participation.

From a theoretical standpoint, the program also reflects principles discussed. Ecoliteracy as embedded in the Profil Pelajar Pancasila framework, prioritizes character development through experiential learning, civic engagement, and environmental ethics. As noted by Gurbuzoglu-Yalmanci and Aydin-Beytur (2023), integrating ecoliteracy early in education cultivates an appreciation of life systems and instills a sense of responsibility toward ecological stewardship. Alqallaf et al., cited in Aswita et al. (2022), further demonstrate that early environmental education is positively correlated with pro-environmental behaviors in adulthood.

Equally significant is the role of community partnerships in sustaining these outcomes. Nurlila and Fua (2022) and Banchonhattakit et al. (2022) argue that collaboration with local stakeholders enhances the reach and depth of sustainability programs. The involvement of NGOs, municipal leaders, and teachers in the Surabaya program provided students with role models and reinforced the application of ecoliteracy outside of academic settings. Such partnerships also create opportunities for students to engage in hands-on environmental projects like urban gardening, biodiversity audits, and clean-up drives—enhancing their agency and commitment.

The second study, conducted by Meilani et al. (2023), involved senior high school (SMA) students in Semarang in a project-based learning (PBL) unit that integrated life-long learning principles and culture-oriented biotechnology. In this context, students were guided by teachers to explore sustainable agriculture techniques rooted in local traditions and to connect biotechnological tools to real-world problems such as food insecurity. The project sparked several student-led proposals focused on food resilience and ethical biotechnology, highlighting critical and creative thinking gains.

This example echoes Kim (2024) and Nayle et al. (2024), who advocate for merging sustainability goals with scientific competencies through biotechnology. The pedagogical model in Meilani's study mirrors the holistic ESD integration recommended by Rahmawati et al. (2022), where ethics, science, and social responsibility converge. Students are not merely passive recipients of knowledge but active participants who question, create, and advocate for sustainable futures.

Moreover, this approach reflects the "lifelong learning" dimension in ESD, which is central to the UNESCO framework discussed in Section 3.1. Meilani's findings demonstrate that ecoliteracy is not confined to ecological facts but expands to include ethical reasoning and civic action. As students conceptualize biotechnology not only as a science but also as a tool for sustainable development, they embody the systems-thinking and normative competencies described by Chen et al. (2022). Table 6 synthesizes the findings from these two studies, providing a comparative lens to evaluate their contributions to ESD outcomes.

Table 6. Ecoliteracy-Oriented Practices

Study	Level & Region	Ecoliteracy Strategy	Stakeholder Roles	Outcomes / Impact
Setyaningrum & Gunansyah (2020)	SD – Surabaya	Surabaya Eco School: 3R, waste audits, green flags	Teachers, city govt., NGO Tunas Hijau	Overall practice rated "cukup baik"; 63 teachers surveyed
Meilani et al. (2023)	SMA – Semarang	Life-long learning + culture-oriented biotech	Teachers guide PJBL; students link biotech to food resilience	Sparks student proposals on sustainable agriculture

Ecoliteracy-based learning anchored in community-oriented sustainability offers a powerful model for embedding ESD into school culture. Through early intervention, community collaboration, and interdisciplinary innovation, such initiatives cultivate environmentally literate citizens equipped to navigate and solve complex sustainability challenges. These findings affirm the central role of ecoliteracy in the broader landscape of transformative education for sustainable development.

Digital and Electronic Media for ESD in Elementary Education

The integration of digital and electronic learning tools into Education for Sustainable Development (ESD) is gradually becoming a critical component of elementary education in Indonesia. While the conceptual foundation for using technology to support ESD is robust, implementation at the classroom level remains limited, particularly in terms of teacher preparedness and depth of integration. This section explores the intersection of digital education tools and systems thinking within the ESD framework, with a focus on elementary-level applications and outcomes (see Table 7).

