Integrating environmental and sustainability education to enhance students' scientific literacy: A systematic literature review

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Abstract
Despite the growing integration of Environmental Education (EE) and Education for Sustainable Development (ESD) into science education, existing reviews have largely focused on sustainability competencies, environmental literacy, or general ESD implementation, providing limited synthesis of how Environmental and Sustainability Education (ESE-ESD) contributes to the multiple dimensions of scientific literacy. This study therefore aims to systematically examine the contribution of ESE-ESD to scientific literacy development, identify the pedagogical approaches used, and explore emerging conceptual, theoretical, and methodological gaps. A Systematic Literature Review (SLR) following the PRISMA 2020 guidelines was conducted using Scopus and Web of Science databases for publications from 2016-2025. After screening and quality appraisal, 32 empirical studies were included in the qualitative synthesis. The findings indicate that ESE-ESD is associated with the development of scientific reasoning, inquiry skills, evidence-based argumentation, ecological understanding, environmental awareness, and informed decision-making. Inquiry-based learning, socioscientific issues, and citizen science were most frequently linked to cognitive and procedural dimensions of scientific literacy, whereas ecological literacy and identity-based approaches were more commonly associated with affective and value-oriented outcomes. This review contributes an integrated synthesis of educational contexts, pedagogical approaches, scientific literacy dimensions, and research gaps, highlighting the need for geographically diverse, longitudinal, and theoretically grounded studies to strengthen sustainability-oriented science education.

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1. Introduction

Science education is currently at a pivotal stage, as ecological, social, and technological issues are becoming increasingly interconnected and require students to understand and evaluate scientific evidence within complex contexts (Gandolfi, 2024; Sjöström, 2025). Challenges such as climate change, environmental degradation, and socio-economic pressures underscore the urgency of developing scientific competencies that are not only conceptual but also applicable and sustainability-oriented (Paz & Clara, 2025; Tytler et al., 2025). In this situation, science education is expected to provide a learning framework capable of bridging scientific knowledge with the ability to solve real-world problems in a more systemic manner. As the complexity of these issues increases, science education is encouraged to adopt interdisciplinary approaches to help students apply scientific understanding in responding to real-world challenges critically and responsibly (Evans & Achiam, 2021; Sørensen & Stenalt, 2025).

In this context, Environmental Education (EE) and Education for Sustainable Development (ESD) are increasingly recognized as important pedagogical frameworks within science education. While EE traditionally emphasizes environmental awareness, ecological knowledge, and responsible environmental behavior, ESD adopts a broader perspective by integrating environmental, social, and economic dimensions of sustainability. In this review, the term Environmental and Sustainability Education (ESE) is used as an umbrella concept encompassing both EE and ESD approaches that seek to connect science learning with sustainability-oriented goals. Through EE and ESD, scientific understanding is integrated with sustainability-related issues (AlAli et al.,

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2025; Hu & Mou, 2025; Li et al., 2025; Sanchez, Piedrahita Guzman, et al., 2025), not merely as supplementary content but as a foundational component of learning that emphasizes systemic thinking, data literacy, decision-making, and the development of sustainability values through authentic experiences. These approaches function to strengthen the connection between scientific concepts and socio-ecological contexts that are relevant to learners, while also expanding opportunities for active engagement in sustainability issues. EE and ESD broaden the scope of science learning through real-world contexts, socioscientific issues, and exploratory activities that position students as agents of change within their environments (Demssie et al., 2023; Green et al., 2022; Prabawani et al., 2022). However, previous studies differ considerably in how EE and ESD are conceptualized and implemented, with some emphasizing environmental awareness and sustainability values, while others focus on scientific reasoning and problem-solving competencies. This conceptual diversity creates challenges in understanding how ESE-ESD contributes specifically to the development of scientific literacy.

Scientific literacy has become a central goal of modern curricula and a key indicator of students' readiness to face 21st-century challenges (Kain et al., 2024; Osborne et al., 2025). Recent studies increasingly emphasize scientific literacy as a multidimensional construct that encompasses scientific knowledge, inquiry skills, evidence evaluation, argumentation, and responsible decision-making in real-world contexts (Bórquez-sánchez, 2025; OECD, 2023; Roy et al., 2025). For the purpose of this review, scientific literacy is understood through four interconnected dimensions: (1) scientific knowledge and conceptual understanding, (2) scientific inquiry and process skills, (3) evidence-based reasoning and argumentation, and (4) attitudes and dispositions toward science and sustainability-related issues. In sustainability-related contexts, scientific literacy is particularly important because learners are expected not only to understand scientific concepts but also to evaluate complex environmental problems and justify actions based on scientific evidence. Since many environmental and sustainability issues are socioscientific in nature, scientific literacy serves as an essential foundation for assessing and responding competently to sustainability challenges.

The integration of ESE-ESD into science education has received considerable attention in research. Many studies report that approaches such as socio-scientific issues (SSI), project-based learning, inquiry-based learning, problem-based learning, and STEM-ESD can enhance ecological understanding, critical thinking, environmental awareness, and evidence-based decision-making (Kuswandi et al., 2025; Sihombing et al., 2024). In addition, approaches grounded in local potential and sustainability-oriented projects can deepen students' connectedness to their environment and provide authentic contexts for scientific practice (Fu, 2025; Lestari & Suyanto, 2024). However, these studies employ highly diverse pedagogical models, resulting in outcomes that are difficult to compare directly.

