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EDUCATION FOR SUSTAINABLE DEVELOPMENT IN CHEMISTRY EDUCATION: A SYSTEMATIC LITERATURE REVIEW OF RESEARCH TRENDS, PEDAGOGICAL APPROACHES, AND ENVIRONMENTAL AWARENESS

Alfira Julian Pratiwi [1*], Rafidah Almira Samosir [1], Wulan Dwi Safitri[1], Mutia Ardila [1], Ekin Dwi Arif Kurniawan [1]
[1]Chemistry Education Study Program, State University of Medan, Medan, Indonesia
[*]Email: alfirajulian@unimed.ac.id

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ABSTRACT

This study synthesizes research on the integration of Education for Sustainable Development (ESD) into chemistry education through a Systematic Literature Review (SLR). Following the PRISMA 2020 framework, 22 research journal articles published between 2022 and 2026 were identified from five academic databases and analyzed using thematic synthesis. The literature search was conducted up to May 14, 2026, identifying five publications for 2026; therefore, these five publications represent only the studies available up to the final search date. The findings reveal a fluctuating publication pattern, with the highest number of studies identified in 2025. The reviewed studies originated from diverse geographical contexts, with Indonesia contributing the largest number of publications. Most studies were conducted in high school or secondary school settings, followed by higher education, with high school students and pre-service or prospective teachers being the most frequently represented participants. Green Chemistry and its derivatives were the most frequently reported approaches, followed by Problem-Based Learning, Socio-Scientific Issues, ESD-based STEM/STEAM, and Project-Based Learning. The reported environmental awareness outcomes covered diverse dimensions of environmental and sustainability awareness, including environmental issues, pollution and waste, responsibility, sustainability, and resource use. The review also identified challenges in curriculum integration, teachers' knowledge and pedagogical capacity, and institutional support, while highlighting opportunities through teacher professional development, contextual and project-based learning, sustainability competency development, and institutional and interdisciplinary collaboration. These findings provide an overview of the current landscape and directions of ESD integration in chemistry education.

Keywords: Education for Sustainable Development (ESD), chemistry education, systematic literature review, environmental awareness

INTRODUCTION

Global environmental challenges, such as climate change, water and air pollution, and increasing waste generation, have become major barriers to achieving sustainable development in the twenty-first century (Borreguero et al., 2024). Human activities that ignore environmental balance have led to ecosystem degradation, thereby affecting the well-being of both present and future generations (Perwitasari et al., 2023). This situation has encouraged various countries to integrate sustainability principles into their education systems as a strategy to build environmental awareness and responsibility (Despotović et al., 2021). Education is seen as a crucial instrument for shaping knowledge, attitudes, and behaviors that support sustainable development. Through its Education for Sustainable Development (ESD) initiative, UNESCO highlights the importance of equipping learners with the knowledge, skills, and competencies needed to address environmental, social, and economic challenges in support of sustainable development (UNESCO, 2014; UNESCO, 2018).

ESD represents an educational approach that incorporates environmental, social, and economic perspectives into the teaching and learning process. Through this approach, learners are expected not only to develop an understanding of sustainability concepts but also to acquire the ability to make responsible decisions that contribute to environmental protection and social well-being (Widyawati et al., 2025). The growing emphasis on ESD reflects its recognized contribution to achieving the Sustainable Development Goals (SDGs), especially SDG 4 on quality education. Previous studies have reported that integrating ESD into learning promotes environmental literacy and strengthens students' critical thinking, problem-solving skills, and understanding of sustainability issues (Refmidawati & Megahati S, 2023; Vidal & Kuckuck, 2025).

Within science education, especially in the field of chemistry education, the application of ESD has strong relevance (Miladinović, 2024; Refmidawati & Megahati S, 2023). Chemistry studies various phenomena directly related to sustainability issues, such as environmental pollution, waste management, renewable energy, green chemistry, natural resource utilization, and the design of environmentally sustainable materials (Tabasso et al., 2020; Zuin et al., 2021). Therefore, chemistry education provides an important platform for developing students' environmental awareness while strengthening the sustainability competencies through learning that connects chemical concepts to real-world problems in society (Miladinović, 2024; Refmidawati & Megahati S, 2023). Recent research shows that chemistry education integrating sustainable development issues commonly focuses on topics such as comparing conventional

plastics with biodegradable alternatives, water pollution, green experiments, the use of environmentally friendly pesticides, and natural-based biodiesel (Anggraeni & Rohaeti, 2026; Hasanah et al., 2025; Mellyzar et al., 2025).

In line with these developments, various ESD-based learning strategies have begun to be implemented in chemistry education. Problem-Based Learning (PBL) approaches (Vaz et al., 2025), Project-Based Learning (PjBL) (Gusmiarni & Jufri, 2024), Socio-Scientific Issues (SSI), green chemistry, and sustainability-based STEM are among the approaches used to integrate sustainable development issues into learning. For example, recent research has implemented PBL-based learning contextualized with Socio-Scientific Issues (SSI) in chemistry education. (S. W. Putri et al., 2025) Compared with conventional instructional approaches, the integration of ESD has been shown to produce greater improvements in students' chemical literacy and environmental awareness. (Susilawati et al., 2021)

Evidence from previous studies indicates that ESD-oriented green chemistry instructional materials not only improve students' understanding of environmental issues but also develop their critical thinking skills and inspire them to adopt behaviors that support sustainable development (Sunday et al., 2025; Widyawati et al., 2025). These findings suggest that the effectiveness of ESD implementation largely depends on educators' readiness, highlighting the need to strengthen ESD integration in pre-service chemistry teacher education (Widyawati et al., 2025). Accordingly, pre-service chemistry teacher education should systematically embed ESD principles to ensure that future teachers not only acquire a strong foundation in chemistry but also develop the capacity to design sustainability-oriented learning experiences (T. S. Putri & Rohaeti, 2025; Timbuleng et al., 2024). As a result, an increasing number of studies have explored how ESD can be integrated into chemistry education and evaluated its effects on learning outcomes and students' environmental awareness.

