



Integrated Science Learning for Sustainable Development: A Systematic Literature Review of Models, Impacts, and Future Directions

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ABSTRACT

This study aims to analyze the development of integrated science learning in the context of Education for Sustainable Development (ESD) through a systematic literature review. The study focuses on identifying dominant integration models, examining their implementation, and exploring their impact and research gaps. A systematic literature review approach was employed following PRISMA guidelines. Data were collected from the Scopus database using predefined search criteria, resulting in 20 selected articles published between 2016 and 2026. Data were extracted using a structured matrix and analyzed through qualitative content analysis and thematic synthesis. The findings reveal that integrated science learning is primarily implemented through transdisciplinary, STEAM-based, and interdisciplinary approaches. These approaches show positive impacts on students' cognitive, affective, and skill-based outcomes, particularly in enhancing critical thinking, collaboration, and problem-solving abilities. However, the implementation remains inconsistent, with challenges related to curriculum structure, teacher readiness, and assessment practices. Furthermore, the integration of ESD is often implicit rather than systematically embedded, and the measurement of sustainability competencies remains limited. This study highlights the need for more coherent and operational models that integrate curriculum structure, real-world context, and sustainability orientation. The findings provide important implications for the development of integrated science learning frameworks that support sustainable development in education.



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INTRODUCTION

The growing complexity of global challenges, such as climate change, environmental degradation, and socio-economic inequality, has intensified the demand for education systems to equip learners with the knowledge, skills, and values necessary for sustainable development. In this context, Education for Sustainable Development (ESD) has emerged as a transformative paradigm that emphasizes interdisciplinary understanding, critical thinking, and real-world problem solving. Science education plays a crucial role in this transformation, particularly in fostering scientific literacy and sustainability awareness among learners (Kubisch et al., 2021; Putri & Rizaldi, 2024; Tasdemir & Gazo, 2020).

However, conventional science education remains largely fragmented, characterized by discipline-based structures that limit students' ability to connect concepts across domains and apply knowledge to complex real-world issues. Such fragmentation often leads to superficial understanding and reduces the relevance of science learning in addressing sustainability-related problems (Bouwman & Béneker, 2018; McPhail, 2018). This condition highlights the need for more integrative approaches that can bridge disciplinary boundaries and promote meaningful learning.

In response, integrated science learning has gained increasing attention as an approach that connects knowledge across disciplines and links learning to real-life contexts. This approach includes various models such as interdisciplinary, multidisciplinary, and transdisciplinary integration. Among these, transdisciplinary approaches are widely recognized for their potential to integrate academic knowledge with societal issues and sustainability challenges (Burnard et al., 2021; Ertas, 2022). Furthermore, the development of STEM and STEAM education has reinforced this movement by incorporating multiple domains, including the arts, to foster holistic and creative learning experiences (Lage-Gómez & Ros, 2021; Nidiasari et al., 2026; Wilson et al., 2021).

Despite its growing popularity, the implementation of integrated science learning remains inconsistent and often lacks conceptual clarity and empirical validation. While many studies report positive outcomes such as improved critical thinking, collaboration, and student engagement, these findings are frequently based on qualitative data or self-reported measures (Atkinson-Toal, 2024; ElSayary, 2021). Empirical evidence demonstrating direct impacts on scientific literacy and sustainability competencies is still limited. In addition, the integration of ESD within science curricula is often implicit rather than systematically embedded, resulting in fragmented implementation (Dmochowski et al., 2016; Perdani et al., 2024; van der Knaap, 2022).

Previous studies have proposed various models of curriculum integration, including transdisciplinary frameworks, STEAM-based approaches, and structured integration models such as Fogarty's model. For instance, transdisciplinary models emphasize collaboration and real-world problem solving (Straub et al., 2021), while STEAM approaches integrate multiple domains to support creativity and innovation (Burnard et al., 2022). However, there is still a lack of comprehensive synthesis that systematically maps these approaches and evaluates their relevance to ESD and science education outcomes.

Although previous studies have examined integrated science learning, STEAM education, and transdisciplinary approaches separately, few reviews have systematically synthesized how these approaches contribute to Education for Sustainable Development (ESD). Existing reviews often focus on specific instructional models, educational levels, or disciplinary contexts, leaving limited understanding of how curriculum integration models collectively support sustainability competencies and science literacy. Furthermore, no review has explicitly mapped the relationships among integration approaches, ESD principles, and learning outcomes within a unified conceptual framework. This gap highlights the need for a comprehensive synthesis that not only identifies dominant approaches but also develops a coherent framework for future research and practice.