Although the contributions of ESE-ESD to scientific literacy have been widely examined, empirical findings remain highly variable. Some studies report significant improvements in the cognitive aspects of scientific literacy, whereas others highlight impacts on attitudes or sustainability-related actions without substantial changes in scientific competencies (Masalimova et al., 2023; Pamuk et al., 2022). This variation arises from differences in intervention designs, scientific literacy measurement instruments, participant education levels, intervention duration, and socio-cultural contexts (Gould et al., 2018; Zhao et al., 2024). Moreover, most studies focus on only one dimension of scientific literacy or a single component of ESD, leaving the overall effectiveness of this integration insufficiently mapped (Guerrero & Sjöström, 2025; Hajj-hassan & Chaker, 2024). This situation indicates the need for a more comprehensive synthesis to understand how various ESE-ESD approaches contribute to each dimension of scientific literacy.

As the number of publications continues to grow in recent years, existing literature reviews still exhibit a fragmented nature. Some reviews examine ESD integration in a general sense, while others evaluate environmental issue-based learning without explicitly linking it to scientific literacy (Cole, 2019; Xiong et al., 2025). Previous studies have focused on sustainability competencies, environmental literacy, sustainability literacy, or broader educational outcomes (Kaya & Elster, 2019; Redman et al., 2021; Sanchez, Guzman, et al., 2025; Sposab & Rieckmann, 2024), but they rarely provide a comprehensive synthesis of how ESE-ESD interventions specifically contribute to the multiple dimensions of scientific literacy across different educational contexts. Furthermore, previous reviews tend to focus on single approaches or specific educational outcomes and therefore provide limited evidence regarding the comparative effectiveness of inquiry-based learning, socioscientific issues, citizen science, ecological literacy, and sustainability-oriented curricula in developing scientific literacy. Consequently, there remains no comprehensive evidence synthesis that explains how different ESE-ESD approaches contribute to various dimensions of scientific literacy across educational contexts. This lack of synthesis limits the development of evidence-based recommendations for science educators, curriculum developers, and sustainability education practitioners.

Based on these gaps, this study conducts a Systematic Literature Review of Scopus-indexed publications that examine the integration of EE and ESD in science education with the aim of enhancing scientific literacy. Unlike previous reviews that focus on ESD implementation in general, sustainability competencies, environmental literacy, or isolated sustainability-related outcomes, this review specifically examines the relationship between ESE-ESD integration and the development of scientific literacy across multiple educational

contexts. The originality of this review lies in the integration of four analytical dimensions within a single framework: (1) educational contexts, (2) pedagogical approaches and instructional strategies, (3) dimensions of scientific literacy, and (4) conceptual and methodological research gaps. Specifically, the review seeks to map the characteristics of existing research, including methodological designs and educational contexts; identify the pedagogical models, approaches, and strategies used to integrate ESE-ESD within science learning; analyze the effects of these interventions on the various dimensions of scientific literacy; and synthesize emerging trends, challenges, and unresolved conceptual or methodological gaps that require further investigation. Through this comprehensive examination, the study aims to establish a clearer understanding of how ESE-ESD has been implemented across diverse learning contexts and the extent to which these efforts contribute to strengthening students' scientific literacy. In line with these aims, the present review is guided by the following research questions:

(RQ1) How does Environmental and Sustainability Education (ESE-ESD) contribute to the development of students' scientific literacy in formal and nonformal educational settings?

(RQ2) Which models, strategies, and pedagogical approaches are most effective in integrating ESE-ESD to enhance scientific literacy based on the available empirical evidence?

(RQ3) What conceptual, theoretical, and methodological gaps emerge in the literature regarding the integration of ESE-ESD and scientific literacy, and what implications do these gaps hold for future research?

2. Method

This study adopts a Systematic Literature Review (SLR) design with a qualitative synthesis approach to identify, analyze, and map how Environmental Education (EE) and Education for Sustainable Development (ESD) are integrated into science education and how such integration contributes to the enhancement of students' scientific literacy. The review process followed the PRISMA 2020 protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), ensuring transparency, rigor, and consistency across the stages of identification, screening, and inclusion (Page et al., 2021). The object of this review consisted of empirical studies examining the integration of Environmental Education (EE) and Education for Sustainable Development (ESD) within science education and their contribution to students' scientific literacy. The subjects represented in the reviewed studies included students at primary, secondary, and tertiary education levels in both formal and non-formal educational settings. As this study employed a systematic review design, article selection was conducted through purposive sampling based on predefined inclusion and exclusion criteria. Data collection involved systematic database searching, screening, eligibility assessment, quality appraisal, data extraction, and qualitative synthesis.