The growing number of studies on the integration of ESD into chemistry education highlights the need for a systematic review to examine research trends, instructional approaches, and their contribution to students' environmental awareness (Inayah et al., 2022). Through the systematic synthesis of findings across a range of educational contexts, an SLR provides a more holistic understanding of a research topic than isolated empirical studies (Page et al., 2021). However, existing research is still scattered across various educational levels, learning models, and competency focuses, such as environmental awareness, chemical literacy, critical thinking skills, and sustainability competencies (Mellyzar et al., 2025). Although numerous studies have investigated ESD in chemistry education, evidence integrating their findings to explain its

contribution to students' environmental awareness is still limited (Hasanah et al., 2025). Unlike previous studies, which generally discussed the integration of ESD or Green Chemistry in general, this study synthesizes the implementation of ESD in chemistry education with an emphasis on environmental awareness and identifies trends, challenges, and opportunities for its implementation for the 2022–2026 period.

In response to this research gap, the present study employs a Systematic Literature Review (SLR) to synthesize studies published between 2022 and 2026 on the integration of ESD into chemistry education. The review seeks to map publication trends, examine approaches to ESD implementation, evaluate their contributions to environmental awareness and sustainability competencies, and identify the major challenges associated with their implementation. The findings are expected to provide valuable evidence for improving chemistry education curricula, informing sustainability-oriented instructional practices, and guiding future research in chemistry education.

RESEARCH METHODS

Research Design

This study employed a Systematic Literature Review (SLR) to synthesize empirical research on the integration of ESD into chemistry education, including reported environmental awareness outcomes. The review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (Page et al., 2021). The review process consisted of five main stages: literature searching, study screening and eligibility assessment, methodological quality appraisal, data extraction, and thematic synthesis. These procedures were designed to support a transparent and systematic process of study identification, selection, appraisal, and synthesis.

Research Questions

The review was guided by four research questions (RQs), which were formulated to define the scope of the review and guide the literature search, study selection, data extraction, and synthesis. The research questions are presented in Table 1.

Table 1. Research Questions (RQ)

Codes	Research Questions
RQ1	How have research trends on the integration of Education for Sustainable Development (ESD) into chemistry education evolved between 2022 and 2026?
RQ2	What learning models, approaches, and strategies are used to integrate ESD in chemistry education?

RQ3	What environmental awareness outcomes are reported in studies of ESD implementation in chemistry education?
RQ4	What challenges and opportunities are associated with the implementation of Education for Sustainable Development (ESD) in chemistry education?

Information Sources and Search Strategy

A systematic literature search was conducted using five academic databases: Scopus, ERIC, Dimensions, Google Scholar, and Garuda. These databases were selected to obtain relevant international and Indonesian publications addressing Education for Sustainable Development (ESD), sustainability-oriented approaches, and chemistry education. The final search was conducted on May 14, 2026, and the search period was limited to publications from 2022 to 2026.

The search strategy was developed around two primary concepts: ESD and chemistry education. Related terms and synonyms were combined using the Boolean operator "OR" within each concept, while the two concepts were connected using "AND." Environmental awareness was treated as a key analytical focus rather than a mandatory search concept to avoid excluding relevant studies that examined environmental awareness using related terms or reported it as an outcome without explicitly using the term "environmental awareness." The core search strings and the number of records retrieved are documented in Table 2.

Table 2. Database-Specific Search Strategies

Data base	Search Date	Search Field	Records Retrieved	Search String
Scopus	May 14, 2026	TITLE-ABS-KEY	112	(("Education for Sustainable Development" OR ESD OR "sustainable development education" OR "education for sustainability" OR "sustainability education") AND ("chemistry education" OR "chemistry teaching" OR "chemistry learning" OR "chemical education" OR "chemistry instruction"))
ERIC	May 14, 2026	Title/Abstract/ Descriptors	56	
Dimensions	May 14, 2026	Title and Abstract	138	
Google Scholar	May 14, 2026	Search interface	214	
Garuda	May 14, 2026	Search interface	37	

Screening and Eligibility Assessment

Following the database search, all retrieved records were compiled into a single reference database, and duplicate records were identified and removed before the screening process. A total of 557 records were identified from five databases: Scopus (n = 112), ERIC (n

= 56), Dimensions (n = 138), Google Scholar (n = 214), and Garuda (n = 37). After removing 87 duplicate records, 470 unique records remained for screening.

The screening and study selection process was conducted in two stages and involved three reviewers. In the first stage, the titles and abstracts of the 470 records were screened against the predefined inclusion and exclusion criteria presented in Table 3. Records that did not meet the eligibility criteria were excluded at this stage. Specifically, 352 records were excluded because they were not related to chemistry education, did not discuss ESD, were not relevant to sustainability, or were not research articles. Consequently, 118 records were retained for full-text assessment.

Table 3. Inclusion and Exclusion Criteria

Aspects	Criteria Inclusion	Exclusion Criteria
Year of Publication	2022–2026	Before 2022
Language	Indonesian, English	Other Languages
Document Type	Research Journal Articles	Proceedings, Book, Book Chapters
Topics	ESD in chemistry education	Beyond chemistry education
Article Access	Full text available	Full text not available
Research Focus	Environmental awareness	Not discussing that aspect
Article Description	Peer-reviewed	Non peer-reviewed

In the second stage, the full texts of the 118 potentially eligible articles were assessed against the same predefined eligibility criteria. At this stage, 96 articles were excluded because the full text was not available (n = 18), the publication was a review article (n = 22), the publication was a conference proceeding (n = 15), and the study did not measure or discuss environmental awareness (n = 41). Following the full-text assessment, 22 studies met all eligibility criteria and were included in the final systematic literature review.

The three reviewers participated in the screening and eligibility assessment. Screening decisions were reviewed among the reviewers to ensure consistency in the application of the eligibility criteria. Any disagreements regarding study eligibility were discussed among the three reviewers and resolved through consensus. The complete study selection process is presented in the PRISMA flow diagram (Figure 1).