Therefore, this study aims to conduct a systematic literature review to (1) map the existing models and approaches of integrated science learning, (2) synthesize key findings regarding their implementation and impact in the context of sustainable development, and (3) identify research gaps and propose future directions for advancing science education. Unlike previous studies that tend to focus on specific models or contexts, this review provides an integrative synthesis that connects curriculum integration approaches with ESD and science literacy outcomes. In doing so, it offers a more

coherent framework for understanding how integrated science learning can be systematically designed to support sustainable development.

METHOD

Research Design

This study employed a systematic literature review (SLR) design to identify, evaluate, and synthesize existing research on integrated science learning in the context of sustainable development. The SLR approach was chosen to provide a comprehensive and structured overview of current research trends, models, and empirical findings. The review process followed the general principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to ensure transparency, rigor, and reproducibility.

Data Sources and Search Strategy

The systematic review followed a structured multi-phase procedure to identify and select relevant studies. In the initial phase, keywords and related terms were identified through an extensive review of thesauruses, academic dictionaries, prior literature, and key publications in the field of integrated science learning and Education for Sustainable Development (ESD). Based on this process, a comprehensive search query was constructed and applied to the selected database.

The search was primarily conducted using the Scopus database, employing combinations of keywords related to integrated science learning, curriculum integration, and sustainability. The complete search string used in this study is presented in Table 1.

Table 1. The search strings

Database	Search string
Scopus	TITLE-ABS-KEY ("integrated science learning" OR "integrated curriculum" OR "transdisciplinary learning" OR "STEAM education") AND TITLE-ABS-KEY ("science education" OR "science learning") AND TITLE-ABS-KEY ("sustainable development" OR "ESD" OR "sustainability") AND PUBYEAR > 2016 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"))

Inclusion and Exclusion Criteria

To ensure the relevance and quality of the selected studies, predefined inclusion and exclusion criteria were applied. These criteria guided the selection process and ensured consistency in identifying eligible studies (Table 2).

Table 2. Inclusion and Exclusion Criteria

Criteria Type	Description
Inclusion	Peer-reviewed journal articles; studies focusing on integrated science learning or curriculum integration; related to Education for Sustainable Development (ESD) or sustainability; empirical, conceptual, or mixed-method studies; published in English; publication period 2016–2026
Exclusion	Conference papers, book chapters, theses, and non-peer-reviewed publications; studies not related to science education; articles without a clear integration approach; duplicate publications

Study Selection Process

The Study Selection Process can be seen in Figure 1. During the identification stage, a total of 28 articles published between 2016 and 2026 were retrieved from the Scopus database. The relatively limited number reflects the specificity of the search query focusing on integrated science learning,

science education, and sustainable development. In the screening phase, duplicate and irrelevant articles were removed through title and abstract evaluation. Subsequently, full-text screening was conducted to assess eligibility based on relevance, scope, and methodological suitability. Articles not meeting the inclusion criteria were excluded. As a result, 20 articles were included in the final analysis.

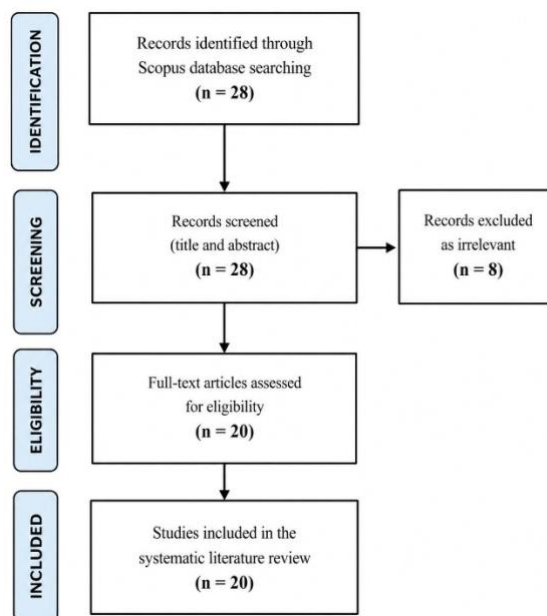


Fig.1. PRISMA flow diagram of study selection process

Data Extraction and Instruments

Data extraction was conducted using a structured review matrix developed by the authors. The extracted data included author(s), year of publication, research problem, methodology, instruments, integration model, ESD context, STEM/STEAM context, key findings, and research gaps (see Table 3).