In the identification stage, the Scopus database was selected as the primary source due to its broad coverage and stringent peer-review standards, complemented by additional searches in the Web of Science (WoS) to prevent omission of relevant studies not indexed in Scopus. The search strategy employed combinations of the following keywords:

("environmental education" OR "education for sustainable development" OR "sustainability education" OR "sustainability competencies" OR "environmental sustainability" OR "systems thinking" OR "socio-scientific issues" OR SSI) AND ("scientific literacy" OR "science literacy" OR "environmental literacy" OR "sustainability literacy") AND ("science education" OR "STEM education" OR learning OR pedagogy).

The publication period was limited to 2016-2025 to capture recent developments in ESE–ESD integration within science education following the adoption of the Sustainable Development Goals (SDGs) in 2015 and the increasing emphasis on sustainability-oriented educational practices. Scopus served as the primary database because of its extensive coverage of high-quality international journals, while Web of Science was used as a complementary database to identify potentially relevant studies that were not indexed in Scopus and to improve database triangulation.

The initial screening phase evaluated articles based on publication year, document type, subject area, and language. These general criteria are summarized in Table 1.

Table 1. General Selection Criteria

No	Criteria	Inclusion	Exclusion
1	Year of publication	2016-2025	Before 2016, after 2025
2	Document type	Original research article	Conference paper, review, book chapter, note, editorial, book, report
3	Subject area	Science education, environmental education, sustainability education, social sciences	Engineering, medicine, computer science, physics, chemistry, nursing, economics, mathematics, unrelated fields
4	Language	English	Non-English

The exclusion of non-English publications was applied to ensure consistency in the review process and accuracy in data interpretation. However, this criterion may introduce language bias by excluding potentially relevant studies published in other languages. Likewise, restricting the review to peer-reviewed journal articles may introduce publication bias by excluding grey literature, reports, dissertations, and conference proceedings. These limitations were acknowledged when interpreting the review findings. Following the general screening, a more detailed assessment of titles, abstracts, and keywords was conducted using specific exclusion criteria. Articles were removed if they did not integrate ESE-ESD into science education, did not involve student participants, did not address scientific literacy, or did not report empirical findings. These criteria are presented in Table 2.

Table 2. Specific Exclusion Criteria

No	Criteria	Inclusion	Exclusion
1	Research focus	Studies related to EE-ESD in science education	Studies unrelated to environmental/sustainability education
2	Subject of research	Students in school or university	Teachers, community members, general population
3	Literacy component	Articles that assess or discuss scientific literacy	Articles that do not include scientific literacy
4	Type of study	Empirical data-based studies	Opinion papers, conceptual papers, policy briefs, non-empirical articles
5	Pedagogical relevance	Integration of ESE-ESD into learning activities	Articles discussing environmental issues without learning context

Next, the remaining articles were evaluated based on specific inclusion criteria to ensure eligibility for full synthesis. Eligible studies were required to explicitly describe ESE–ESD integration in science education, articulate the pedagogical model or instructional approach used, involve student participants, and report outcomes related to scientific literacy. These criteria are listed in Table 3.

Table 3. Specific Inclusion Criteria

No	Criteria
1	The terms environmental education, education for sustainable development, sustainability education, or socio-scientific issues, and scientific literacy appear in the title, abstract, or keywords.
2	The article describes empirical research involving the integration of EE-ESD in science education at school or university levels.
3	The article explains a pedagogical model, instructional strategy, or intervention based on EE-ESD.
4	The article discusses or measures one or more dimensions of scientific literacy.
5	The research involves student participants (primary, secondary, or tertiary).
6	The article presents empirical findings regarding the impact of ESE-ESD integration on students' scientific literacy.

Data extraction was conducted using a structured review matrix. Information extracted from each study included publication year, country, educational level, participant characteristics, research design, ESE-ESD approach, pedagogical model, scientific literacy dimensions assessed, data collection instruments, and key findings. The extracted data were subsequently coded and organized to facilitate cross-study comparison and thematic analysis. The synthesis process employed qualitative thematic synthesis. Studies were grouped according to educational context, pedagogical approach, and scientific literacy dimensions. Recurring patterns and findings were then categorized into broader themes to identify trends, intervention effectiveness, and conceptual or methodological gaps within the literature.

A quality assessment of all included studies was conducted using the Joanna Briggs Institute (JBI) Critical Appraisal Checklists, adjusted to each study design (quasi-experimental, qualitative, or cross-sectional). The appraisal examined methodological clarity, data collection validity, measurement reliability, and alignment between evidence and conclusions. Studies that did not meet the minimum quality standards were excluded. The quality assessment was conducted to ensure the methodological rigor and credibility of the evidence included in the review. Rather than serving as the primary basis for article exclusion, the appraisal was used to evaluate the overall quality and trustworthiness of the included studies. All studies met the minimum quality criteria and were therefore retained for the final synthesis. This process ensured that only methodologically sound studies were included in the final synthesis.

