

THE DEVELOPMENT OF EDUCATION FOR SUSTAINABLE DEVELOPMENT (ESD) IMPLEMENTATION IN CHEMISTRY EDUCATION: A LITERATURE REVIEW

Munawwarah^{1*}, Hastuti Agussalim²

^{1,2}Department of Chemistry, Faculty of Mathematic and Natural Science, Universitas Negeri Makassar, Makassar, Sulawesi Selatan, Indonesia

Article Info

Article history:

Received 01/08/2025

Accepted 15/10/2025

Published 24/10/2025

Keywords:

Chemistry Education;

ESD;

Green Chemistry;

Literature Review;

Sustainability Competencies

ABSTRACT

The accelerating global sustainability crisis has made it increasingly urgent to transform science education into a catalyst for sustainable development. Chemistry education, with its direct link to real-world issues such as energy, the environment, and health, plays a vital role in achieving this transformation. This study conducts a systematic literature review of the implementation of *Education for Sustainable Development (ESD)* in chemistry education from 2012 to 2025. A total of 15 international and national articles were analyzed to map theoretical models, instructional innovations, and student outcomes related to ESD integration. The analysis identifies two main strands of contribution: conceptual contributions, which focus on developing frameworks and didactic theories, and practical contributions, which emphasize instructional media, laboratory modules, and project-based learning approaches. Practical studies dominate the literature, showing strong impacts on students' chemistry literacy, creativity, and sustainability awareness. However, competencies such as critical thinking, problem-solving, and action competence remain underexplored. The findings underscore the need for a more balanced research agenda that bridges theory and practice while systematically developing a broader range of sustainability competencies. This review highlights that chemistry education holds substantial potential not only to enhance scientific understanding but also to cultivate responsible citizens capable of addressing complex challenges for a sustainable future.

This is an open access article under the [CC BY-SA](#) license.



Corresponding Author:

Munawwarah

Department of Chemistry, Faculty of Mathematics and Science, Universitas Negeri Makassar, Makassar, Sulawesi Selatan, Indonesia

Email: munawwarah@unm.ac.id

1. INTRODUCTION

The issue of sustainable development has become a global agenda that has gained widespread attention through the Sustainable Development Goals (SDGs), particularly target 4.7, which emphasizes the pivotal role of education in shaping global citizens who are environmentally conscious, socially just, and oriented toward future well-being (Mahaffy et al., 2019). Chemistry education holds a strategic position in supporting this agenda, as it not only investigates phenomena at the molecular level but is also closely connected to real-world challenges such as energy, the environment, food, health, and technology (Corrêa Gomes & Zuin, 2023; Zowada et

al., 2018). It is essential to incorporate systems thinking within chemistry education, allowing students to understand and tackle complex, interdisciplinary problems related to sustainable development (Blatti et al., 2019; Pazicni & Flynn, 2019). The integration of green chemistry principles and sustainability into curricula empowers students with the knowledge, skills, attitudes, and values necessary for fostering sustainability (Armstrong et al., 2019; Rahmawati et al., 2022). Through creative, values-based learning approaches, students become engaged in addressing their ethical views concerning environmental issues, ensuring that future generations are equipped to deal with the challenges of a sustainable future (Rahmawati et al., 2023). Therefore, the potential of chemistry education to contribute to sustainable development is substantial, as it prepares students not only to understand chemical concepts but also to translate this understanding into actions that promote sustainability in their communities (Wissinger et al., 2021; Zidny et al., 2021).

The concept of Education for Sustainable Development (ESD) emerges as an educational framework that does not merely incorporate environmental issues into the curriculum but rather transforms the learning paradigm to cultivate sustainability competencies (Fuertes et al., 2019; Odintsova, 2024). These competencies include systems thinking, anticipatory skills, strategic abilities, collaboration, and normative-ethical dimensions (Pimpa, 2024). In chemistry education, ESD can be implemented through various approaches, such as green chemistry, socio-scientific issues (SSI), project-based learning, environmentally friendly laboratory practices, and interactive digital media (Albareda-Tiana et al., 2018; Soini et al., 2019). The integration of these approaches enhances students' academic engagement and prepares them to navigate and address complex sustainability challenges (Waltner et al., 2019). For example, project-based learning has been shown to significantly contribute to the development of critical thinking skills and the ability to work collaboratively on sustainability issues, thus allowing students to apply their knowledge in real-world contexts (Redman & Wiek, 2021). Furthermore, fostering an understanding of green chemistry principles within the ESD framework empowers students to make informed decisions that positively impact environmental and social sustainability (Moreno-Pino et al., 2021; Salovaara et al., 2019). Overall, ESD in chemistry education plays a vital role in preparing students to become responsible global citizens who are equipped to tackle the sustainability challenges of the future (Karvonen et al., 2023).

Nevertheless, the implementation of Education for Sustainable Development (ESD) in chemistry education still faces various challenges. Several studies have found that teachers and pre-service teachers often demonstrate a limited understanding of ESD, equating it primarily with environmental education (Ichinose, 2017; Lamanauskas & Malinauskienė, 2024). This narrow interpretation hinders the incorporation of broader sustainability principles into their teaching approaches (Hepper, 2021). Additionally, the scarcity of instructional materials that explicitly integrate ESD makes it challenging for educators to apply sustainable practices within their classrooms (Anyolo et al., 2018). Research indicates that while ESD can enhance chemistry literacy and student creativity, more comprehensive sustainability competencies such as critical thinking and action competence have not yet been systematically evaluated (Félix, 2023). This lack of evaluation underscores the necessity for targeted professional development and resources to support teachers in effectively integrating ESD into their curricula (Zulfarina et al., 2023), thereby fostering a richer understanding of sustainability issues among students (Schönstein & Budke, 2024). As a result, there is an urgent need to bridge these gaps to fully realize the potential of ESD in chemistry education (Larsson & Samuelsson, 2019; Semiz & Işler, 2020).