Table 3. Data Extraction Framework

Component	Description
Author & Year	Study identification
Research Problem	Main issue addressed
Methodology	Research design used
Instruments	Tools used (survey, interview, etc.)
Integration Model	Fogarty, STEAM, Transdisciplinary
ESD Context	Explicit / implicit sustainability
STEM Context	Presence of STEM/STEAM
Key Findings	Main results
Research Gap	Identified limitations

Data Analysis Techniques

The data were analyzed using qualitative content analysis and thematic synthesis. The analysis involved coding key concepts, categorizing studies based on integration types (e.g., interdisciplinary, transdisciplinary, STEAM), and identifying patterns across studies. Thematic analysis was applied to synthesize similarities and differences among findings, while gap analysis was conducted to identify limitations and future research directions. This approach enabled a systematic and in-depth understanding of integrated science learning in the context of sustainable development.

RESULTS AND DISCUSSION

Overview of Selected Studies

This section presents an overview of the selected studies to provide a general understanding of the research landscape on integrated science learning for sustainable development. A total of 20 articles were included in the final analysis, representing diverse research contexts, methodologies, and integration approaches. In terms of publication trends, the selected studies were published between 2016 and 2026, with a noticeable increase in recent years, particularly after 2020. This trend reflects the growing academic interest in integrated and transdisciplinary approaches to address complex global challenges such as sustainability and climate change (Kubisch et al., 2021; Lage-Gómez et al., 2026).

Regarding educational levels, the studies were conducted across multiple contexts, including primary, secondary, and higher education. Several studies focused on primary and secondary levels through curriculum implementation and classroom-based interventions (Gürkan, 2021; Wu et al., 2021), while a larger proportion addressed higher education contexts, particularly in relation to sustainability integration and transdisciplinary learning (Dmochowski et al., 2016; Tasdemir & Gazo, 2020). This indicates that integrated approaches are more frequently implemented in higher education, where interdisciplinary collaboration and curriculum flexibility are more established. From a methodological perspective, the studies employed a variety of research designs, including qualitative, quantitative, mixed-methods, and conceptual approaches. Qualitative and conceptual studies were dominant, reflecting the exploratory and theoretical nature of transdisciplinary and integrated learning research (Burnard et al., 2021; O’Sullivan, 2025). Empirical studies, although present, often relied on surveys, interviews, or case studies, with limited use of rigorous experimental designs (ElSayary, 2021; Wilson et al., 2021).

In terms of integration approaches, the majority of studies adopted transdisciplinary and STEAM-based models, emphasizing real-world problem solving and holistic learning (Ertas, 2022; Lage-Gómez & Ros, 2021; Msweli et al., 2023). Only a limited number of studies applied structured curriculum integration frameworks such as the Fogarty model, which focus on systematic connections between disciplines (Bouwman & Béneker, 2018). This trend suggests a shift toward more flexible and context-driven approaches, although it may also contribute to inconsistencies in implementation and evaluation. Overall, the overview indicates that integrated science learning is increasingly recognized as a promising approach for supporting sustainable development. However, the field remains fragmented in terms of methodological rigor, conceptual clarity, and empirical validation, highlighting the need for more systematic and evidence-based research. A comprehensive summary of the characteristics, research contexts, methodological approaches, integration models, and key findings of the selected studies is presented in Table 4.

Table 4. Overview of Selected Studies

Category	Subcategory	Sources	Description
Publication Year	2016–2020	(Bouwman & Béneker, 2018; Dmochowski et al., 2016; McPhail, 2018; Tasdemir & Gazo, 2020).	Early development phase of integrated and sustainability-focused approaches
	2021–2026	(Atkinson-Toal, 2024; Ben-Horin et al., 2023; Burnard et al., 2021, 2022; ElSayary, 2021; Ertas, 2022; Gürkan, 2021; Kubisch et al., 2021; Lage-Gómez et al., 2026; Lage-Gómez & Ros, 2021; Msweli et al., 2023; O’Sullivan, 2025; Straub et al., 2021; van der Knaap, 2022;	Rapid growth, especially in transdisciplinary and STEAM approaches