The PRISMA flow process summarizes the selection results in Figure 1. From an initial 174 articles, one duplicate was removed. Automated filtering excluded 26 articles outside the 2016-2025 range, 16 articles not indexed in Q1-Q4 journals, and 3 articles without abstracts, yielding 128 articles for screening. At this stage, 66 were excluded due to irrelevance, leaving 62 articles for full-text review. Of these, 43 were unavailable in full-text format. An additional search in the Web of Science identified 13 eligible articles. Ultimately, 19 articles from the primary database and 13 from supplementary sources met all criteria, resulting in a final corpus of 32 studies included in this SLR. More specifically, the final corpus consisted of 19 studies retrieved from Scopus and 13

studies identified through the supplementary Web of Science search. All 32 studies fulfilled the inclusion criteria and passed the quality appraisal process, forming the basis of the qualitative synthesis.

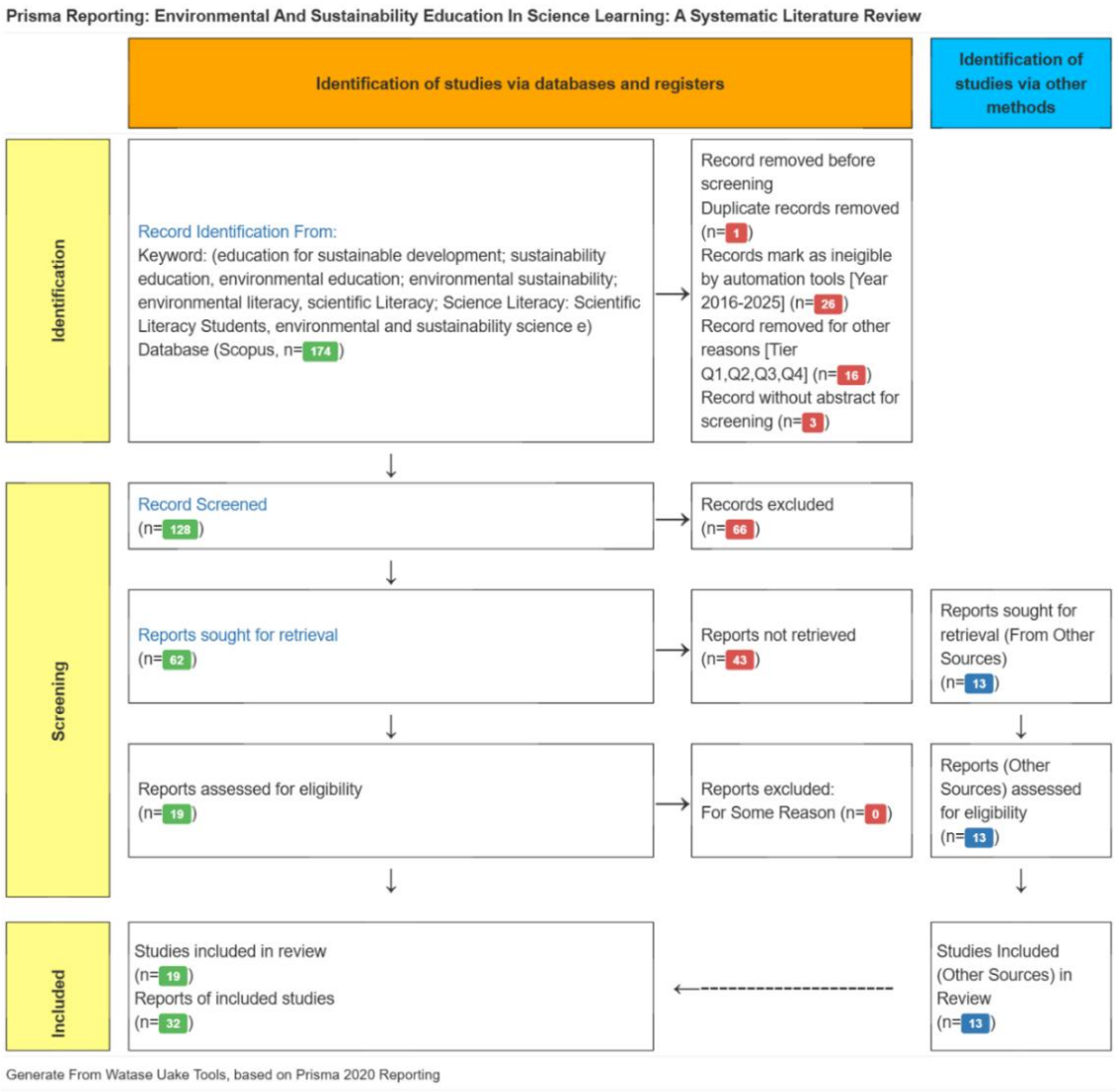

Figure 1. Identification, Screening, and Inclusion Steps

3. Results and Discussion

The present Systematic Literature Review includes 32 peer-reviewed articles originating from four countries, with a strong geographical concentration in Europe. Switzerland constitutes the largest proportion, contributing 16 publications (50%), followed by the United Kingdom with 11 studies (34.4%). Four studies (12.5%) were conducted in the United States, while only one study (3.1%) originated from the Netherlands. The absence of publications from Asia, Africa, Latin America, and Australia indicates that research on the integration of Environmental and Sustainability Education (ESE–ESD) and scientific literacy remains dominated by high-income Western countries, particularly Europe. Methodologically, quasi-experimental designs dominate the dataset (47%), followed by qualitative approaches (28%) and conceptual or theoretical works (25%). In terms of educational levels, the studies most frequently involve secondary education (28%), followed by higher education (16%), primary education (12%), and teacher education (12%), with several studies situated in non-formal, community-based, or unspecified contexts. This distribution suggests that current ESE–ESD research focuses predominantly on adolescents and university students groups considered developmentally capable of engaging with complex socio-environmental issues while younger learners and broader community populations remain underexplored.