However, despite the increasing number of studies integrating *Education for Sustainable Development (ESD)* into chemistry education, existing research remains fragmented and limited in scope. Most studies tend to emphasize either the conceptual development of ESD models or the creation of instructional media without systematically linking both dimensions. Moreover, the lack of synthesis between these two directions has resulted in a partial understanding of ESD implementation—where conceptual frameworks are not fully reflected in practical classroom innovations, and practical efforts often lack strong theoretical grounding. Therefore, it is essential to synthesize these two strands into an integrated framework that bridges theory and practice, providing a clearer direction for advancing sustainable chemistry education. Moreover, previous works often focus on environmental aspects of sustainability while neglecting social and economic dimensions, leading to a partial understanding of ESD implementation. In addition, there has been little comprehensive synthesis that maps the progression of ESD implementation in chemistry education across different contexts and time periods. This indicates a clear gap in the literature—a lack of integrative reviews that holistically analyze theoretical models, pedagogical innovations, teacher readiness, and student competencies within the ESD framework. Addressing this gap is essential to guide future research and practice toward a more balanced and comprehensive approach to sustainable chemistry education.

In light of these conditions, a literature review is needed to examine the development of Education for Sustainable Development (ESD) implementation in chemistry education from 2012 to 2025. This review aims to: (1) map the various models, strategies, and media that have been developed; (2) identify achievements and challenges in the implementation of ESD in chemistry education; and (3) uncover research gaps that can serve as a basis for future research and innovation. By systematically analyzing the existing literature, researchers can gain insights into the diverse approaches and pedagogical practices that enhance ESD within chemistry curricula, highlighting the importance of a holistic and interdisciplinary curriculum design (Perello-Marín et al., 2018). Furthermore, the findings of this review are expected to provide a comprehensive overview of the trajectory of ESD implementation in chemistry education, as well as serve as a foundation for the development of policies, curricula, and future research (Kolleck et al., 2017). Addressing these gaps will empower educators to foster sustainability competencies among students, ultimately contributing to global sustainability goals (Büssing et al., 2018).

2. METHOD

This study employs a systematic literature review approach focusing on articles that discuss the implementation of Education for Sustainable Development (ESD) in chemistry education. The reviewed articles encompass the development of didactic models, innovations in learning media, teacher and pre-service teacher profiles, as well as the outcomes of ESD implementation for students. Data sources were drawn from various open-access databases, both international and national. The international journals reviewed include Chemistry Education Research and Practice (RSC Publishing), International Journal of Science Education (Taylor & Francis), Sustainability (MDPI), Nature Sustainability, and Current Opinion in Green and Sustainable Chemistry. The selection of these international journals was based on their scientific reputation, indexing status, and thematic relevance to the topic of Education for Sustainable Development (ESD) in chemistry education. Chemistry Education Research and Practice (CERP) and the International Journal of

Science Education (IJSE) are widely recognized as leading journals in science education research, particularly in chemistry pedagogy and curriculum innovation. Sustainability (MDPI) and Nature Sustainability were chosen because they are interdisciplinary journals that regularly publish high-impact studies related to sustainability education and policy, providing a broader contextual understanding of ESD. Meanwhile, Current Opinion in Green and Sustainable Chemistry specifically addresses issues of sustainability and green chemistry, aligning closely with the core dimensions of ESD integration in chemistry teaching. Therefore, these journals collectively represent a scientifically robust and thematically coherent body of literature suitable for identifying both conceptual developments and practical innovations in ESD-oriented chemistry education.

In addition, relevant articles from several Sinta-accredited national journals on chemistry education and ESD were also included. Article searches were conducted using keywords such as “Education for Sustainable Development” + “chemistry education,” “ESD” + “chemistry teaching,” “green chemistry education,” “socio-scientific issues” + “chemistry,” as well as combinations of “ESD” with “critical thinking” or “action competence.” In the selection process, inclusion and exclusion criteria were established to ensure the suitability of the articles for the study objectives. The inclusion criteria consisted of open-access articles published in reputable journals, focusing on chemistry education with ESD integration, in the form of conceptual studies, model/media development, or empirical studies, and published between 2012 and 2025. Exclusion criteria included articles discussing ESD in general without a chemistry context, short proceedings without peer review, or paywalled articles that could not be fully accessed. The selection procedure followed four stages. First, at the initial identification stage, 50 articles were retrieved from database searches. Second, after screening based on titles and abstracts, the number was reduced to 20 articles. Third, during the eligibility stage by reading the full texts, 5 articles were eliminated for not meeting the inclusion criteria.

Fourth, a total of 15 final articles were included and used as the main basis for analysis. Data from the selected articles were analyzed using a thematic approach. The analysis was conducted by categorizing research findings into several major themes: (1) didactic models and theories of ESD in chemistry education; (2) ESD-based learning media and innovations such as modules, experiments, e-books, or digital applications; (3) teacher and pre-service teacher profiles related to their understanding and readiness for ESD; and (4) student competency achievements within the ESD framework, including scientific literacy, creativity, and sustainability awareness. The results of the analysis were then presented in the form of a literature matrix table and supported by graphs and diagrams to strengthen the data synthesis.

3. RESULTS AND DISCUSSION

Based on the article selection process through a systematic literature review approach, 15 relevant articles were identified concerning the implementation of Education for Sustainable Development (ESD) in chemistry education. These articles represent research developments over the past decade, ranging from the development of conceptual didactic models at the international level to innovations in ESD-based media and learning tools within national contexts. In addition, several articles highlight the profiles of chemistry teachers and pre-service teachers in relation to their understanding and awareness of sustainability, as well as students’ achievements in chemistry literacy, creativity, and sustainability awareness. Accordingly, the synthesis of these 15 articles

provides a comprehensive overview of the trajectory of ESD implementation in chemistry education, encompassing both theoretical frameworks and classroom practices. A more systematic overview of the findings from the fifteen selected articles is presented in the form of a matrix in Table 1. This matrix contains concise information on the authors, year of publication, research objectives, methods employed, main findings, contributions to strengthening ESD, and limitations of each study. The presentation of this table is intended to facilitate readers in observing the variation of research foci, ranging from conceptual models and learning media innovations to studies on teachers, pre-service teachers, and students. Thus, Table 1 serves as a foundation for conducting more in-depth thematic analysis and synthesis in the subsequent discussion section in the Table 1.