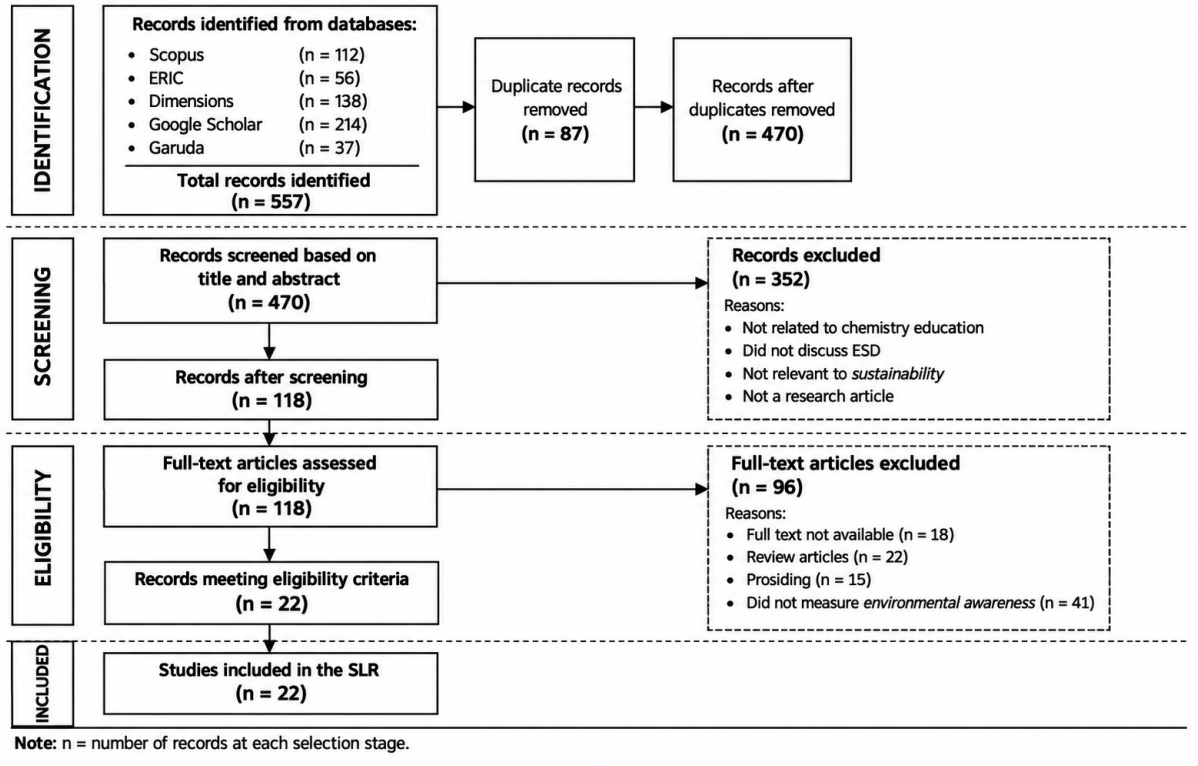


Figure 1. Article Selection Flow Chart Based on PRISMA 2020

Methodological Quality Appraisal

The methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018). Because the included studies employed different research designs, each study was assessed using the MMAT criteria applicable to its respective design. The assessment began with two screening questions addressing the clarity of the research question or objective and the appropriateness of the collected data for addressing the research question or objective. Subsequently, five design-specific methodological criteria were applied according to the research design of each study. These criteria addressed aspects of sampling, measurement, data completeness, confounding, data collection and analysis, and coherence or integration of findings, as applicable to each design. Each criterion was rated as "Yes," "No," or "Can't tell." Three reviewers participated in the appraisal process, and disagreements were discussed and resolved through consensus. The appraisal findings were used to identify methodological strengths and limitations and to inform the interpretation of the synthesized evidence. Detailed study-level appraisal results are provided in Supplementary Table S1.

Data Extraction Procedure

Data extraction was conducted using a predefined data extraction framework developed to ensure consistency and alignment with the four research questions. The framework specified the variables to be extracted from each included study, including study code, publication year, country, research design, educational level, chemistry topic, learning model or approach, learning strategy, environmental awareness outcomes, assessment methods, challenges, and opportunities (Supplementary Table S2). For each of the 22 included studies, relevant information was extracted from the full text and recorded in a structured data extraction matrix (Supplementary Table S3). The extraction process was conducted by the three reviewers involved in the study selection process. Each reviewer examined the eligible articles and recorded information according to the predefined variables. The extracted information was subsequently compared among the reviewers to ensure consistency and completeness. Any discrepancies in the extracted data were discussed among the three reviewers and resolved through consensus. The finalized extraction matrix was then used as the basis for the descriptive synthesis and thematic analysis addressing the four research questions.

Data Synthesis and Thematic Analysis

The extracted data were synthesized using descriptive and thematic approaches. RQ1 was addressed through descriptive synthesis of publication year, country, educational level, and research design to identify research trends. For RQ2, RQ3, and RQ4, the extracted qualitative information was analyzed thematically. First, relevant findings were assigned initial codes representing the learning models and strategies, environmental awareness outcomes, and challenges and opportunities reported across the studies. Second, codes with similar meanings were grouped into broader categories based on conceptual similarities. Third, related categories were compared across studies and synthesized into overarching themes corresponding to RQ2, RQ3, and RQ4. The resulting themes were reviewed against the extracted data to ensure that they were supported by the findings of the included studies. A single study could contribute to more than one category or theme when its findings addressed multiple aspects of a research question. The final coding and thematic synthesis are presented in Supplementary Table S4.

RESULTS AND DISCUSSION

Methodological Quality of the Included Studies

Following the PRISMA 2020 study selection process, 22 studies that met all predefined eligibility criteria were included in the systematic literature review. The methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018). Because the included studies employed different research designs, each study was appraised using the MMAT criteria corresponding to its respective design. The appraisal comprised two screening questions and five design-specific methodological criteria. The screening questions assessed whether the research question or objective was clearly stated and whether the collected data were appropriate for addressing the research question or objective. The design-specific criteria were then applied according to the methodological design of each study, covering aspects such as sampling, measurement, outcome completeness, confounding, data collection and analysis, and coherence or integration of findings, as applicable. Three reviewers participated in the appraisal process, and any disagreements were discussed and resolved through consensus.