Category	Subcategory	Sources	Description
Educational Level	Primary Education	Wilson et al., 2021; Wu et al., 2021)	Focus on thematic and early-stage integration
	Secondary Education	(Gürkan, 2021; Lage-Gómez & Ros, 2021; Wu et al., 2021)	Curriculum integration and subject linkage
	Higher Education	(McPhail, 2018; Wilson et al., 2021; Wu et al., 2021)	Dominated by sustainability and transdisciplinary approaches
		(Atkinson-Toal, 2024; Dmochowski et al., 2016; Straub et al., 2021; Tasdemir & Gazo, 2020; van der Knaap, 2022)	
Research Method	Qualitative	(Atkinson-Toal, 2024; Bouwmans & Béneker, 2018; Dmochowski et al., 2016; Gürkan, 2021; McPhail, 2018; Tasdemir & Gazo, 2020; Wu et al., 2021)	Case studies, interviews, thematic analysis
	Quantitative	(Msweli et al., 2023; Straub et al., 2021)	Survey and statistical analysis
	Mixed Methods	(ElSayary, 2021; Lage-Gómez et al., 2026; Lage-Gómez & Ros, 2021; Tasdemir & Gazo, 2020; Wilson et al., 2021)	Combined approaches
	Conceptual	(Ben-Horin et al., 2023; Burnard et al., 2021, 2022; Ertas, 2022; Kubisch et al., 2021; O’Sullivan, 2025; van der Knaap, 2022)	Framework and model development
Integration Model	Transdisciplinary	(Atkinson-Toal, 2024; ElSayary, 2021; Ertas, 2022; Gürkan, 2021; Kubisch et al., 2021; Lage-Gómez et al., 2026; Straub et al., 2021; Tasdemir & Gazo, 2020)	Focus on real-world problem solving and boundary-crossing
	STEAM	(Ben-Horin et al., 2023; Burnard et al., 2021, 2022; Lage-Gómez & Ros, 2021; Msweli et al., 2023; Wilson et al., 2021; Wu et al., 2021)	Integration of science with arts and technology
	Interdisciplinary/Fogarty	(Bouwmans & Béneker, 2018; McPhail, 2018; O’Sullivan, 2025)	Structured curriculum integration
	Others	(Dmochowski et al., 2016; van der Knaap, 2022)	Hybrid or emerging models

Models of Integrated Science Learning

The analysis of the selected studies reveals that integrated science learning is implemented through several dominant approaches, primarily transdisciplinary integration, STEAM-based learning, and interdisciplinary or structured curriculum models such as the Fogarty model. Each of these approaches reflects different orientations toward knowledge integration, learning design, and the role of real-world contexts.

Transdisciplinary integration appears as the most dominant approach across the reviewed studies. This model emphasizes the integration of knowledge across disciplinary boundaries while

directly connecting learning to real-world problems and societal challenges. Several studies highlight its relevance in addressing complex issues such as sustainability, climate change, and social responsibility (Ertas, 2022; Kubisch et al., 2021; O’Sullivan, 2025). In practice, transdisciplinary learning often involves collaboration across disciplines and engagement with authentic contexts, such as community-based projects or boundary-crossing collaborations (Atkinson-Toal, 2024; Straub et al., 2021). These characteristics make it highly compatible with the principles of Education for Sustainable Development (ESD), particularly in promoting systems thinking and action-oriented learning.

However, despite its strong conceptual foundation, the implementation of transdisciplinary approaches remains challenging. Several studies report issues related to the lack of clear operational frameworks, teacher readiness, and curriculum constraints (van der Knaap, 2022; Wu et al., 2021). In many cases, only a portion of classroom practices achieves genuine transdisciplinary integration, indicating a gap between theoretical ideals and practical application. This suggests that transdisciplinary approaches, while conceptually robust, are often difficult to sustain within formal education systems.

In addition to transdisciplinary approaches, STEAM (Science, Technology, Engineering, Arts, and Mathematics) has emerged as a prominent model of integration. STEAM-based learning emphasizes the combination of multiple disciplines to foster creativity, innovation, and problem-solving skills. Empirical studies indicate that STEAM can enhance student engagement, collaboration, and higher-order thinking (Lage-Gómez & Ros, 2021; Msweli et al., 2023; Wilson et al., 2021). A distinctive feature of this approach is the integration of the arts, which supports multiple ways of knowing and facilitates deeper conceptual understanding (Burnard et al., 2021, 2022).

Nevertheless, the effectiveness of STEAM integration largely depends on its implementation. Some studies suggest that STEAM activities may remain at a superficial level, where disciplines are combined without meaningful conceptual connections (Ben-Horin et al., 2023). In such cases, integration becomes more symbolic than substantive, limiting its impact on deeper learning outcomes. This indicates that while STEAM offers a practical and accessible entry point for integration, it requires careful design to ensure conceptual coherence.

Compared to transdisciplinary and STEAM approaches, fewer studies explicitly apply structured curriculum integration models such as the Fogarty model. These models focus on systematically connecting concepts across disciplines while maintaining disciplinary rigor. Research shows that such approaches can support coherent curriculum design and alignment with assessment systems (Bouwman & Béneker, 2018; McPhail, 2018). As a result, they are often more feasible to implement in formal educational settings where curriculum structures are fixed.