Salam and Hamdu (2022) provide a case study involving the use of digital e-learning modules for Grade 5 students in Indonesian elementary schools. Their research incorporated videos, quiz applications, and multimedia-based tasks to introduce sustainability-related science topics, targeting the development of systems thinking. While students exhibited familiarity with the digital tools—especially as remote learning became common during the COVID-19 pandemic—the integration of ESD content within the modules was limited. Most teachers were unfamiliar with the core competencies of ESD and had not received training specific to sustainability pedagogy. Nevertheless, the study reported that teachers demonstrated a strong willingness to learn and implement ESD more fully if provided with adequate support and resources.

This outcome aligns with the broader literature emphasizing the necessity of teacher digital competency for successful ESD integration. Prabawani et al. (2022) argue that teachers' digital skillsets must go beyond technical proficiency and encompass pedagogical fluency in using digital platforms to promote sustainability values. Interactive learning formats, such as gamified mobile applications, can effectively engage students in systems thinking and environmental stewardship when implemented with appropriate pedagogical frameworks.

Despite the promise of these tools, research indicates that systemic barriers still hinder effective adoption. Alnasib (2023) and Lamanauskas and Malinauskienė (2024) report that the primary challenges include a lack of formal training on ESD concepts, limited curriculum resources, and inconsistent institutional support. These constraints mirror the findings in Salam and Hamdu (2022), where the absence of structured ESD content within digital modules limited their transformative potential.

From a theoretical perspective, this situation underscores the gap between ESD policy aspirations and practical classroom realities. The Kurikulum Merdeka encourages independent, contextual, and digitally enhanced learning; however, without targeted capacity-building initiatives, the practical realization of these objectives remains elusive. As Goller and Rieckmann (2022) note, a shift toward transformative pedagogy requires coherent alignment across policy, teacher training, and classroom tools.

Teacher attitudes also play a central role in ESD technology adoption. Lamanauskas and Malinauskienė (2024) emphasize that positive educator beliefs about sustainability significantly enhance the likelihood of ESD implementation. Conversely, apprehension about digital teaching methods may reduce the frequency and quality of ESD integration. Peng et al. (2023) and Shakir et al. (2024) highlight that improving teachers' self-efficacy through targeted training in digital pedagogy and sustainability content leads to better outcomes in both teaching practice and student engagement.

The pedagogical value of e-learning for ESD lies in its ability to facilitate interactive, interdisciplinary, and student-centered learning environments. For example, gamified applications and blended learning platforms allow students to simulate environmental decision-making, experiment with scenarios, and reflect on sustainability consequences. Hanisch and Eirdosh (2023) found that game-based environmental education platforms significantly increased elementary students' ability to apply systems thinking and problem-solving strategies to real-world environmental issues.

However, the effectiveness of these tools is contingent on teachers' abilities to design or adapt content that explicitly targets ESD competencies. Zenasni et al. (2024) emphasize that transformative learning in ESD must integrate cognitive, affective, and psychomotor domains. This requires educators to move beyond basic digital literacy and adopt instructional strategies that foster reflective and experiential learning—skills not typically included in standard teacher education programs.

Blended learning models—combining digital and face-to-face instruction—have emerged as a promising avenue for advancing ESD in primary education. These models allow for flexible delivery of content while maintaining opportunities for collaborative exploration and inquiry-based learning. Uhrqvist et al. (2021) argue that blended models are particularly well-suited to ESD because they promote both student autonomy and collective responsibility.

Table 7. Digital / Electronic Media for ESD Delivery

Study	Digital Tool / Platform	ESD Competency Targeted	Teacher / Student Familiarity	Impact / Limitation
Salam & Hamdu (2022)	E-learning modules (video, quiz apps) in Grade 5 SD	Systems thinking	Teachers unfamiliar with ESD; students accustomed to online learning	Teachers keen to learn ESD; limited explicit integration so far

Table 7 illustrates the gap between student readiness and teacher capability in delivering digital ESD content. While students are generally accustomed to interactive and visual platforms, the effective integration of sustainability principles into such media remains sporadic. As a result, ESD outcomes—particularly in systems thinking and ethical reasoning—are inconsistently achieved.