The 22 included studies comprised 10 quantitative descriptive studies, four quantitative non-randomized studies, seven qualitative studies, and one mixed-methods study. These classifications followed the methodological orientation of the respective studies rather than being determined solely by the presence of numerical data or descriptive statistical analysis. The complete study-level appraisal, including the applicable MMAT criteria and individual judgments, is presented in Supplementary Table S1. For descriptive interpretation, the appraisal responses were additionally summarized using a predefined numerical scheme. “Yes,” “Can’t tell,” and “No” were assigned values of 1, 0.5, and 0, respectively, and the resulting values were converted into percentages. This numerical summary was used only to provide a descriptive overview of methodological appraisal across the included studies. It was not considered an official MMAT score and was not used as an automatic criterion for study exclusion.

As shown in Table 4, 15 studies (68.18%) had high descriptive appraisal values (≥80%), while seven studies (31.82%) had moderate values (60–79%). No study fell within the low category (<60%). Among the 10 quantitative descriptive studies, five were categorized as high and five as moderate. Of the four quantitative non-randomized studies, two were categorized as high and two as moderate. All seven qualitative studies were categorized as high, as was the single mixed-methods study. The descriptive appraisal therefore indicates that the included

studies generally demonstrated adequate methodological characteristics for synthesis, while some studies contained criteria rated as "Can't tell" or "No." The criterion-level judgments provide a more detailed indication of specific methodological strengths and limitations across the studies.

Table 4. Descriptive Summary of Methodological Appraisal of the Included Studies

Research design	No. of studies	High (≥80%)	Moderate (60–79%)	Low (<60%)
Quantitative descriptive	10	5 (A1, A2, A14, A15, A16)	5 (A4, A8, A9, A12, A20)	0
Quantitative non-randomized	4	2 (A17, A18)	2 (A21, A22)	0
Qualitative	7	7 (A3, A5, A6, A7, A11, A13, A19)	0	0
Mixed methods	1	1 (A10)	0	0
Total	22	15	7	0

The "Can't tell" and "No" judgments were interpreted as indications of insufficient methodological information or potential methodological limitations rather than as automatic grounds for exclusion. Accordingly, the appraisal findings were used to identify methodological strengths and limitations and to support a cautious interpretation of the synthesized evidence. Detailed study-level judgments are provided in Supplementary Table S1.

Characteristics of Analyzed Articles

The findings of the analysis and synthesis reveal that the selected studies were published between 2022 and 2026 and represent research conducted across diverse geographical and educational contexts. To characterize the reviewed literature, the studies were analyzed based on three main aspects: country of origin, educational setting, and participant characteristics. These categories provide an overview of the geographical distribution of the research, the educational contexts in which ESD was implemented, and the groups involved in the studies. For 2026, the literature search identified five publications (22.73%) up to the final search date of May 14, 2026. Therefore, the number of studies identified for 2026 represents publications available up to the search date and does not reflect the complete publication output for the entire year.

Based on the country of origin of the research Indonesia had the highest number of publications (Mellyzar et al., 2025; Mitarlis et al., 2023; T. S. Putri & Rohaeti, 2025; Rahmawati et al., 2022; Solihah et al., 2024), with 5 articles (22.73%), followed by Germany

with 2 articles (9.09%) (Linkwitz & Eilks, 2022; Liskes & van Vorst, 2026). Meanwhile, China (Li & Eilks, 2024), Thailand (Yeerum et al., 2022), Japan (Imai et al., 2022), Chile (Martinez & Rushton, 2025a), Spain (Alfonso & Yáñez, 2024), Kazakhstan (Zhadyra et al., 2026), Colombia (Herrera et al., 2026), Brazil (Júnior et al., 2026), India (Yenduri et al., 2026), Singapore (Widyantoro et al., 2025), the Philippines (Ramirez & Paderna, 2025), and several international collaborative studies each contributed one article (4.55%) (Dobbelaar & Richter, 2022; Tantayanon et al., 2025). The geographical distribution of the reviewed studies reflects the increasing global interest in integrating ESD into chemistry education across diverse educational environments (Quiroz-Martinez & Rushton, 2025). Table 5 provides an overview of the main characteristics of the studies included in this review.

Table 5. Characteristics of Analyzed Articles

Characteristics	Categories	Frequency (f)	Percentage (%)
Countries	Indonesia	5	22.73
	Germany	2	9.09
	China	1	4.55
	Thailand	1	4.55
	Japan	1	4.55
	Chile	1	4.55
	Spain	1	4.55
	Kazakhstan	1	4.55
	Colombia	1	4.55
	United Kingdom–United States	2	9.09
	Brazil	1	4.55
	India	1	4.55
	Singapore	1	4.55
	Thailand–Sri Lanka–Philippines	1	4.55
	Philippines	1	4.55
	Multi-country (22 countries)	1	4.55
	Total	22	100.00
Educational Setting	Higher Education	9	40.90
	High School / Secondary School	13	59.10
	Total	22	100.00
Participants	High School Students	11*	—
	Pre-service / Prospective Teachers	8*	—
	Current Chemistry/Science Teachers	4*	—
	Lecturers / Faculty / Program Heads	2*	—

**Note: Frequencies for participants may exceed the total number of reviewed articles because individual studies could be classified into more than one category. Therefore, percentages are not reported for these categories.*

The distribution of educational settings indicates that research on ESD in chemistry education has been carried out at several educational levels. Secondary or high school was the

most common context, accounting for 13 of the 22 articles (59.1%). This was followed by higher education, which was identified in 9 articles (40.9%). The larger proportion of studies at the secondary school level suggests that this stage of education has become an important context for examining the application of ESD in chemistry learning (Li & Eilks, 2024; Linkwitz & Eilks, 2022; Zhadyra et al., 2026). At this level, chemistry education can provide opportunities for students to connect scientific concepts with environmental issues and sustainability challenges encountered in everyday life (Liskes & van Vorst, 2026; Ramirez & Paderna, 2025). The considerable number of studies in higher education also indicates growing attention to sustainability within university-based chemistry learning and teacher preparation. Such attention reflects the strategic role of chemistry students and prospective teachers as agents of change, who are expected to develop the capacity to integrate sustainability principles into educational practices as well as real-life contexts (Poya, 2026; T. S. Putri & Rohaeti, 2025).