Table 1. Literature Matrix of 15 Articles on ESD in Chemistry Education

No	Author(s) & Year	Objective/Topic	Method & Sample	Main Findings	Contribution to ESD	Limitations
1	Burmeister, Rauch & Eilks (2012)	Propose a model for integrating ESD in chemistry	Conceptual article	Four models: green chemistry, content addition, SSI, school development	Provides a foundational framework for integrating ESD in chemistry	Not empirically tested
2	Jegstad & Sinnes (2015)	Develop the "Chemistry Teaching for the Future" model	Conceptual article	Five categories (content, context, methodology, ESD competences, lived ESD)	Offers guidance for planning ESD units	Not classroom tested
3	Burmeister & Eilks (2013)	Profile of chemistry pre-service teachers' understanding of ESD	Survey n=184 (87 students, 97 novice teachers)	Positive attitudes, vague understanding of ESD	Highlights gaps in teacher education for ESD	Sample limited to Germany
4	Burmeister, Schmidt-Jacob & Eilks (2013)	Understanding of experienced teachers	Interviews with senior teachers	Varied understanding, confusion in implementation	Emphasizes importance of teacher professional development on ESD	Limited generalizability
5	Herranen, Yavuzkaya	Develop eco-reflexive	Theoretical & collaborative analysis	Six categories (values,	Provides a professional language for	Not widely tested

	& Sjöström (2021)	didactic model		content, society, eco-reflexivity, etc.)	chemistry–ESD teachers	
6	Mahaffy et al. (2019)	Apply systems thinking (STICE)	Position article (<i>Nature Sustainability</i>)	Connects molecules ↔ Earth systems & society	Bridges molecular level and sustainability	Conceptual, needs classroom application
7	Review Greening the Chemistry Curriculum (2022)	Strategies for ESD-oriented chemistry curriculum	Curriculum review & practices	Spiral integration, green chemistry, ST throughout curriculum	Maps curriculum strategies aligned with SDGs	Not specific to high school chemistry
8	Wahyu Nur Isnaeni & Budimarwanti (2025)	Needs analysis for chemistry enrichment book (green chemistry & SDGs)	Survey with 7 high school teachers	85.7% of teachers lacked related materials; preferred print+ebook	Validates teachers' real material needs	Small sample, self-reported data
9	Fau et al. (2025)	Android-based ESD media (colloid topic)	R&D (4D) + quasi-experiment n=64	Significant improvement in chemistry literacy (d=2.194)	Provides empirical evidence for effectiveness of ESD media	Single topic, posttest-only
10	Nurfadilah & Siswanto (2020)	Integrating STEAM + ESD on polymers	One class, n=32	High creative attitude, low creative thinking (36.8%)	Indicates ESD supports creativity development	No control group, implicit ESD integration
11	Bawadi et al. (2025)	Project-Based Learning (PBL) for understanding ESD	Review of 13 articles	PBL enhances critical thinking & problem-solving	Highlights ESD pedagogical strategies	Secondary literature
12	Khoirunnisa et al. (2022)	Profile of chemistry pre-service teachers'	Survey with 64 students	60.5% unfamiliar with ESD, moderate awareness	Evidences the need to integrate ESD in teacher	Sample limited to one university

		understanding of ESD			education institutions	
13	Al Idrus et al. (2020)	Environmental chemistry practicum module based on green chemistry	R&D module development	Module valid & effective, positive student responses	Laboratory work as a medium for ESD	Context limited
14	Sari & Purtadi (2020)	High school chemistry experiments based on ESD	R&D + validation	Experiments validated (80–83%), environmentally friendly	Contributes to sustainability literacy	Small scale, no critical thinking/action on competence test
15	Handayani et al. (2023)	Contextual chemistry KIT/worksheets based on ESD	R&D + validity testing	KIT valid, effective in enhancing students' scientific literacy	Supports practical action (simple, contextual experiments)	Only initial stage of implementation

As shown in Table 1, the fifteen reviewed articles demonstrate a diversity of foci and approaches in integrating Education for Sustainable Development (ESD) into chemistry education. Several studies emphasized the development of conceptual models and didactic frameworks aimed at effectively embedding ESD into the chemistry curriculum. For instance, Zuin et al. highlighted green and sustainable chemistry's principles in educational settings, which aligns with integrating ESD into chemistry instruction (Zuin et al., 2019). In contrast, national studies often concentrated on the development of instructional media, including modules, contextual chemistry kits, ESD-based experiments, and Android applications, which have been shown to enhance students' chemistry literacy (York & Orgill, 2020). Additionally, some studies explored the profiles of chemistry teachers and pre-service teachers, revealing positive attitudes toward ESD, though with a limited understanding primarily focused on environmental dimensions. Other research indicated that the integration of ESD could encourage students to achieve competencies such as creativity and sustainability awareness. Thus, Table 1 provides a summary of the reviewed studies, illustrating the trends and directions of ESD research in chemistry education concerning theory, practice, and pedagogical implications (Harta et al., 2019).

Beyond the matrix, the findings of this literature review are also summarized quantitatively to show the distribution of research foci across the fifteen analyzed articles. This visualization is important as it illustrates the proportional contributions of each category of study, ranging from the development of conceptual models, innovations in instructional media, examinations of teacher and pre-service teacher profiles, to research emphasizing specific competencies or pedagogical strategies. Accordingly, this distribution enables readers to observe the tendencies and trajectories of ESD research in chemistry education more clearly and systematically. The distribution is presented in the form of a pie chart in Figure 1.