While the use of digital and electronic media in elementary-level ESD instruction remains in its early stages, it holds significant potential. Addressing current gaps in teacher training, curricular alignment, and content design can transform these tools into powerful assets for cultivating sustainability awareness and systems thinking among young learners. Realizing this potential will require coordinated efforts across education policy, technology development,

and professional practice—ensuring that digital innovation supports rather than hinders the goals of transformative sustainability education.

Curriculum Gaps and Policy Discontinuity in ESD Implementation

Despite increasing attention to Education for Sustainable Development (ESD) within classroom practices, its institutionalization at the curriculum level remains inconsistent and often fragmented. In the Indonesian context, as shown in Table 8, while many teachers initiate sustainability-themed learning activities, systemic adoption is hindered by the absence of formal ESD frameworks in national syllabi, particularly in core science subjects such as physics and biology. This section discusses these gaps through empirical case analyses and literature alignment, exploring how teacher-led innovation compensates for policy discontinuity while advocating for broader curriculum reform.

A notable example of curriculum misalignment is seen in the topic of rotational dynamics (*Dinamika Rotasi*) in physics education. While national guidelines address standard concepts like torque, inertia, and angular momentum, they omit opportunities to contextualize these principles in sustainability issues. As shown in Table 8, ESD-related entry points such as wind turbine design, renewable energy systems, or circular motion in ecological mechanisms are absent. In response, educators have independently developed ProBLES worksheets and STEAM-based tasks to introduce sustainability connections. These grassroots innovations reflect what Anamezie and Gumbo (2023) describe as "teacher-led pedagogical resistance"—where educators bridge curricular shortcomings by embedding ESD into science instruction through hands-on, contextually grounded activities.

This finding aligns with Jauhariyah et al. (2021) and Badi'ah et al. (2024), who argue that integrating ESD into the physics curriculum enhances both conceptual understanding and relevance to global challenges. The omission of ESD indicators from national syllabi creates systemic blind spots, reinforcing the urgent call for curricular integration to promote interdisciplinary and socially responsible learning. Furthermore, Sund and Gericke (2020) emphasize that empowered teachers are more likely to localize sustainability content effectively, even in the absence of top-down policy mandates.

In biology, similar curricular gaps are evident in modules related to environmental change. Current textbooks and lesson plans often restrict content to ecological definitions and pollution types, failing to activate broader ESD competencies such as systems thinking, critical inquiry, or SDG alignment. As shown in Table 8, validated biology modules designed by educators incorporate all 15 core ESD indicators, embedding these into C1–C6 level tasks based on Bloom's taxonomy. These teacher-driven efforts demonstrate the feasibility of integrating sustainability competencies into existing subjects without overhauling structural frameworks.

These findings resonate with studies by Martínez et al. (2021) and Wijayanti et al. (2021), who highlight the lack of interdisciplinary coherence in STEM curricula. Current materials rarely link scientific phenomena to societal challenges, weakening student engagement and underutilizing science education as a lever for sustainable thinking. Theoretical frameworks in Section 3.3 emphasize that curriculum reform should go beyond content delivery and embed ESD through inquiry-based, problem-solving approaches that bridge knowledge with practice.

Table 8. Curriculum–ESD Alignment & Gaps

Subject / Topic	Current Curriculum Coverage	Potential ESD Entry Point	Observed Gap	Teacher Initiated Innovation
Physics – Dinamika Rotasi	Standard kinematics, torque, inertia	Connect rotation to sustainable	ESD absent in national syllabus	ProBLES worksheet &

Subject / Topic	Current Curriculum Coverage	Potential ESD Entry Point	Observed Gap	Teacher Initiated Innovation
		tech (e.g., wind turbine toys)		STEAM tasks designed locally
Biology – Environmental Change Module	Basic ecology & pollution	Embed 4C skills via ESD scenarios (SDGs linkage)	No mandated ESD indicators	Validated ESD-based module integrates full 15 indicators

A key insight emerging from this analysis is that educators are not passive recipients of policy; they are active agents shaping pedagogical transformation. Rundgren and Yamada (2023) assert that when teachers are trusted and supported to exercise curriculum agency, ESD becomes more embedded, impactful, and culturally relevant. This bottom-up innovation, however, must be matched with top-down alignment in curriculum policy to ensure scalability and sustainability.