The participant characteristics further show that ESD research in chemistry education involves groups with different educational roles. High school students constituted the largest participant group, occurring in 11 studies, followed by pre-service or prospective teachers in 8 studies. Current chemistry or science teachers were involved in 4 studies, whereas lecturers, faculty members, or program heads were included in 2 studies. This distribution suggests that research on ESD in chemistry education extends beyond students' learning experiences to include the preparation and professional development of teachers, as well as perspectives from higher education stakeholders (Mellyzar et al., 2025). The relatively substantial involvement of pre-service teachers is particularly relevant because their understanding of sustainability may influence how ESD is subsequently incorporated into classroom practice (Imai et al., 2022; Mitarlis et al., 2023; T. S. Putri & Rohaeti, 2025). It should also be noted that the participant categories were not mutually exclusive, as some studies involved more than one participant group. Consequently, the frequencies in this category exceed the total number of articles included in the review and should not be interpreted as mutually exclusive article counts.

Research Trends in ESD in Chemistry Education (RQ1)

The synthesized evidence indicates a fluctuating pattern of research publications on the integration of ESD into chemistry education during the 2022–2026 period. As shown in Figure 2, the number of publications decreased from 5 articles in 2022 to 1 article in 2023, before increasing to 4 articles in 2024 and reaching a peak of 7 articles in 2025. For 2026, five publications were identified based on the literature search conducted through May 14, 2026;

therefore, this figure represents only publications available up to the search date. Overall, the publication pattern does not demonstrate a consistent upward trend, but rather reflects fluctuations in research activity, with the highest number of publications recorded in 2025.

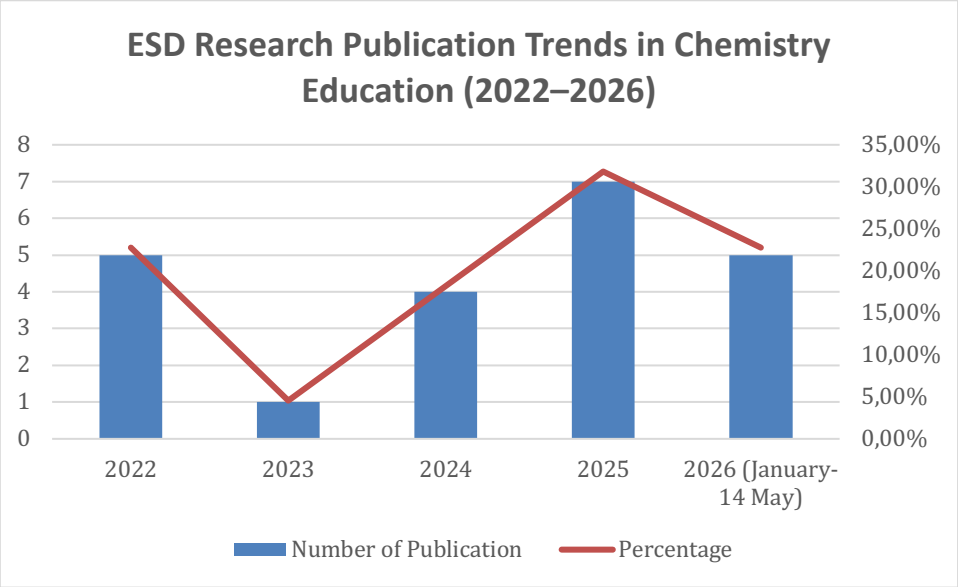


Figure 2. Trends in ESD Research Publications in Chemistry Education in 2022–2026

Based on Figure 2, the number of publications in 2022 was recorded at 5 articles (Dobbelaar & Richter, 2022; Linkwitz & Eilks, 2022; Yeerum et al., 2022), or 22.73% of the total articles analyzed. This number decreased significantly in 2023 to 1 article (4.55%) (Mitarlis et al., 2023). This decrease may be due to the limited number of studies explicitly examining the implementation of ESD in chemistry education during that period, especially those that met the inclusion criteria for this study.

In 2024, the number of publications increased again to 4 articles (18.18%). This increase in the number of publications indicates a trend consistent with various recent studies emphasizing the importance of integrating sustainability aspects into chemistry education through the development of relevant curricula, teaching materials, and learning models (Martinez, 2024; Mellyzar et al., 2025; Widyawati et al., 2025). In addition, Green Chemistry and Sustainability Literacy (Mellyzar et al., 2025) are gaining increasing attention as effective approaches to foster environmental awareness, enhance critical thinking skills, and develop students' sustainability competencies (Quiroz-Martinez & Rushton, 2025). This phenomenon could be one of the factors driving the increase in the number of publications in 2025, indicating growing interest among the scientific community in the strategic role of chemistry education in supporting the sustainable development agenda (Li & Eilks, 2024; Salsabila & Hernani, 2025).

Research activity reached its peak in 2025, when seven studies (31.82%) were published, representing the highest annual publication output during the review period. This increase suggests a growing scholarly interest in integrating ESD into chemistry education, reflecting broader international efforts to support the Sustainable Development Goals (SDGs) (Salsabila & Hernani, 2025). In particular, the trend aligns with the increasing emphasis on SDG 4, which promotes quality education and the integration of sustainable development into educational systems (Rahmawati et al., 2022; Ramirez & Paderna, 2025).