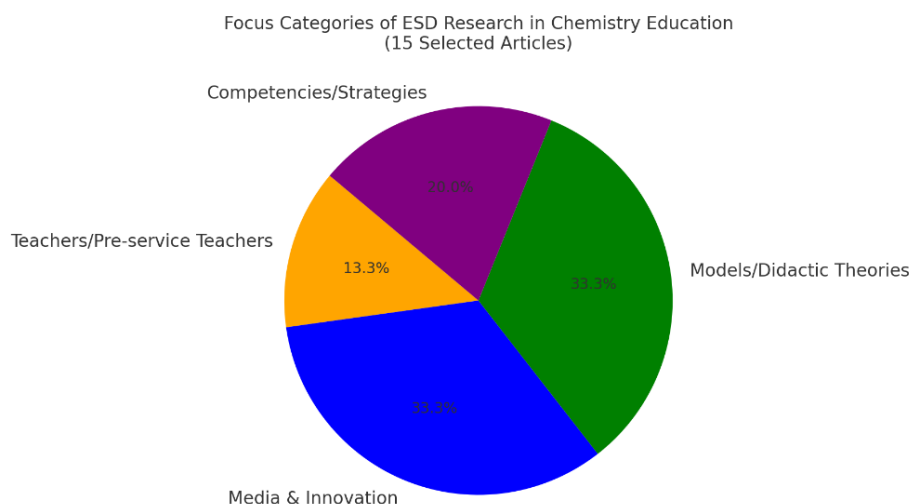


Figure 1. Focus Categories of ESD Research in Chemistry Education (15 Selected Articles)

As shown in Figure 1, the distribution of research focus from the 15 analyzed articles demonstrates a relatively balanced tendency between studies on models and didactic theories and those on media and learning innovations, each accounting for 33.3% or five articles. This finding indicates that research on ESD in chemistry education is not solely oriented toward the development of conceptual foundations but also emphasizes practical implementation through the design of media, strategies, and innovative teaching tools. Thus, the balanced direction between theoretical and practical development can be interpreted as an effort to ensure that the principles of ESD do not remain at the level of abstract ideas, but are truly applied in the context of chemistry learning so that they are more easily understood and experienced by students. On the other hand, studies focusing on competencies and learning strategies only contribute 20% (three articles), while research concerning teachers and pre-service teachers is even smaller, amounting to 13.3% (two articles) (Zuhaida et al., 2024). This distribution indicates that, although the areas of didactic theory and instructional media have developed considerably, the focus on enhancing student competencies and preparing teachers to integrate Education for Sustainable Development (ESD) into chemistry education remains relatively limited. In fact, both aspects play a critical role in the overall success of ESD implementation. As highlighted by Su et al., the systematic fostering of sustainability competencies is essential for ensuring that future teachers are equipped to meet the demands of ESD integration (Su et al., 2023). Thus, this gap can be identified as an opportunity for future research, particularly studies exploring how sustainability competencies can be integrated into educational frameworks.

As the demand for competent educators in ESD grows, it becomes increasingly important to enrich teacher education programs and curricula (Waltner et al., 2018). Findings from Pascual et al. echo this need by emphasizing interdisciplinary approaches in teacher training, which can help create agents of change for sustainability (Pascual et al., 2020). Moreover, initiatives aimed at developing pedagogical competencies among pre-service teachers are crucial, as they lay the foundation for effective ESD integration in classroom settings (Schönstein & Budke, 2024). Addressing these research gaps will enable educators to better prepare teachers to navigate the complexities of sustainability issues, ultimately enhancing the impact of ESD in chemistry

education. As outlined in Figure 1, the distribution of research foci on the implementation of ESD in chemistry education reveals a relatively balanced tendency between studies on models and didactic theories and those on instructional media innovations, while research addressing student competencies and the role of teachers remains less prevalent. This finding indicates that ESD research has developed not only in the conceptual domain but has also begun to move toward concrete classroom applications through the development of teaching materials and innovative media. To provide a more comprehensive overview, it is also important to further examine how the contributions of each study can be mapped into two broad categories, namely conceptual contributions and practical contributions. Such a presentation is expected to clarify the trajectory of ESD research in chemistry education, whether it primarily provides theoretical foundations or offers concrete innovations that can be directly implemented in teaching practice in the Table 2.

Tabel 2. Types of Contributions of ESD Research in Chemistry Education

Conceptual Contributions (6 articles)	Practical Contributions (9 articles)
Integration model of ESD (green chemistry, SSI, content addition, school development)	Curriculum strategies for ESD integration
<i>Chemistry Teaching for the Future</i> model	Enrichment book on green chemistry & SDGs
Profile of pre-service chemistry teachers' understanding of ESD	Android-based ESD media (colloid topic)
Experienced teachers' understanding of ESD	STEAM + ESD integration in polymer topic
<i>Eco-reflexive didactic model</i>	Project-Based Learning (PBL) to support ESD
Systems Thinking in Chemistry Education (STICE) framework	Profile of pre-service chemistry teachers' awareness of ESD
	Environmental chemistry practicum module based on green chemistry
	High school chemistry experiments designed with ESD principles
	Contextual chemistry KIT/worksheets based on ESD, enhancing scientific literacy

Based Table 2 as presented in the summary table, the contributions of research on ESD in chemistry education can be grouped into two main categories: conceptual contributions and practical contributions. Articles with conceptual contributions generally focus on the development of models, frameworks, and didactic theories that serve as foundations for integrating sustainability principles into chemistry teaching. For instance, the integration model proposed by Burmeister, Rauch, & Eilks (2012) or the Chemistry Teaching for the Future model developed by Jegstad & Sinnes (2015) provide theoretical perspectives on how chemistry instruction can be aligned with the goals of sustainable development. Similarly, the systems thinking approach advanced by Mahaffy et al. (2019) offers a conceptual framework that links molecular-level chemistry to global sustainability issues. Such contributions are essential, as they provide the language and conceptual tools needed by educators to systematically design curricula and teaching

strategies grounded in ESD. Meanwhile, the majority of the analyzed studies (9 articles) provide practical contributions in the form of instructional media, teaching tools, or pedagogical strategies that can be directly implemented in the classroom. These articles encompass a wide range of innovations, including green chemistry laboratory modules, environmentally friendly chemistry experiments, contextualized chemistry kits, and Android-based digital applications. Furthermore, several studies highlight the importance of project-based learning (PBL) as a pedagogical strategy to foster students' critical thinking and problem-solving abilities. Practical research of this nature offers empirical evidence that integrating ESD into chemistry education can improve student outcomes, particularly in terms of scientific literacy, creativity, and sustainability awareness. Thus, practical contributions play a crucial role in bridging the gap between ESD theory and classroom practice, while also addressing teachers' and students' real needs for relevant and sustainability-oriented learning materials.