The characteristics of the 32 studies included in this review are summarized in Table 4. The table presents the distribution of studies according to authorship, country of origin, and article codes used throughout the synthesis. As shown in Table 4, the reviewed literature is geographically concentrated in a limited number of countries, particularly Switzerland and the United Kingdom, indicating an uneven global distribution of research on ESE–ESD and scientific literacy.

Table 4. List of articles analyzed at the inclusion stage

No	Author and Year	Country	Article Code
1	Chen et al. (2025)	United State	A1
2	Alali et al. (2025)	Switzerland	A2
3	Atst (2025)	Switzerland	A3
4	Jhang & Lin (2025)	Switzerland	A4
5	Jensen & Jensen (2025)	United Kingdom	A5
6	Kramar & Knez (2025)	Switzerland	A6
7	Paz & Clara (2025)	Switzerland	A7
8	Macintosh & Asghar (2025)	Switzerland	A8
9	Arntzen et al. (2025)	United Kingdom	A9
10	Basheer et al. (2025)	Switzerland	A10
11	Pessoa et al. (2025)	United State	A11
12	Abdullahi et al. (2024)	Switzerland	A12
13	Baena-morales et al. (2024)	United Kingdom	A13
14	Eymur & Çetin (2024)	Netherlands	A14
15	Karmakar (2024)	United Kingdom	A15
16	Van et al. (2024)	United Kingdom	A16
17	Osborne et al. (2024)	United Kingdom	A17
18	Celestino (2023)	Switzerland	A18
19	Ajaps (2023)	United Kingdom	A19
20	Cincera tdcet al. (2023)	United Kingdom	A20
21	Väljataga & Mettid (2022)	Switzerland	A21
22	Jimenez & Alvarez-hevia (2022)	United Kingdom	A22
23	Oberbauer et al. (2021)	United State	A23
24	Georgiou & Kyza (2023)	Switzerland	A24
25	Zidny et al. (2021)	Switzerland	A25
26	Salovaara et al.(2021)	United Kingdom	A26
27	Bourn & Soysal (2021)	Switzerland	A27
28	Bezeljak & Scheuch(2020)	Switzerland	A28
29	Schleicher (2020)	Switzerland	A29
30	Saunders et al.(2018)	United Kingdom	A30
31	Hsu et al. (2018)	Switzerland	A31
32	Tapia-Fonllem et al. (2017)	United State	A32

3.1. Contribution of ESE-ESD to the Development of Scientific Literacy

Evidence from the reviewed studies indicates that the integration of Environmental and Sustainability Education (ESE-ESD) makes a substantial contribution to strengthening multiple dimensions of students' scientific literacy. Embedding learning within environmental and sustainability contexts has been shown to enhance scientific reasoning, evidence-based argumentation, data interpretation, ecological conceptual understanding, and decision-making competencies in socio-environmental situations. Inquiry-based studies (Chen et al., 2025; Eymur & Çetin, 2024; Oberbauer et al., 2021; Saunders et al., 2018; Väljataga & Mettid, 2022) consistently report improvements in scientific thinking as students engage directly in observation, problem exploration, data analysis, and the construction of evidence-based conclusions.

Similarly, the Socioscientific Issues (SSI) approach (Georgiou & Kyza, 2023; Paz & Clara, 2025; Pessoa et al., 2025; Van et al., 2024) strengthens scientific literacy by involving students in discussions of complex environmental problems that require them to critically evaluate scientific information, integrate social dimensions, and formulate defensible scientific arguments. Citizen science initiatives (Hsu et al., 2018; Oberbauer et al., 2021; Saunders et al., 2018; Schleicher & Schmidt, 2020) provide authentic scientific experiences that deepen understanding of scientific processes through field data collection, repeated observations, and participation in community-based research. Additionally, approaches such as ecological literacy and identity-based environmental learning (AlAli et al., 2025; Baena-morales et al., 2024; Jensen & Jensen, 2025; Karmakar, 2024; Tapia-Fonllem et al., 2017; Zidny et al., 2021) cultivate strong ecological understanding and positive attitudes toward science affective foundations that are essential for sustained engagement in scientific inquiry and for the holistic development of scientific literacy.