In 2026, the number of identified publications decreased to 5 articles (22.73%) compared with 7 articles in 2025. Nevertheless, five publications had already been identified by the final search date, indicating continued research activity on the integration of ESD in chemistry education during the early part of 2026 (Liskes & van Vorst, 2026; Yenduri et al., 2026). It should be noted that the literature search was conducted up to May 14, 2026. Therefore, the five publications identified for 2026 do not represent the total number of publications that may have been published during the remainder of the year. Thus, the number of publications identified for 2026 may increase as additional publications become available after the final search date, providing further evidence of research activity in ESD and chemistry education (Mellyzar et al., 2025). Overall, despite the year-to-year fluctuations, the identification of publications throughout the review period indicates continued research activity on the integration of sustainability principles into chemistry education (Dobbelaar & Richter, 2022; Herrera et al., 2026; Mellyzar et al., 2025).

Models and Strategies for the Implementation of ESD in Chemistry Education (RQ2)

A synthesis of 22 articles shows that the implementation of ESD in chemistry education is carried out through various learning models and strategies that link chemical concepts to sustainability issues. In this context, ESD serves as an overarching educational framework for integrating sustainability principles into chemistry education, while Green Chemistry and related approaches are used as instructional approaches through which these principles can be addressed in chemistry learning. Based on the analysis in Table 6, Green Chemistry and related approaches were the most frequently reported approaches among the reviewed studies, appearing in 10 articles. These approaches included Green Chemistry (Widyantoro et al., 2025), Green Analytical Chemistry (GAC) (Yeerum et al., 2022), Green and Sustainable Chemistry (GSC) (Yenduri et al., 2026; Zuin et al., 2021), and Green Chemistry Education (Zuin et al., 2021). Their primary focus is on encouraging more environmentally friendly chemistry

practices through waste reduction, the use of safer materials, energy efficiency, and sustainable resource utilization.

The high use of the Green Chemistry approach indicates that ESD integration in chemistry education is often achieved by connecting chemistry material to environmental issues faced by society (Salsabila & Hernani, 2025). Various studies have shown that this approach not only helps students understand the concept of sustainability but also increases environmental awareness, responsible decision-making skills, and an understanding of the role of chemistry in supporting sustainable development (Vaz et al., 2025; Widyantoro et al., 2025; Zuin et al., 2021).

Problem-Based Learning (PBL) was identified as the second most frequently applied instructional approach after Green Chemistry, appearing in five of the reviewed studies (Figure 3). This approach engages students in examining authentic environmental issues and applying their chemistry knowledge to develop appropriate solutions, thereby fostering meaningful connections between scientific concepts and real-world sustainability challenges (T. S. Putri & Rohaeti, 2025; Zhadyra et al., 2026). Therefore, PBL is considered effective in developing critical thinking, problem-solving, scientific argumentation, and decision-making skills, which are essential components of sustainability competencies (Herrera et al., 2026; Mellyzar et al., 2025).

Table 6. ESD Implementation Models and Approaches in Chemistry Education

Learning Models or Approaches	Frequency (f)	Articles
Green Chemistry and its derivatives (Green Analytical Chemistry, Green and Sustainable Chemistry, Green Chemistry Education)	10	A2, A4, A5, A6, A11, A13, A14, A15, A19, A20
Problem-Based Learning (PBL)	5	A10, A11, A16, A17, A18
Socio-Scientific Issues (SSI)	3	A8, A18, A21
ESD-based STEM/STEAM	3	A3, A19, A22
Project-Based Learning (PjBL)	2	A12, A22
Laboratory-Based Learning	1	A9
Case-Based Learning (CBL)	1	A15
Integration of Sustainability into Chemistry Education	1	A7
Survey Sustainable Chemistry	1	A1

Note: A single article can be classified into more than one category because some studies integrate more than one learning approach.

The Socio-Scientific Issues (SSI) approach was found in three of the articles analyzed. This approach connects chemistry concepts to various real-world issues (Liskes & van Vorst, 2026), such as the use of single-use plastics, climate change, and sustainable consumption. This

allows students to understand not only the scientific aspects but also consider the social, economic, cultural, and ethical dimensions in decision-making (S. W. Putri et al., 2025). Various studies have shown that the application of SSI can improve critical thinking skills, scientific argumentation, scientific literacy, and responsible decision-making on sustainability issues (Fernández et al., 2022; Högström et al., 2025). Furthermore, this approach strengthens the role of chemistry education in developing critical chemical literacy and sustainability competencies needed to address the challenges of sustainable development (Prastika & Arianingrum, 2024; Sjöström et al., 2024).

The ESD-based STEM/STEAM approach was found in three articles analyzed. This approach integrates science, technology, engineering, art, and mathematics in chemistry learning through investigative activities (Tantayanon et al., 2025), experiments, and projects oriented towards solving environmental problems (Arfika et al., 2025). Various studies have shown that the integration of STEM/STEAM with ESD can enhance creativity, collaboration, critical thinking, and problem-solving skills necessary to address sustainable development challenges (Domenici, 2022; Rahmawati et al., 2022). Furthermore, the implementation of project-based STEM/STEAM also contributes to strengthening sustainability consciousness and systems thinking, thus preparing students to develop innovative solutions to various sustainability issues (Auh et al., 2026; Vilmala et al., 2025).