However, structured integration models tend to be less flexible in addressing real-world and sustainability-related issues. Their emphasis on maintaining disciplinary boundaries may limit opportunities for contextual and problem-based learning. Consequently, they are less frequently associated with ESD-oriented practices compared to transdisciplinary approaches.

Overall, the findings indicate that each model offers distinct strengths and limitations. Transdisciplinary approaches provide strong alignment with real-world problem solving and sustainability but lack operational clarity. STEAM offers practical and engaging learning experiences but risks superficial integration. Meanwhile, structured models such as Fogarty ensure coherence and rigor but may lack contextual relevance. These patterns suggest that no single model fully addresses the demands of integrated science learning for sustainable development, highlighting the need for more balanced and integrative approaches.

Integration of ESD in Science Learning

The integration of Education for Sustainable Development (ESD) within integrated science learning represents a central theme across the reviewed studies. However, the analysis reveals that the incorporation of ESD is not uniform and can be broadly categorized into explicit and implicit integration. Several studies demonstrate explicit integration of ESD, where sustainability concepts are deliberately embedded as core learning objectives. These studies typically address real-world issues such as climate change, environmental degradation, and resource management, and are often designed to develop sustainability competencies, including systems thinking, problem-solving, and responsible decision-making (Kubisch et al., 2021; Tasdemir & Gazo, 2020). In such contexts, ESD is not treated as an additional topic but as a guiding framework that shapes the structure and purpose of learning.

Transdisciplinary approaches are frequently associated with this type of integration, as they naturally connect scientific knowledge with societal and environmental challenges.

In contrast, many studies exhibit implicit integration of ESD, where sustainability-related themes are present but not systematically incorporated into the learning design. For example, some studies include topics such as energy, environment, or social issues without explicitly framing them within ESD principles or sustainability competencies (Dmochowski et al., 2016; Wu et al., 2021). In these cases, ESD appears more as contextual content rather than a structured pedagogical approach. Similarly, in several STEAM-based implementations, sustainability is introduced as part of project themes, but lacks clear alignment with broader ESD goals (Lage-Gómez & Ros, 2021).

This distinction between explicit and implicit integration highlights a critical issue in the current literature. While sustainability is frequently mentioned, it is often not systematically embedded within curriculum design, learning objectives, or assessment frameworks. As a result, the potential of integrated science learning to support sustainability competencies is not fully realized. Another key finding relates to the misalignment between ESD principles and instructional practices. Although many studies emphasize real-world problem solving and interdisciplinary learning, few provide clear strategies for assessing sustainability-related outcomes. Most evaluations focus on general outcomes such as engagement, collaboration, or thinking skills, rather than specific indicators of sustainability literacy (ElSayary, 2021; Wilson et al., 2021). This suggests that ESD integration remains conceptually strong but operationally underdeveloped.

Furthermore, the integration of ESD is often influenced by the chosen model of integration. Transdisciplinary approaches tend to support deeper and more authentic engagement with sustainability issues, whereas structured or disciplinary-based models may limit the scope of ESD integration. However, even in transdisciplinary contexts, challenges such as curriculum constraints, teacher readiness, and lack of assessment tools hinder effective implementation (van der Knaap, 2022).

Overall, the findings indicate that although ESD is widely recognized as an important component of integrated science learning, its implementation remains inconsistent and fragmented. The distinction between explicit and implicit integration reveals that sustainability is often present in discourse but not fully operationalized in practice. This underscores the need for more systematic frameworks that clearly integrate ESD principles into curriculum design, instructional strategies, and assessment.

Impact of Integrated Science Learning

The reviewed studies consistently report that integrated science learning has a positive impact on various aspects of student learning, including cognitive development, affective engagement, and skill acquisition. However, a closer examination reveals that these outcomes vary in depth, measurement, and validity. From a cognitive perspective, integrated science learning is frequently associated with improvements in higher-order thinking skills, such as critical thinking, problem-solving, and systems thinking. Several studies indicate that transdisciplinary and STEAM-based approaches can enhance students' ability to connect concepts across disciplines and apply knowledge to real-world problems (Lage-Gómez et al., 2026; Msweli et al., 2023; Wilson et al., 2021). In particular, learning environments that incorporate authentic, problem-based contexts appear to support deeper conceptual understanding. However, most of these findings are derived from qualitative data or self-reported measures, with limited use of standardized assessments to evaluate actual gains in scientific literacy.