Across the reviewed studies, the contribution of ESE–ESD appears to vary according to the dimension of scientific literacy being assessed. Inquiry-based learning, SSI, and citizen science approaches consistently support cognitive and procedural dimensions, including scientific reasoning, inquiry skills, and evidence-based argumentation. In contrast, ecological literacy, identity-based learning, and behavior-oriented sustainability approaches primarily strengthen affective dimensions such as environmental awareness, motivation, ecological identity, and sustainability values. This pattern suggests that ESE-ESD does not contribute uniformly across all dimensions of scientific literacy; rather, different pedagogical approaches tend to promote different aspects of scientific literacy. Consequently, scientific literacy within ESE-ESD contexts should be understood as a multidimensional construct that develops through complementary learning experiences rather than through a single instructional model. This finding suggests that the effectiveness of ESE-ESD should not be evaluated solely

through gains in scientific knowledge or cognitive achievement. Rather, comprehensive evaluation requires consideration of cognitive, procedural, epistemic, and affective dimensions, as different pedagogical approaches appear to influence different aspects of scientific literacy.

To further synthesize the reported outcomes across studies, Table 5 presents the major patterns of scientific literacy contributions associated with ESE-ESD integration. Rather than ranking interventions according to effectiveness, the table categorizes studies based on the dominant dimensions of scientific literacy reported in their findings, thereby facilitating comparison across diverse pedagogical approaches and research contexts.

Table 5. Patterns of Reported Contributions of ESE-ESD Integration to Scientific Literacy

Contribution Pattern	Key Scientific Literacy Outcomes	Article Codes
Multi-dimensional Contributions	Reasoning, inquiry skills, argumentation, data interpretation, decision-making	A1, A7, A14, A23, A24, A30
Cognitive and Awareness Contributions	Awareness, eco-identities, content knowledge	A2, A10, A16, A18, A25, A31, A32
Affective and Motivational Contributions	Attitudes, motivation, perceptions	A3, A9, A11, A12, A26
Conceptual Contributions	Conceptual frameworks, models of integration	A5, A8, A13, A17, A19, A27

The categories presented in Table 5 should not be interpreted as measures of causal effectiveness. Rather, they represent patterns of reported outcomes identified through qualitative synthesis of the included studies. Studies classified as "Multi-dimensional Contributions" reported outcomes across multiple dimensions of scientific literacy, particularly reasoning, inquiry, argumentation, and decision-making. "Cognitive and Awareness Contributions" primarily reported gains in ecological understanding, environmental awareness, and content knowledge, whereas "Affective and Motivational Contributions" focused on attitudes, motivation, and perceptions toward sustainability-related issues. "Conceptual Contributions" refer to studies that proposed theoretical or conceptual frameworks without directly assessing student outcomes. This categorization was developed to facilitate cross-study comparison rather than to establish a hierarchy of intervention effectiveness.

From a science education perspective, the environmental and sustainability issues addressed in the reviewed studies including climate change, biodiversity loss, pollution, resource management, and sustainable consumption provide meaningful contexts for scientific literacy development. These issues require students not only to understand scientific concepts but also to evaluate evidence, analyze uncertainty, and make informed decisions regarding complex environmental challenges. Consequently, ESE-ESD integration supports the application of scientific knowledge to real-world sustainability problems, which aligns with contemporary views of scientific literacy as a competence for responsible citizenship and environmental decision-making.

3.2. Effective Pedagogical Models and Approaches

A review of the included studies shows that eleven categories of pedagogical approaches have been implemented to integrate ESE-ESD in ways that strengthen students' scientific literacy. Among these approaches, inquiry-based learning emerges as the most widely applied and consistently impactful model, particularly in enhancing scientific reasoning and argumentation (Chen et al., 2025; Eymur & Çetin, 2024; Oberbauer et al., 2021; Saunders et al., 2018; Väljataga & Mettid, 2022). Socioscientific Issues (SSI) also play a central role, as they blend scientific concepts with socially relevant challenges, helping students understand how scientific knowledge intersects with sustainability and public decision-making (Georgiou & Kyza, 2023; Paz & Clara, 2025; Pessoa et al., 2025; Van et al., 2024).

Citizen science contributes by promoting direct engagement with real environmental data, enabling learners to collect, interpret, and apply scientific information in authentic contexts (Hsu et al., 2018; Oberbauer et al., 2021; Saunders et al., 2018; Schleicher & Schmidt, 2020). Other approaches including green chemistry (Basheer et al., 2025; Bourn & Soysal, 2021; Celestino, 2023), ecological literacy (AlAli et al., 2025; Jensen & Jensen, 2025; Karmakar, 2024; Zidny et al., 2021), game-based learning (Jhang & Lin, 2025; Kramar & Knez, 2025), and transformative learning (Ajaps, 2023; Bourn & Soysal, 2021) demonstrate varied but meaningful contributions, particularly in nurturing environmental awareness, conceptual understanding, and dispositions that support long-term engagement with scientific and sustainability issues.

To facilitate comparison across studies, the pedagogical models and approaches identified in the reviewed literature are summarized in Table 6. The table illustrates the diversity of instructional approaches employed to integrate ESE-ESD into science education and highlights the predominance of inquiry-based learning, SSI, and citizen science approaches.