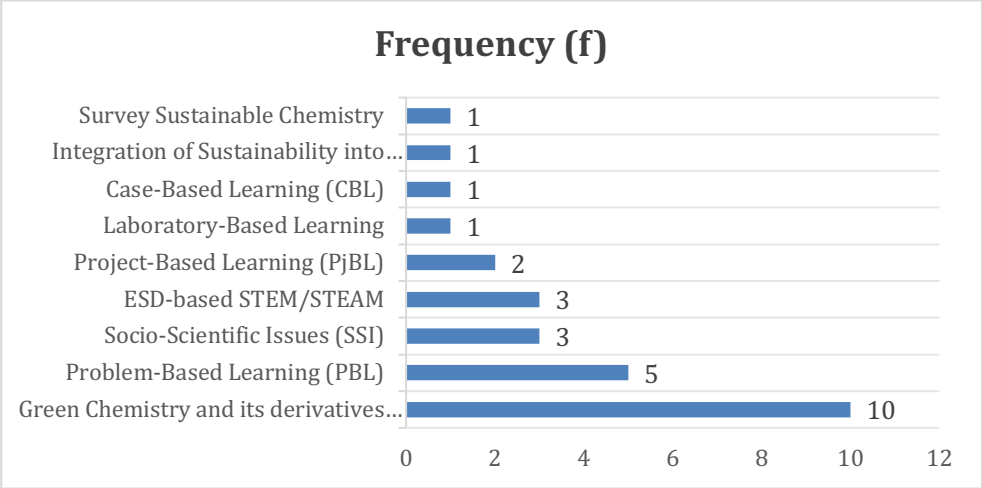


Figure 3. Distribution of ESD Implementation Models and Approaches in Chemistry Education

Furthermore, several studies have used Project-Based Learning (PjBL), Laboratory-Based Learning, and Case-Based Learning (CBL) as ESD strategy implementations. Although relatively few in number, these approaches have demonstrated effectiveness in increasing

student engagement, connecting learning to real-world contexts (Pratiwi et al., 2025), and developing competencies relevant to 21st-century needs (Poya, 2026).

Overall, the synthesis of results indicates that ESD implementation in chemistry education is dominated by contextual, student-centered learning approaches that focus on solving real-world problems (Ssossé et al., 2021). Green Chemistry and Problem-Based Learning are the two most widely used approaches because they are able to integrate chemical concepts with current issues directly (Armstrong et al., 2019; Paristiowati et al., 2019; Suryawati et al., 2020), thus making a significant contribution to the development of environmental awareness and inviting students to participate (Amran et al., 2019). These findings indicate that the application of ESD in chemistry education is mostly done through a contextual learning approach that connects chemical concepts with real-world issues.

Reported Environmental Awareness Outcomes of ESD Implementation in Chemistry Education (RQ3)

A synthesis of 22 articles identified several environmental awareness outcomes reported in studies of ESD implementation in chemistry education. The reported outcomes included awareness of global environmental issues (Dobbelaar & Richter, 2022; Imai et al., 2022), waste management and environmental pollution (Júnior et al., 2026; Mellyzar et al., 2025; Pratiwi et al., 2023; Yeerum et al., 2022), environmental responsibility (Li & Eilks, 2024; Quiroz-Martinez, 2024), sustainability awareness (T. S. Putri & Rohaeti, 2025; Yenduri et al., 2026), and responsible use of resources (Table 7) (Imai et al., 2022; Linkwitz & Eilks, 2022). Across the reviewed studies, the reported outcomes reflected students' and teachers' understanding, concern, and responsibility toward various environmental issues (Arshad et al., 2020; Dolenc Orbanić & Kovač, 2021).

Table 7. Reported Environmental Awareness Outcomes of ESD Implementation

Environmental Awareness Themes	Frequency (f)	Articles
Awareness of global environmental issues (climate change, global warming, plastic pollution)	6	A1, A4, A5, A9, A18, A21
Waste management and environmental pollution	6	A2, A3, A4, A9, A13, A16
Responsibility and concern for the environment	6	A3, A7, A8, A15, A16, A20
Sustainability awareness	6	A6, A11, A12, A14, A17, A19
Responsible use of resources	5	A1, A2, A4, A5, A14

Note: *A single article can contribute to more than one environmental awareness theme*

Awareness of global environmental issues was reported in various studies that address the topics of climate change (Linkwitz & Eilks, 2022), global warming, plastic pollution (Martín-Alfonso & Yáñez, 2024), and various environmental challenges related to the Sustainable Development Goals (SDGs) (Dobbelaar & Richter, 2022; Imai et al., 2022). The reviewed studies described students' understanding of the relationship between human activities and environmental problems at the global level.

Waste management and environmental pollution were also frequently reported as environmental awareness outcomes in the reviewed studies (Yeerum et al., 2022). The reported outcomes included an understanding of safer chemical use (Imai et al., 2022), awareness of waste management practices (Rahmawati et al., 2022), and recognition of the importance of reducing environmental pollution (Sethi et al., 2024; Armstrong et al., 2019). Several studies also reported students' awareness of the importance of reducing environmental impacts and responding responsibly to environmental issues (Celestino, 2023; Wulandari & Mitarlis, 2023). Responsibility and concern for the environment were also identified as important environmental awareness outcomes in the reviewed studies. Several studies reported students' awareness of environmental responsibility and concern in relation to environmental problems and sustainability issues (Li & Eilks, 2024; Quiroz-Martinez, 2024). These findings indicate that environmental awareness was also reflected in students' concern for environmental issues and their recognition of individual and collective responsibility in addressing them (Rabbani et al., 2025; Yusuf & Fajri, 2022).

The theme of sustainability awareness was also frequently reported in the analyzed articles. The reviewed studies described students' understanding of the interrelationships among environmental (Mitarlis et al., 2023), social, and economic aspects of sustainable development (Anggraeni & Rohaeti, 2026; Refmidawati & Megahati S, 2023). Several studies also reported environmental attitudes and responsibilities related to sustainable behavior. These findings indicate that the reported environmental awareness outcomes encompassed cognitive, affective, and behavioral dimensions (Pancarani & Sari, 2026). Responsible use of resources was also reported as an environmental awareness outcome in the reviewed studies. The reported findings described students' awareness of the importance of using natural and chemical resources responsibly and considering resource conservation in chemistry-related activities (Imai et al., 2022; Linkwitz & Eilks, 2022).