In terms of affective outcomes, integrated approaches are widely reported to increase student motivation, engagement, and interest in learning. STEAM-based learning, in particular, is often associated with enjoyable and meaningful learning experiences, as it combines creativity with scientific inquiry (Lage-Gómez & Ros, 2021). Similarly, transdisciplinary approaches that involve real-world issues can foster a sense of relevance and purpose, which is essential for sustainability-oriented learning (Kubisch et al., 2021). Nevertheless, these outcomes are predominantly measured through perception-based instruments, such as questionnaires and interviews, which may not fully capture long-term attitudinal change.

Regarding skill development, integrated science learning is found to support a range of competencies, including collaboration, communication, creativity, and problem-solving. These skills

are particularly evident in project-based and inquiry-based learning environments, where students are required to work in teams and engage in complex tasks (Ertas, 2022; Tasdemir & Gazo, 2020). In the context of ESD, such competencies are essential for preparing learners to address sustainability challenges. However, similar to cognitive and affective outcomes, the assessment of these skills is often limited to descriptive or qualitative evaluations, without standardized measurement frameworks.

Despite these reported benefits, several limitations can be identified across the studies. One of the main issues is the lack of rigorous empirical evidence, particularly in terms of experimental or longitudinal research designs. Many studies rely on small sample sizes, case studies, or short-term interventions, which restrict the generalizability of the findings (Atkinson-Toal, 2024; ElSayary, 2021). In addition, there is a notable absence of consistent indicators for measuring key outcomes such as scientific literacy and sustainability competencies.

Another important concern is the misalignment between claimed outcomes and measurement methods. While studies often report improvements in complex competencies, such as critical thinking or sustainability awareness, the instruments used to assess these outcomes are not always aligned with these constructs. As a result, there is a risk that the reported impacts may overestimate the actual effectiveness of integrated science learning.

Overall, the findings suggest that integrated science learning holds significant potential to enhance cognitive, affective, and skill-based outcomes. However, the current evidence base remains limited in terms of methodological rigor and measurement validity. This indicates the need for more robust research designs, standardized assessment tools, and longitudinal studies to better understand the actual impact of integrated science learning in the context of sustainable development.

Challenges in Implementation

Despite the promising potential of integrated science learning, the reviewed studies reveal several persistent challenges that hinder its effective implementation. These challenges are multidimensional, involving curriculum structure, teacher readiness, assessment practices, and the complexity of integration itself. One of the most frequently reported challenges relates to curriculum constraints and structural rigidity. In many education systems, curricula are still organized based on disciplinary boundaries, making it difficult to implement integrated or transdisciplinary approaches. Studies indicate that assessment systems, which are often discipline-based, further reinforce this fragmentation and discourage integration (Bouwman & Béneker, 2018; McPhail, 2018). As a result, even when integrated learning is introduced, it tends to remain partial or superficial.

Another major issue concerns teacher readiness and professional capacity. Implementing integrated science learning requires teachers to possess not only strong disciplinary knowledge but also the ability to collaborate across fields and design interdisciplinary or transdisciplinary learning experiences. Several studies highlight that teachers often face difficulties in selecting appropriate themes, aligning learning objectives, and designing assessments for integrated curricula (Gürkan, 2021; Wu et al., 2021). In addition, limited professional development opportunities further constrain teachers' ability to adopt innovative approaches.

The complexity of designing integrated learning also poses significant challenges. Unlike traditional teaching, integrated approaches require the alignment of multiple components, including content integration, pedagogical strategies, and real-world contexts. This complexity is particularly evident in transdisciplinary models, where the absence of clear operational guidelines makes implementation highly dependent on teacher interpretation (van der Knaap, 2022). Consequently, the quality of implementation varies widely across contexts.

Assessment is another critical challenge. Many studies report a lack of appropriate tools for evaluating integrated learning outcomes, particularly those related to higher-order thinking, collaboration, and sustainability competencies. Existing assessment practices tend to focus on disciplinary knowledge, which may not adequately capture the outcomes of integrated learning (ElSayary, 2021). This misalignment between learning objectives and assessment practices limits the effectiveness of integrated approaches and reduces their perceived value in formal education systems.

In addition, time constraints and institutional limitations are frequently identified as barriers. Integrated learning often requires extended time for planning, collaboration, and implementation, which may not align with rigid school schedules or institutional policies. Collaborative teaching, which is

essential for interdisciplinary integration, is also difficult to sustain due to logistical and organizational challenges (Straub et al., 2021). Overall, these challenges indicate that the implementation of integrated science learning is not merely a pedagogical issue, but also a systemic one. While theoretical models emphasize the benefits of integration, practical constraints at the curriculum, institutional, and teacher levels significantly influence its success. Addressing these challenges requires not only innovative instructional design but also structural changes in curriculum policy, teacher training, and assessment systems.