Table 6. Summarizes the pedagogical models identified across the reviewed studies and their distribution within the literature

No	Models	Number of Article	Article Code
1	Socioscientific Issues	4	A7, A11, A16, A24
2	Inquiry-based Learning	5	A1, A14, A21, A23, A30
3	Citizen Science	4	A23, A29, A30, A31
4	Green Chemistry / ESD Chemistry	3	A10, A18, A27
5	Ecological/Eco-literacy	4	A2, A5, A15, A25
6	Sustainability Curriculum	3	A3, A11, A17
7	Transformative Learning	2	A19, A27
8	Psychological/Identity	2	A2, A13
9	Hybrid/Game-based Learning	2	A4, A6
10	Theoretical and Conceptual Model	6	A5, A8, A13, A17, A19, A27
11	Behavior-based ESD Model	2	A12, A32

As shown in Table 6, inquiry-based learning, Socioscientific Issues (SSI), and citizen science represent the most frequently reported pedagogical approaches associated with scientific literacy development. These approaches share a common characteristic of actively engaging students in scientific inquiry, evidence evaluation, and real-world environmental problem solving. In contrast, ecological literacy, transformative learning, and identity-based approaches appear more strongly connected to affective and value-oriented dimensions of scientific literacy, highlighting the complementary roles of different pedagogical models within ESE-ESD integration.

3.3. Conceptual, Theoretical, and Methodological Gaps in Research

The literature reveals several critical gaps that warrant attention. Notably, there is a pronounced geographical bias: nearly all studies are situated within developed-country contexts, leaving empirical insights from the Global South largely absent. Additionally, an imbalance exists in the educational levels addressed; research overwhelmingly focuses on secondary and higher education, while primary, early childhood, non-formal, and community-based settings remain underexplored. Most interventions are also short-term, which constrains understanding of the sustained impacts of ESE-ESD integration on scientific literacy. Furthermore, many studies examine only a limited subset of scientific literacy dimensions often cognitive or affective hindering a comprehensive understanding of the interplay among these dimensions. Conceptually, existing ESE-ESD integration models frequently lack fully developed theoretical frameworks, particularly in articulating the complex relationships between scientific competence, sustainability values, and environmental identity. Collectively, these gaps underscore the need for more geographically diverse, longitudinal, and theoretically grounded research to advance both understanding and practice in this field.

Beyond these descriptive gaps, the reviewed studies reveal deeper conceptual and methodological challenges. The strong concentration of research in European contexts suggests that current understandings of ESE-ESD and scientific literacy may be shaped by specific socio-cultural, educational, and policy environments. Consequently, the applicability of existing findings to regions characterized by different environmental priorities, educational infrastructures, and sustainability challenges remains uncertain. This limitation raises important questions regarding the contextual transferability of current ESE-ESD models and highlights the need for more geographically diverse evidence. Methodologically, considerable variation exists in how scientific literacy is conceptualized and measured. While some studies operationalize scientific literacy through scientific knowledge, reasoning, and inquiry skills, others emphasize attitudes, environmental awareness, or sustainability-related behaviors. Such inconsistencies make cross-study comparisons difficult and limit the possibility of determining which pedagogical approaches most effectively foster comprehensive scientific literacy. The absence of standardized multidimensional assessment frameworks therefore represents a significant methodological challenge for future research.

At the theoretical level, many studies implicitly assume that participation in sustainability-oriented learning environments will automatically enhance scientific literacy. However, relatively few studies explicitly explain the mechanisms through which environmental and sustainability contexts contribute to the development of scientific reasoning, evidence evaluation, argumentation, and decision-making competencies. Future studies would benefit from more integrative theoretical frameworks capable of explaining how scientific knowledge, sustainability competencies, environmental identity, and responsible action interact within ESE-ESD learning processes. Table 7 summarizes the educational levels represented in the reviewed studies. The distribution reveals a clear concentration of research at secondary and higher education levels, whereas early childhood, community-based, and non-formal educational settings remain comparatively underrepresented. This imbalance may influence current understandings of how ESE-ESD contributes to scientific literacy across different learner populations. Taken together, these conceptual, theoretical, and methodological gaps indicate that future ESE-ESD research should prioritize longitudinal designs, broader geographical representation, multidimensional scientific literacy assessments, and theoretically integrated models capable of explaining how sustainability learning contributes to scientific literacy development.

Table 7. Presents the distribution of educational levels represented in the included studies, highlighting the dominance of secondary and higher education contexts.

No	Educational Level	Article Codes
1	Early Childhood	A15
2	Primary Education (Elementary)	A2, A4, A11, A22
3	Secondary Education (Lower & Upper Secondary)	A1, A14, A16, A18, A20, A21, A23, A24, A30
4	Higher Education (University)	A3, A12, A26, A27, A32
5	Pre-service Teacher Education	A10, A28
6	In-service Teachers	A9
7	Non-formal Youth Education	A7
8	Community-based Education	A31
9	General Population	A29
10	Not Specified	A5, A6, A8, A13, A17, A19, A25

The synthesis of the 32 articles reviewed in this study demonstrates that the integration of Environmental and Sustainability Education (ESE-ESD) plays a significant role in developing students' scientific literacy across various educational levels. Scientific literacy is shown to strengthen more effectively when science learning is embedded within authentic environmental and sustainability contexts, where students are required to reason scientifically, evaluate evidence, and make informed decisions in real-world situations. Inquiry-based learning emerges as the most effective approach, consistently enhancing students' scientific reasoning, argumentation, and data analysis skills (Chen et al., 2025; Eymur & Çetin, 2024; Oberbauer et al., 2021; Saunders et al., 2018; Väljataga & Mettid, 2022). By enabling students to engage directly in scientific processes such as observing phenomena, exploring problems, and constructing evidence-based conclusions this approach provides meaningful opportunities to experience science as a practice.