Challenges and Opportunities for the Implementation of ESD in Chemistry Education (RQ4)

The synthesis of the 22 selected studies shows that the integration of ESD into chemistry education presents both substantial challenges and promising opportunities for advancing sustainable education. Evidence from several studies suggests that ESD has not yet been systematically embedded within chemistry curricula and is often implemented only to a limited extent (Mellyzar et al., 2025; Quiroz-Martinez, 2024). Consequently, its implementation largely depends on the individual initiatives of teachers or curriculum developers, leading to variations and inconsistencies in classroom practice (Rasmawan, 2023). Furthermore, teachers' understanding of the concept of sustainability still focuses more on the environmental dimension, while social and economic aspects have not received equal attention (Quiroz-Martinez, 2024; Widyantoro et al., 2025). Therefore, strengthening teachers' professional competencies and developing curricula that explicitly integrate sustainable development principles are needed to support a more comprehensive implementation of ESD in students' chemistry learning (Mellyzar et al., 2025; Ramirez & Paderna, 2025), as well as the need for stronger institutional support (Table 8).

Table 8. Challenges of ESD Implementation in Chemistry Education

Challenges	Frequency (f)	Articles
ESD curriculum integration is not optimal	2	A7, A16
Teachers' competence and understanding related to ESD are still limited	2	A7, A15
The implementation of real action competence still needs to be strengthened	2	A16, A20
The need for institutional support and multidisciplinary collaboration	2	A15, A16

Nevertheless, various opportunities for implementing ESD in chemistry education have also been identified. Based on the thematic synthesis, these opportunities can be grouped into four main areas: curriculum and instructional integration (Mellyzar et al., 2025; Poya, 2026) , development of sustainability competencies (Fenibo et al., 2021; Rabbani et al., 2025; Widyawati et al., 2025), professional development (Tantayanon et al., 2025; Widyantoro et al., 2025), and institutional and interdisciplinary collaboration (Table 9) (Herrera-Herrera et al., 2026; Mellyzar et al., 2025).

Table 9. Opportunities for ESD Implementation in Chemistry Education

Opportunities	Frequency (f)	Articles
Strengthening curriculum and instructional integration	2	A12, A16

Teacher professional development and capacity building	2	A7, A15
Expansion of contextual, project-based, and real-world learning	2	A7, A19
Institutional and interdisciplinary collaboration	2	A11, A16

The first opportunity concerns curriculum and instructional integration. The reviewed studies indicate that sustainability issues can be incorporated into chemistry education through real-world contexts, SDG-oriented projects, contextual learning, and interdisciplinary approaches (Mellyzar et al., 2025; Poya, 2026). This integration facilitates connections between chemistry concepts and environmental and sustainability challenges, making learning more relevant to students' everyday lives (González et al., 2020; Widyantoro et al., 2025).

The second opportunity relates to the development of sustainability competencies. The reviewed studies reported competencies such as critical thinking, problem-solving, collaboration, communication, systems thinking, creativity, and sustainability literacy (Fenibo et al., 2021; Quiroz-Martinez, 2024; Rabbani et al., 2025; Widyawati et al., 2025). The development of these competencies creates opportunities for students to apply chemistry knowledge to real-world sustainability issues and develop potential solutions through problem-solving and collaboration (Brundiers et al., 2021; Vidal & Kuckuck, 2025).

The third opportunity involves teacher education and professional development. Several studies highlight the importance of strengthening teachers' knowledge and pedagogical capacity to translate sustainability concepts into chemistry learning activities (Widyantoro et al., 2025). The reviewed studies reported that professional development and experiential learning offered opportunities for teachers to explore sustainability and Green Chemistry and develop strategies for integrating these principles into classroom practice (Tantayanon et al., 2025).

Finally, institutional and interdisciplinary collaboration represents an important opportunity for strengthening ESD implementation. Collaboration across disciplines and between educational institutions, researchers, communities, and other stakeholders can provide broader contexts and resources for sustainability-oriented chemistry education (Mellyzar et al., 2025). Such collaboration may also help connect classroom learning with research, community needs, and institutional sustainability initiatives (Herrera-Herrera et al., 2026).

CONCLUSION

This systematic literature review provides an overview of how ESD has been integrated into chemistry education across 22 studies published between 2022 and 2026. The evidence

reveals a geographically diverse but uneven research landscape, with Indonesia contributing the largest share of publications, while several countries were represented by only a single study. Research activity also varied across the review period, reaching its highest level in 2025 and its lowest in 2023. The five studies identified for 2026 were available up to the final search date of May 14, 2026 and therefore do not represent the complete publication output for that year. The literature was concentrated mainly in secondary education and higher education, with students and pre-service or prospective teachers representing the most frequently studied groups.

The synthesis indicates that ESD integration in chemistry education is characterized by the use of diverse chemistry-specific and pedagogical approaches. Green Chemistry and its derivatives emerged as the most prominent approach, alongside Problem-Based Learning, Socio-Scientific Issues, ESD-based STEM/STEAM, and Project-Based Learning. Collectively, these approaches illustrate a shift toward connecting chemistry learning with sustainability challenges and contexts beyond the conventional treatment of chemical concepts. Rather than being implemented through a single instructional model, ESD is incorporated through multiple pathways that enable chemistry education to engage with environmental and sustainability concerns.

The environmental awareness findings further indicate that sustainability-oriented chemistry education addresses environmental awareness as a multidimensional construct. The reviewed studies encompassed environmental knowledge and awareness, responsibility and concern, waste and pollution issues, sustainability awareness, and responsible resource use. This breadth suggests that the relationship between chemistry learning and environmental sustainability is being explored through varied real-world issues and learning contexts, rather than being limited to a single aspect of environmental awareness.

Overall, the reviewed literature reveals both opportunities and challenges in integrating ESD into chemistry education. While diverse approaches and learning contexts provide opportunities to connect chemistry with real-world environmental issues and develop sustainability-related competencies, several challenges remain, particularly in curriculum integration, teachers' knowledge and pedagogical capacity regarding sustainability, and institutional support and collaboration. The reviewed studies also highlight opportunities to advance ESD through teacher education and professional development, contextual and project-based learning, sustainability competency development, and institutional and interdisciplinary collaboration. Future research should therefore focus on strengthening the systematic integration of ESD into chemistry curricula, enhancing teacher preparation and professional

development, and developing learning and assessment approaches that comprehensively address environmental awareness and sustainability competencies across a wider range of educational contexts.

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