Research Gaps and Future Directions

The analysis of the selected studies reveals several critical gaps that limit the advancement of integrated science learning, particularly in relation to sustainable development. These gaps highlight the need for more systematic, rigorous, and contextually grounded research to strengthen both theoretical and practical contributions in this field. One of the most prominent gaps is the lack of robust empirical evidence. While many studies report positive impacts of integrated science learning, most rely on qualitative approaches, small-scale case studies, or self-reported data. Experimental and longitudinal studies remain limited, making it difficult to establish causal relationships or evaluate long-term effects on learning outcomes. In particular, there is a need for more rigorous measurement of scientific literacy and sustainability competencies, using validated and standardized instruments.

Another significant gap concerns the lack of conceptual clarity and operational frameworks. Although transdisciplinary and STEAM approaches are widely promoted, many studies do not provide clear guidelines for implementation. Concepts such as “integration,” “transdisciplinary learning,” and “sustainability” are often used broadly without precise definitions or instructional models. This lack of clarity contributes to inconsistent implementation and makes it difficult to compare findings across studies. The review also identifies a gap in the systematic integration of ESD within science learning. While sustainability themes are frequently included, they are often embedded implicitly rather than explicitly structured within curriculum design, learning objectives, and assessment strategies. As a result, ESD tends to function as contextual content rather than as a guiding pedagogical framework. Future research should focus on developing models that integrate ESD in a more coherent and measurable way.

In addition, there is a noticeable imbalance between theoretical development and practical application. Many studies propose innovative conceptual models, such as transdisciplinary frameworks or STEAM integration, but lack empirical validation in real classroom settings. Conversely, empirical studies often focus on specific implementations without linking findings to broader theoretical frameworks. Bridging this gap requires research that combines strong theoretical grounding with rigorous empirical testing. Another important gap relates to the limited attention to assessment and evaluation frameworks. Current studies rarely provide clear methods for assessing integrated learning outcomes, particularly those related to higher-order thinking and sustainability competencies. The development of valid and reliable assessment tools is essential to ensure that the impact of integrated science learning can be accurately measured and compared.

Based on these identified gaps, several directions for future research can be proposed. First, there is a need for longitudinal and experimental studies to provide stronger evidence of the effectiveness of integrated science learning. Second, future research should aim to develop operational models of integration that combine conceptual strength with practical applicability. Third, studies should focus on explicitly embedding ESD principles within curriculum design and assessment. Finally, greater attention should be given to teacher professional development and institutional support, as these factors play a crucial role in successful implementation. Overall, addressing these gaps requires a more balanced approach that integrates theory, practice, and evaluation. By doing so, future research can contribute to the development of more coherent and impactful integrated science learning frameworks that effectively support sustainable development.

Toward a Conceptual Framework

The findings of this review indicate that no single model of integrated science learning fully addresses the complex demands of Education for Sustainable Development (ESD). Transdisciplinary approaches offer strong connections to real-world problems and sustainability issues, yet often lack

clear operational structures. STEAM-based models provide practical and engaging learning experiences, but may result in superficial integration when not carefully designed. Meanwhile, structured curriculum models, such as the Fogarty model, ensure coherence and disciplinary rigor, but may be limited in addressing complex, real-world contexts. These limitations suggest the need for a more balanced and integrative conceptual framework that combines the strengths of existing approaches while addressing their weaknesses. Based on the synthesis of the reviewed studies, this study proposes a conceptual framework that integrates three key dimensions: curriculum structure, contextual relevance, and sustainability orientation. To address the identified gaps, a conceptual framework is proposed, as illustrated in Figure 2.

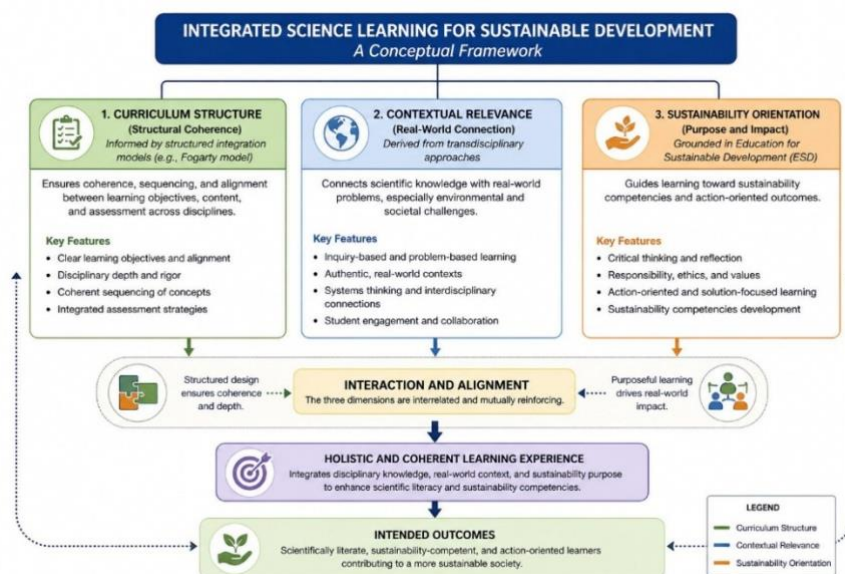


Fig.2. Conceptual framework of integrated science learning for sustainable development