Taken together, it is evident that practical contributions in Education for Sustainable Development (ESD) within chemistry education are emphasized, as highlighted in the literature Mahaffy et al. (2021). This trend reflects a strong commitment to implementing ESD-based chemistry education that is practical and readily adopted by educational institutions. Nonetheless, the prevalence of practical contributions emphasizes the need for more theoretical research that can reinforce the conceptual foundations of ESD and enhance its integration into chemistry education (Wissinger et al., 2021). For instance, systems thinking is increasingly recognized as a crucial element in addressing sustainability challenges in chemistry education (Christodoulou & Grace, 2019). Therefore, maintaining a balance between conceptual and practical research is vital for the advancement of ESD studies, ensuring both innovative teaching tools and solid theoretical frameworks that support their effective application (Talanquer & Szozda, 2024). Furthermore, integrating ESD into the chemistry curriculum necessitates effective pedagogical approaches that encompass both practical applications and theoretical understanding (Mukhambetaliyeva et al., 2025). While current focus on practical contributions is beneficial, it poses a risk of undermining essential theoretical developments that inform effective teaching (Murti & Hernani, 2023). By exploring diverse pedagogical strategies such as socio-scientific inquiry-based learning, educators can foster critical thinking and systems-thinking skills among students (Herranen et al., 2021). This dual focus on practice and theory will enhance student learning experiences and better prepare future chemistry educators to address sustainability issues comprehensively. Recent literature emphasizes that the dynamic interplay between practical and conceptual contributions is crucial for establishing a robust educational framework aligned with sustainability principles.

Following the discussion of research foci and the types of contributions (Table 2), it is equally important to examine the competencies or learning outcomes emphasized in the reviewed studies. This dimension sheds light on the extent to which ESD-oriented chemistry education fosters not only theoretical understanding but also transformative skills and dispositions among learners. As summarized in Table 3, the identified competencies include chemistry literacy, creativity, sustainability awareness, critical thinking, problem-solving, and action competence. The mapping of these outcomes provides valuable insights into how ESD research in chemistry education translates into measurable student achievements, while also highlighting areas that remain underexplored and warrant further investigation in the Table 3.

Tabel 3. Types of Competencies or Learning Outcomes Highlighted in ESD Research in Chemistry Education

Competency/Outcome	Examples of Studies	Main Findings
Chemistry Literacy	Fau et al. (2025), Handayani et al. (2023)	Android-based media and contextual KIT effectively improved students' chemistry literacy.
Creativity (Attitudes & Skills)	Nurfadilah & Siswanto (2020)	Integration of STEAM + ESD fostered creative attitudes, though creative thinking skills were still relatively low (36.8%).
Sustainability Awareness	Khoirunnisa et al. (2022), Burmeister & Eilks (2013)	Pre-service teachers showed positive attitudes but only moderate awareness of ESD, often limited to environmental aspects.
Critical Thinking & Problem-Solving	Bawadi et al. (2025)	Project-Based Learning (PBL) shown to enhance critical thinking and collaborative problem-solving.
Action Competence	Sari & Purtadi (2020), Al Idrus et al. (2020)	Experiments and practicum modules introduced sustainable practices, but systematic evaluation of students' action competence was still lacking.

As shown in Table 3, the reviewed studies highlight a range of competencies and learning outcomes that reflect the diverse ways in which ESD has been implemented in chemistry education. Among these, chemistry literacy emerges as a prominent focus, with studies such as Fau et al. (2025) and Handayani et al. (2023) demonstrating that Android-based media and contextualized chemistry kits can significantly improve students' ability to connect chemical concepts with real-world sustainability issues. These findings suggest that literacy in chemistry, when embedded in an ESD framework, goes beyond content knowledge to encompass the capacity to apply chemistry in addressing societal and environmental challenges. Another important strand is the cultivation of creativity, particularly through the integration of STEAM approaches with ESD. Nurfadilah and Siswanto (2020), for instance, found that while students exhibited strong creative attitudes, their creative thinking skills remained relatively underdeveloped. This indicates that although ESD has the potential to foster innovation and imagination, there is still a need for more intentional instructional designs that explicitly develop higher-order creative competencies. Similarly, research on sustainability awareness such as that conducted by Khoirunnisa et al. (2022) and Burmeister & Eilks (2013) reveals that pre-service teachers often display positive attitudes toward sustainability, but their understanding tends to be limited to environmental dimensions, with little emphasis on social or economic aspects.

Beyond literacy, creativity, and awareness, some studies emphasize higher-level competencies such as *critical thinking*, *problem-solving*, and *action competence*. Bawadi et al. (2025) highlight the role of Project-Based Learning (PBL) in enhancing students' ability to think critically and collaborate in addressing complex sustainability problems. Meanwhile, research by Sari & Purtadi (2020) and Al Idrus et al. (2020) underscores the potential of laboratory modules

and school experiments to promote sustainable practices in chemistry education. However, these studies also note that systematic assessment of students' action competence remains underdeveloped, pointing to a gap in evaluating how learners translate sustainability knowledge into concrete actions. Taken together, Table 3 illustrates that while competencies such as chemistry literacy and creativity have been relatively well explored, critical thinking and action competence remain underrepresented in current research. This imbalance suggests an important agenda for future studies: to broaden the focus of ESD in chemistry education toward developing the full spectrum of sustainability competencies, thereby preparing learners not only to understand sustainability challenges but also to act effectively in addressing them in the Figure 2.