Textbook reform is another critical axis of systemic transformation. Jauhariyah et al. (2021) critique current science textbooks for their lack of real-world linkage and interdisciplinary integration. Without connecting physics concepts to pressing global issues such as climate change, energy transition, or circular economy, the curriculum remains disconnected from students' lived realities. Martínez et al. (2021) suggest that revising syllabi to reflect evolving societal and environmental challenges will help schools operationalize ESD in a coherent and unified manner.

In addition, the pedagogical shift towards ESD requires ongoing professional development. Lüdtke et al. (2024) emphasize that teachers must be equipped not only with sustainability content but also with strategies to integrate it across diverse contexts and disciplines. While the examples in Table 8 show innovative adaptations, not all educators possess the same capacity or resources to do so. Comprehensive ESD training programs—coupled with institutional support—can amplify these efforts and ensure consistency across schools and regions.

Research also suggests that embedding ESD within core subjects such as physics can be most effective when approached through interdisciplinary lenses. Connecting rotational dynamics to energy systems, for example, illustrates how theoretical concepts underpin sustainable technologies. This reflects what Jauhariyah et al. (2021) and Wijayanti et al. (2021) describe as "curricular relevancy"—the practice of aligning classroom knowledge with societal needs and ecological imperatives. When students see how physics or biology contribute to sustainable development, they are more likely to engage with these subjects critically and ethically.

Beyond classroom instruction, systemic support mechanisms are necessary to reduce the burden on individual teachers. Sund and Gericke (2020) highlight that lack of administrative support, limited resources, and minimal curriculum guidance often discourage sustainability-focused innovation. In contrast, Melillán et al. (2023) show that collaborative teacher networks foster knowledge exchange and co-creation of context-specific ESD tools, improving instructional quality and teacher morale.

CONCLUSION

This narrative review has synthesized the current landscape of Education for Sustainable Development (ESD) implementation within Indonesian science education across multiple educational levels, subjects, and instructional models. Drawing on ten empirical studies conducted between 2020 and 2024, the review has revealed a growing yet uneven

integration of ESD into classroom practices, characterized by significant teacher-led innovation amidst gaps in curricular policy and systemic support.

Key findings demonstrate that the most robust ESD integration occurs through STEAM-based project learning, differentiated instruction, ecoliteracy initiatives, and contextualized science modules. These strategies effectively foster students' sustainability competencies, including critical thinking, creativity, systems thinking, and environmental responsibility. However, ESD remains largely absent from formal curricular frameworks, such as in physics topics like rotational dynamics or biology units addressing ecological change. This lack of alignment constrains institutional adoption and places a disproportionate burden on individual educators to initiate ESD practices without standardized guidance.

Despite these challenges, the evidence affirms that when ESD is contextualized through culturally relevant, inquiry-based, and interdisciplinary models, it enhances student engagement and promotes deeper learning. This study contributes to the expanding discourse on sustainability education by illustrating the innovative ways in which Indonesian educators bridge curricular and policy gaps to foster transformative science education.

RECOMMENDATION

The findings underscore the urgent need for curricular reform, professional development, and policy alignment to support systemic ESD implementation. Future research should investigate the longitudinal impacts of ESD-infused instruction on student outcomes, as well as scalable models for integrating sustainability across diverse educational settings. As sustainability challenges intensify globally, embedding ESD meaningfully within national education systems is no longer optional but essential.

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