The first dimension, curriculum structure, is informed by structured integration models such as the Fogarty model. This dimension emphasizes coherence, sequencing, and alignment between learning objectives, content, and assessment. It ensures that integration does not compromise disciplinary depth and provides a clear guide for implementation within formal education systems. The second dimension, contextual relevance, is derived from transdisciplinary approaches. This dimension focuses on connecting scientific knowledge with real-world problems, particularly those related to environmental and societal challenges. It promotes inquiry-based and problem-based learning, enabling students to engage with authentic contexts and develop systems thinking.

The third dimension, sustainability orientation, is grounded in the principles of ESD. This dimension emphasizes the development of sustainability competencies, including critical thinking, responsibility, and action-oriented learning. It ensures that sustainability is not merely included as content, but embedded as a guiding purpose of the learning process. These three dimensions are not independent but interrelated. Effective integrated science learning requires the alignment of structured curriculum design, meaningful real-world context, and clear sustainability goals. The interaction among these dimensions creates a more holistic and coherent learning framework that can support both scientific literacy and sustainability competencies.

This proposed framework addresses several gaps identified in the literature. It provides a more operational structure for implementing integration, strengthens the connection between science learning and sustainability, and offers a foundation for developing assessment strategies aligned with integrated learning outcomes. In doing so, it moves beyond fragmented approaches and toward a more systematic model of integrated science learning. Future research is needed to validate and refine this conceptual framework through empirical studies, particularly in diverse educational contexts. Such efforts are

essential to ensure that the proposed framework is not only theoretically sound but also practically applicable. This review reveals that the challenge of integration lies not in designing new models, but in aligning existing ones within real educational systems.

CONCLUSION AND SUGGESTION

This study provides a systematic overview of integrated science learning in the context of Education for Sustainable Development (ESD), highlighting dominant models, implementation patterns, impacts, and research gaps. The findings show that integrated science learning has strong potential to enhance cognitive, affective, and skill-based outcomes, particularly through transdisciplinary and STEAM approaches. However, its implementation remains inconsistent. Transdisciplinary models are conceptually strong but difficult to operationalize, STEAM approaches are practical but risk superficial integration, and structured models such as Fogarty offer coherence but lack contextual relevance. In addition, ESD is often implicitly included rather than systematically embedded, and the measurement of learning outcomes—especially sustainability competencies—remains limited.

Based on these findings, this study suggests the need for more balanced and coherent approaches that integrate curriculum structure, real-world context, and sustainability orientation. Future research should focus on developing operational models, employing more rigorous and longitudinal designs, and establishing clear assessment frameworks for sustainability competencies. Furthermore, greater attention should be given to teacher professional development and institutional support to ensure effective implementation. These efforts are essential to advance integrated science learning that is not only conceptually strong but also practically applicable in supporting sustainable development. This study offers a conceptual bridge between integration models and ESD-oriented science learning.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article. The authors have no financial, commercial, institutional, or personal relationships that could have appeared to influence the work reported in this paper. The research was conducted independently, and no external funding source or organization had any role in the design, analysis, interpretation, or reporting of the findings.

AUTHOR CONTRIBUTIONS STATEMENT

Conceptualization, R.D.I. and N.D.N.; methodology, R.D.I. and N.D.N.; literature search and data collection, R.D.I.; data curation, R.D.I.; formal analysis, R.D.I. and N.D.N.; investigation, R.D.I.; validation, N.D.N.; visualization, R.D.I.; writing-original draft preparation, R.D.I.; writing—review and editing, N.D.N.; supervision, N.D.N. All authors have read and agreed to the published version of the manuscript.

DECLARATION OF GENERATIVE AI SOURCES

During the preparation of this manuscript, the author(s) used ChatGPT (OpenAI) and Scopus AI (Elsevier) to assist with literature exploration, language refinement, grammar improvement, and structural organization of the manuscript. All generated content was carefully reviewed, revised, and verified by the author(s), who take full responsibility for the final content of the manuscript.

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