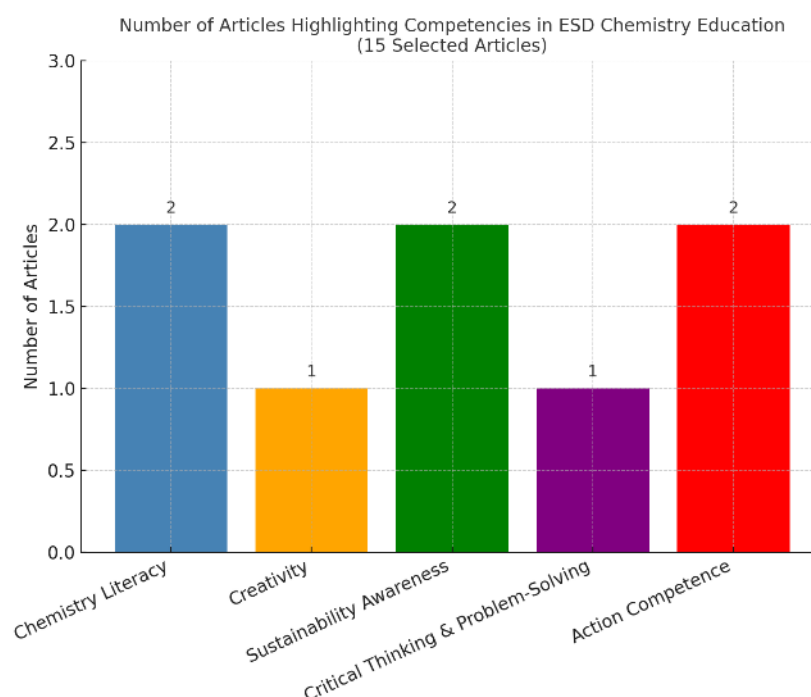


Figure 2. Distribution of Competencies Highlighted in ESD Chemistry Education Research

Based Figure 2 includes eight articles that explicitly reported specific competencies identified within the context of ESD-oriented chemistry education. The remaining studies did not mention measurable competencies and therefore were not represented in this distribution. As illustrated in Figure 2, the distribution of competencies highlighted across the reviewed studies remains relatively modest, with no single competency receiving dominant attention. Chemistry literacy, sustainability awareness, and action competence were each addressed in two studies, indicating some level of emphasis on connecting chemical knowledge with sustainability issues and promoting responsible practices. Meanwhile, creativity and critical thinking/problem-solving were only explored in one study each, suggesting that these higher-order competencies are still underrepresented in current research. This pattern underscores a research gap: while existing studies demonstrate that ESD can foster literacy and awareness, there is still considerable potential for future work to strengthen the cultivation and systematic assessment of critical and creative competencies, which are central to UNESCO's vision of sustainability-oriented education.

In summary, the analysis of research foci, types of contributions, and highlighted competencies demonstrates that the implementation of ESD in chemistry education has progressed

along both theoretical and practical dimensions, with notable achievements in developing instructional media and enhancing students' chemistry literacy. However, the limited attention to higher-order competencies such as creativity, critical thinking, and action competence indicates that the full potential of ESD has not yet been fully realized. These findings highlight the need for future studies to pursue a more balanced research agenda that simultaneously strengthens conceptual frameworks and develops practical innovations while also systematically fostering and assessing a broader range of sustainability competencies. Such efforts will ensure that chemistry education not only contributes to disciplinary knowledge but also empowers learners to become active agents of sustainable development.

Comparative Analysis and Synthesis

Across the fifteen reviewed studies, several patterns and contrasts emerge that provide a deeper understanding of how Education for Sustainable Development (ESD) has evolved within chemistry education. Conceptual and theoretical studies (e.g., Burmeister et al., 2012; Jegstad & Sinnes, 2015; Mahaffy et al., 2019) predominantly aim to establish frameworks that align chemistry learning with sustainability principles through approaches such as systems thinking and green chemistry. These works offer valuable insights into the pedagogical foundations of ESD but remain limited in empirical validation. In contrast, practical studies (e.g., Handayani et al., 2023; Fau et al., 2025; Al Idrus et al., 2020) demonstrate tangible outcomes such as improved chemistry literacy, sustainability awareness, and student engagement, yet often lack theoretical coherence or integration with broader ESD frameworks. A comparison between international and national research also reveals contextual differences. International studies tend to emphasize macro-level perspectives—linking molecular understanding to global sustainability issues—while national research, particularly from developing contexts such as Indonesia, focuses more on localized implementation through practical innovations and resource adaptation. These contextual differences highlight the need for cross-level integration, where global conceptual frameworks can inform local practices, and local innovations can provide empirical feedback to refine global theories.

Furthermore, while both groups of studies recognize the importance of sustainability competencies, the depth and scope of these competencies differ. International works frequently address systems thinking and anticipatory skills, whereas national studies focus on literacy and awareness. This asymmetry suggests a research gap in connecting higher-order competencies, such as critical thinking and action competence, with everyday classroom practices. Future research should aim to bridge this divide by designing integrative pedagogical models that combine conceptual rigor with contextual applicability. Taken together, the comparative synthesis underscores the dual need for theoretical consolidation and practical innovation. Advancing ESD in chemistry education will require not only the continued development of instructional tools but also the systematic integration of these tools into theoretically informed frameworks that cultivate a full spectrum of sustainability competencies. Building upon the previous synthesis, it is essential to highlight the key findings and broader implications of this review. The synthesis of the fifteen reviewed studies demonstrates that Education for Sustainable Development (ESD) in chemistry education has contributed substantially to both theory and practice. Theoretically, this field has expanded the conceptual landscape of chemistry education by introducing integrative frameworks

such as systems thinking, green chemistry, and eco-reflexive didactics that align molecular-level understanding with global sustainability challenges. Practically, it has generated diverse pedagogical innovations—including project-based learning, contextual experiments, and digital media—that enhance students' chemistry literacy and sustainability awareness. These developments indicate that ESD has the potential to serve as a transformative framework for cultivating sustainability-oriented competencies in science education. However, research remains uneven, with limited attention given to critical thinking, problem-solving, and action competence. This gap highlights the need for future studies that establish stronger empirical links between theoretical models and classroom applications, ensuring a coherent and evidence-based progression of ESD implementation in chemistry education.