The Socioscientific Issues (SSI) approach also contributes substantially to the enhancement of scientific literacy by encouraging students to examine the interplay between scientific evidence, social values, and ethical considerations (Georgiou & Kyza, 2023; Paz & Clara, 2025; Pessoa et al., 2025; Van et al., 2024). Exposure to complex issues strengthens students' competencies in argumentation and decision-making, which are essential components of scientific literacy. Meanwhile, citizen science fosters authentic scientific engagement through direct involvement in environmental data collection and interpretation (Hsu et al., 2018; Oberbauer et al., 2021; Saunders et al., 2018; Schleicher & Schmidt, 2020), effectively linking classroom learning with real-life environmental contexts. Other approaches including ecological literacy, identity-based learning, green chemistry, and transformative learning primarily contribute to the affective and dispositional dimensions of scientific literacy (AlAli et al., 2025; Baena-morales et al., 2024; Basheer et al., 2025; Celestino, 2023; Jensen & Jensen, 2025; Karmakar, 2024; Tapia-Fonllem et al., 2017; Zidny et al., 2021). Although these approaches may not always yield substantial cognitive gains, they strengthen students' ecological awareness, motivation, and environmental identity foundational elements that support long-term scientific engagement and sustainability-oriented thinking.

Several challenges also emerge from the literature. The geographical distribution of the reviewed studies is highly concentrated in Europe, particularly in Switzerland and the United Kingdom, which together account for the majority of the included research. This European dominance creates a contextual bias that limits the generalizability of the findings to diverse socio-ecological and cultural settings. Most interventions also span short durations, restricting the ability to evaluate long-term behavioral changes or the sustained development of scientific competencies. Additionally, many studies assess only selected components of scientific literacy, leaving the interactions among cognitive, procedural, epistemic, and affective domains insufficiently understood. Conceptual studies further emphasize the need for integrative theoretical frameworks capable of explaining how scientific knowledge, sustainability values, environmental identity, and scientific action interact within ESE–ESD learning environments.

Importantly, the findings suggest that no single ESE-ESD approach is sufficient to develop all dimensions of scientific literacy simultaneously. Rather, different pedagogical approaches appear to contribute to different dimensions of scientific literacy, with inquiry-based and SSI approaches more strongly associated with cognitive and procedural outcomes, while ecological literacy and identity-based approaches primarily support affective and dispositional outcomes. This indicates the need for more integrated pedagogical frameworks capable of fostering scientific literacy as a multidimensional construct. Overall, while ESE-ESD approaches have been shown to effectively enhance multiple dimensions of scientific literacy, future research must address methodological consistency, expand geographical contexts, and employ multidimensional assessments to develop a more comprehensive understanding of how scientific literacy evolves within sustainability-oriented science education.

4. Conclusion

This Systematic Literature Review demonstrates that the integration of Environmental and Sustainability Education (ESE-ESD) within science education contributes substantially to the development of students' scientific literacy across multiple educational contexts. The synthesis of 32 empirical studies indicates that environmental and sustainability-based learning environments provide meaningful contexts through which learners can strengthen scientific reasoning, inquiry skills, evidence-based argumentation, data interpretation, ecological understanding, and informed decision-making regarding complex socio-environmental issues. The findings further reveal that the contribution of ESE-ESD is multidimensional rather than uniform, with inquiry-based learning, Socioscientific Issues (SSI), and citizen science approaches showing the strongest association with cognitive and procedural dimensions of scientific literacy, while ecological literacy, identity-based learning, transformative learning, and sustainability-oriented approaches contribute more prominently to affective, motivational, and value-related dimensions. Consequently, no single pedagogical model appears sufficient to foster all dimensions of scientific literacy simultaneously, highlighting the importance of combining complementary approaches within sustainability-oriented science education. This review also identifies significant conceptual, theoretical, and methodological gaps within the existing literature, including a strong geographical concentration of studies in European contexts, limited representation of the Global South, an overemphasis on secondary and higher education settings, the predominance of short-term interventions, and considerable inconsistencies in the conceptualization and assessment of scientific literacy across studies. These limitations restrict the generalizability of current findings and hinder the development of a comprehensive understanding of how ESE-ESD supports scientific literacy development over time. Therefore, future research should prioritize geographically diverse and longitudinal investigations, employ multidimensional scientific literacy assessment frameworks, and develop more robust theoretical models capable of explaining the interactions among scientific knowledge, inquiry competencies, sustainability values, environmental identity, and responsible action. Overall, the evidence synthesized in this review suggests that ESE-ESD represents a promising pathway for advancing scientific literacy in the twenty-first century by connecting scientific learning with authentic sustainability challenges and preparing learners to participate critically, responsibly, and effectively in addressing complex environmental and societal issues.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability

The datasets generated during and/ or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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