4. CONCLUSION

This systematic literature review aimed to map models, strategies, and media developed for the implementation of Education for Sustainable Development (ESD) in chemistry education, to identify achievements and challenges in its application, and to reveal research gaps for future advancement. The findings show that ESD research in chemistry education has evolved along two main directions conceptual contributions that strengthen theoretical frameworks such as systems thinking and green chemistry, and practical contributions that focus on instructional media, contextual experiments, and project-based learning. While these practical innovations have significantly improved students' chemistry literacy, creativity, and sustainability awareness, the development of higher-order competencies such as critical thinking, problem-solving, and action competence remains limited. Challenges also persist in teacher understanding and curriculum integration, indicating the need for professional development and stronger policy support. Therefore, future research should prioritize the integration of conceptual and practical approaches to create coherent, evidence-based frameworks that foster a full spectrum of sustainability competencies. Through this balanced agenda, chemistry education can more effectively contribute to achieving global sustainability goals and preparing responsible citizens for a sustainable future.

REFERENCES

- Albareda-Tiana, S., Vidal-Raméntol, S., Pujol-Valls, M., & Fernández-Morilla, M. (2018). Holistic Approaches to Develop Sustainability and Research Competencies in Pre-Service Teacher Training. *Sustainability*. <https://doi.org/10.3390/su10103698>
- Anyolo, E. O., Kärkkäinen, S., & Keinonen, T. (2018). Implementing Education for Sustainable Development in Namibia: School Teachers' Perceptions and Teaching Practices. *Journal of Teacher Education for Sustainability*. <https://doi.org/10.2478/jtes-2018-0004>
- Armstrong, L. B., Rivas, M. C., Zhou, Z., Irie, L., Kerstiens, G. A., Robak, M. T., Douskey, M. C., & Baranger, A. M. (2019). Developing a Green Chemistry Focused General Chemistry Laboratory Curriculum: What Do Students Understand and Value About Green Chemistry? *Journal of Chemical Education*. <https://doi.org/10.1021/acs.jchemed.9b00277>
- Blatti, J. L., S. Garcia, J. A., Cave, D., Monge, F., Cuccinello, A., Portillo, J., Juarez, B. M., Chan, E., & Schwebel, F. (2019). Systems Thinking in Science Education and Outreach Toward a

- Sustainable Future. *Journal of Chemical Education*.
<https://doi.org/10.1021/acs.jchemed.9b00318>
- Büssing, A. G., Schleper, M., & Menzel, S. (2018). Do Pre-Service Teachers Dance With Wolves? Subject-Specific Teacher Professional Development in a Recent Biodiversity Conservation Issue. *Sustainability*. <https://doi.org/10.3390/su11010047>
- Corrêa Gomes, C. J., & Zuin, V. G. (2023). Green and Sustainable Chemistry Teacher Education: Experiences From a Brazilian University. *Sustainable Chemistry*.
<https://doi.org/10.3390/suschem4030020>
- Félix, S. M. (2023). Critical Thinking (Dis)Positions in Education for Sustainable Development—A Positioning Theory Perspective. *Education Sciences*.
<https://doi.org/10.3390/educsci13070666>
- Fuertes, M. T., Martín, M. G., Loss, M. F., & Balaguer-Fàbregas, M. C. (2019). Integrating Sustainability Into Higher Education Curricula Through the Project Method, a Global Learning Strategy. *Sustainability*. <https://doi.org/10.3390/su11030767>
- Harta, J., Pamenang, F. D. N., Listyarini, R. V., Wijayanti, L. W., Hapsari, N. D., Ratri, M. C., Asy'ari, M., & Lee, W. (2019). ANALYSIS STUDENTS' SCIENCE PROCESS SKILLS IN SENIOR HIGH SCHOOL PRACTICUM BASED ON SMALL SCALE CHEMISTRY (SSC). *Unnes Science Education Journal*, 8(3).
<https://doi.org/10.15294/usej.v8i3.31857>
- Hepper, J. (2021). Making Change Visible – An Explorative Case Study of Dealing With Climate Change Deniers in Forest Education. *Journal of Teacher Education for Sustainability*.
<https://doi.org/10.2478/jtes-2021-0005>
- Herranen, J., Yavuzkaya, M., & Sjöström, J. (2021). Embedding Chemistry Education Into Environmental and Sustainability Education: Development of a Didaktik Model Based on an Eco-Reflexive Approach. *Sustainability*. <https://doi.org/10.3390/su13041746>
- Ichinose, T. (2017). An Analysis of Transformation of Teaching and Learning of Japanese Schools That Significantly Addressed Education for Sustainable Development. *Journal of Teacher Education for Sustainability*. <https://doi.org/10.1515/jtes-2017-0013>
- Karvonen, R., Ratinen, I., & Kemi, U. (2023). Promoting Sustainability Competency and Self-Efficacy in Class Teacher Education. *Frontiers in Sustainability*.
<https://doi.org/10.3389/frsus.2023.1205680>
- Kolleck, N., Jörgens, H., & Well, M. (2017). Levels of Governance in Policy Innovation Cycles in Community Education: The Cases of Education for Sustainable Development and Climate Change Education. *Sustainability*. <https://doi.org/10.3390/su9111966>
- Lamanauskas, V., & Malinauskienė, D. (2024). Education for Sustainable Development in Primary School: Understanding, Importance, and Implementation. *European Journal of Science and Mathematics Education*. <https://doi.org/10.30935/scimath/14685>
- Larsson, J., & Samuelsson, I. P. (2019). Collective Resources as a Precursor for Educating Children Toward a Sustainable Global World. *Ecnu Review of Education*.
<https://doi.org/10.1177/2096531119886506>
- Mahaffy, P. G., Matlin, S. A., Whalen, J. M., & Holme, T. A. (2019). Integrating the Molecular Basis of Sustainability into General Chemistry through Systems Thinking. *Journal of Chemical Education*, 96(12), 2730–2741. <https://doi.org/10.1021/acs.jchemed.9b00390>

- Moreno-Pino, F. M., Jiménez-Fontana, R., Cardeñoso Domingo, J. M., & Pilar Goded, M. del. (2021). Study of the Presence of Sustainability Competencies in Teacher Training in Mathematics Education. *Sustainability*. <https://doi.org/10.3390/su13105629>
- Mukhambetaliyeva, Z., Zeinolla, S., & Uzakova, A. (2025). *Pedagogical Aspects of Aligning Chemistry Teachers' Professional Competence With the Sustainable Development Goals*. <https://doi.org/10.20944/preprints202502.2192.v1>
- Murti, A. D., & Hernani, H. (2023). The Contributing of Chemistry Learning in Supporting Education for Sustainable Development: A Systematic Literature Review. *Jurnal Pendidikan Kimia*. <https://doi.org/10.24114/jpkim.v15i1.41233>
- Odintsova, T. (2024). Esg Competences and Skills in Lifelong Education for Sustainability. *Environment Technology Resources Proceedings of the International Scientific and Practical Conference*. <https://doi.org/10.17770/etr2024vol2.8091>
- Pascual, E. S., Sanz, B. U., Martín, O. L., Trabada, A. V., & Díaz, T. (2020). Interdisciplinarity in Teacher Education: Evaluation of the Effectiveness of an Educational Innovation Project. *Sustainability*. <https://doi.org/10.3390/su12176748>
- Pazicni, S., & Flynn, A. B. (2019). Systems Thinking in Chemistry Education: Theoretical Challenges and Opportunities. *Journal of Chemical Education*. <https://doi.org/10.1021/acs.jchemed.9b00416>
- Perello-Marin, M. R., Ribes-Giner, G., & Díaz, O. P. (2018). Enhancing Education for Sustainable Development in Environmental University Programmes: A Co-Creation Approach. *Sustainability*. <https://doi.org/10.3390/su10010158>
- Pimpa, N. (2024). Sustainability. *International Journal of Asian Business and Information Management*. <https://doi.org/10.4018/ijabim.341432>
- Rahmawati, Y., Mardiah, A., Taylor, E., Taylor, P., & Ridwan, A. (2023). Chemistry Learning Through Culturally Responsive Transformative Teaching (CRTT): Educating Indonesian High School Students for Cultural Sustainability. *Sustainability*. <https://doi.org/10.3390/su15086925>
- Rahmawati, Y., Taylor, E., Taylor, P., Ridwan, A., & Mardiah, A. (2022). Students' Engagement in Education as Sustainability: Implementing an Ethical Dilemma-Steam Teaching Model in Chemistry Learning. *Sustainability*. <https://doi.org/10.3390/su14063554>
- Redman, A., & Wiek, A. (2021). Competencies for Advancing Transformations Towards Sustainability. *Frontiers in Education*. <https://doi.org/10.3389/educ.2021.785163>
- Salovaara, J. J., Soini, K., & Pietikäinen, J. (2019). Sustainability Science in Education: Analysis of Master's Programmes' Curricula. *Sustainability Science*. <https://doi.org/10.1007/s11625-019-00745-1>
- Schönstein, R. F., & Budke, A. (2024). Teaching Action Competence in Education for Sustainable Development – A Qualitative Study on Teachers' Ideas, Opinions, Attitudes and Self-Conceptions. *Frontiers in Education*. <https://doi.org/10.3389/educ.2023.1256849>
- Semiz, G. K., & Işler, I. (2020). Middle School Pre-Service Mathematics Teachers' Opinions Related to Mathematics Education for Sustainability. *Eurasian Journal of Educational Research*. <https://doi.org/10.14689/ejer.2020.89.6>
- Soini, K., Korhonen-Kurki, K., & Asikainen, H. (2019). Transactional Learning and Sustainability Co-Creation in a University – Business Collaboration. *International Journal of Sustainability in Higher Education*. <https://doi.org/10.1108/ijshe-11-2018-0215>

- Su, C. S., Díaz-Levicoy, D., Vásquez, C., & Hsu, C. C. (2023). Sustainable Development Education for Training and Service Teachers Teaching Mathematics: A Systematic Review. *Sustainability*. <https://doi.org/10.3390/su15108435>
- Waltner, E.-M., Rieß, W., & Mischo, C. (2019). Development and Validation of an Instrument for Measuring Student Sustainability Competencies. *Sustainability*. <https://doi.org/10.3390/su11061717>
- Wissinger, J. E., Visa, A., Saha, B., Matlin, S. A., Mahaffy, P. G., Kümmerer, K., & Cornell, S. (2021). Integrating Sustainability Into Learning in Chemistry. *Journal of Chemical Education*. <https://doi.org/10.1021/acs.jchemed.1c00284>
- York, S., & Orgill, M. (2020). ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education. *Journal of Chemical Education*. <https://doi.org/10.1021/acs.jchemed.0c00382>
- Zidny, R., Eilks, I., & Laraswati, A. N. (2021). A Case Study on Students' Application of Chemical Concepts and Use of Arguments in Teaching on the Sustainability-Oriented Chemistry Issue of Pesticides Use Under Inclusion of Different Scientific Worldviews. In *Eurasia Journal of Mathematics Science and Technology Education*. <https://doi.org/10.29333/ejmste/10979>
- Zowada, C., Gulacar, O., & Eilks, I. (2018). Innovating Undergraduate General Chemistry by Integrating Sustainability-Related Socio-Scientific Issues. *Action Research and Innovation in Science Education*. <https://doi.org/10.51724/arise.9>
- Zuhaida, A., Widodo, A., Prima, E. C., & Solihat, R. (2024). Developing Indicators for Science Teacher Competency in Stem-Esd Learning. *Proceedings of ICE*. <https://doi.org/10.32672/pice.v2i1.1310>
- Zuin, V. G., Segatto, M. L., Zandonai, D. P., Grosseli, G. M., Stahl, A. M., Zanotti, K., & Silva Andrade, R. da. (2019). Integrating Green and Sustainable Chemistry Into Undergraduate Teaching Laboratories: Closing and Assessing the Loop on the Basis of a Citrus Biorefinery Approach for the Biocircular Economy in Brazil. *Journal of Chemical Education*. <https://doi.org/10.1021/acs.jchemed.9b00286>
- Zulfarina, Z., Azizahwati, A., & Ruslindawati, R. (2023). Analysis of Education for Sustainable Development (ESD) as a Basis for Development of Biotechnology Teaching Materials. *SHS Web of Conferences*. <https://doi.org/10.1051/shsconf/202317302001>