American Journal of Interdisciplinary Research and Innovation (AJIRI)

ISSN: 2833-2237 (ONLINE

VOLUME 5 ISSUE 3 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Interdisciplinary Research and Innovation (AJIRI)

Volume 5 Issue 3, Year 2026
ISSN: 2833-2237 (Online)
DOI: https://doi.org/10.54536/ajiri.v5i3.8504
https://journals.e-palli.com/home/index.php/ajiri

Integrating Sustainable Development Goals (SDGs) in Chemistry Education Through Education for Sustainable Development (ESD): A Systematic Review

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Article Information

Received: June 22, 2026

Accepted: September 01, 2026

Published: September 09, 2026

Keywords

Chemistry Education, Education for Sustainable Development, Green Chemistry, Sustainability, Sustainable Development Goals

ABSTRACT

This systematic literature review covered the integration of SDGs into chemistry education through Education for Sustainable Development (ESD). It examined the SDGs addressed, ESD-based teaching methods applied, and chemistry concepts or sustainability contexts applied for integration. A systematic search in the ERIC, ScienceDirect, Google Scholar, and Scopus databases was conducted according to predefined keywords and inclusion/exclusion criteria. Articles published in the period from 2020 to 2026 and including secondary students, chemistry teachers, or higher education students and teachers were analyzed. Thus, 28 studies were found for thematic analysis. It is revealed that all 17 SDGs are presented in the literature, but there were differences in the context of integration. SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 4 (Quality Education) are most frequently integrated in chemistry lessons. Interdisciplinary learning, systems thinking, experiential learning/lab work, problem/project-based learning, context-based learning, and collaborative learning are the most widespread ESD-based approaches. The most frequent entry points for SDG integration are green chemistry and sustainable lab practices. Next in order are water and environmental pollution, energy and combustion, chemical reactions and stoichiometry, organic/agricultural chemistry, plastics/polymers, and analytical chemistry. These results serve as the foundation for the development of the curriculum, instruction, and teacher development in SDG chemistry education.

INTRODUCTION

The pressing need to make education a means of sustainable development has intensified due to the increasing complexity of environmental, social, and economic challenges worldwide. Issues such as resource depletion, environmental degradation, biodiversity loss, climate change, and unsustainable consumption patterns have become pressing global concerns that threaten the well-being of present and future generations. According to UNESCO (2020), addressing these challenges requires not only technological and economic advancement but also a transformation in human behavior, attitudes, and values toward sustainability. Consequently, education has been recognized as a key driver in promoting sustainable development by equipping learners with the knowledge, skills, and values needed to understand and address sustainability issues. This view is supported by Lubis *et al.* (2022), who emphasized that environmental degradation and socio-scientific issues can be effectively addressed through the implementation of sustainable education.

In response to these global challenges, the United Nations introduced the 17 Sustainable Development Goals (SDGs), recognizing education as a fundamental enabler for achieving sustainable development. The quality of education plays a vital role in preparing citizens who are capable of contributing to sustainable societies and supporting national and global development. To facilitate this goal, Education for Sustainable Development (ESD) has been recognized as an educational framework that promotes the achievement of the SDGs by developing learners' sustainability knowledge, competencies, values, and responsible actions (Sutanto, 2017; UNESCO, 2019; Wolff *et al.*, 2017).

Among the different disciplines, science education has significant potential to support the achievement of the SDGs because it naturally explores environmental phenomena, technological innovations, and the interaction between humans and nature. Moreover, science learning promotes critical thinking, investigative skills, and problem-solving competencies, which are central to the objectives of ESD (Lathifah *et al.*, 2024). However, traditional science education often emphasizes conceptual understanding and theoretical knowledge without sufficiently connecting scientific concepts to real-world sustainability issues (Nugroho *et al.*, 2025). Consequently, students may understand scientific principles yet fail to recognize their relevance to contemporary environmental and societal challenges. Integrating ESD into science education provides opportunities to contextualize scientific concepts through authentic sustainability issues, including climate change, renewable energy, biodiversity conservation, and waste management.

Despite its recognized importance, the implementation of ESD in science education continues to face several challenges, including limited teacher understanding, insufficient curriculum support, and a lack of appropriate

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instructional resources (KR & SB, 2024). Although various instructional approaches and educational programs have been developed to address these concerns, a comprehensive synthesis of ESD implementation within science education remains limited.

Within science education, chemistry occupies a unique position because chemistry concepts are closely linked to sustainable development through topics such as green chemistry, environmental chemistry, energy, pollution control, and resource management (Eilks & Linkwitz, 2022; Zidny *et al.*, 2021). As discussed by Anggraeni and Rohaeti (2026), there are four major approaches for integrating sustainable development into chemistry education: adopting green chemistry practices in laboratory activities, incorporating sustainability concepts into chemistry content, utilizing socio-scientific issues as learning contexts, and embedding chemistry education within ESD-based school development initiatives.

The integration of sustainable development issues into chemistry education enables learners to connect scientific knowledge with real-world sustainability challenges. For example, Li *et al.* (2023) explored biodegradable and conventional plastics within the context of green chemistry to examine the contribution of Confucian ecological ethics to chemistry education for sustainable development. Similarly, Araripe and Zeidler (2024) utilized issues related to plastic pollution and harmful additives in children's toys to promote critical thinking, systems thinking, and sustainability awareness. Such contextualized learning experiences enable students to recognize the role of chemistry in addressing sustainable development challenges while fostering responsible attitudes and behaviors.

Nevertheless, implementing ESD within chemistry education remains challenging. Constraints such as limited instructional resources, inadequate educational materials, insufficient curriculum integration, and teachers' difficulties in connecting sustainable development issues with chemistry concepts continue to hinder effective classroom implementation (Widyawati *et al.*, 2025; Clarisa *et al.*, 2020). These challenges underscore the need for evidence that can guide educators in integrating sustainability more effectively into chemistry teaching.

Several review studies have examined research trends in ESD within chemistry education (Rasmawan, 2024; Sihombing *et al.*, 2024; Kusumaningrum *et al.*, 2023; Zidny *et al.*, 2021). These reviews primarily focused on the implementation of ESD through various instructional strategies and learning models that contribute to sustainable development. Among them, Rasmawan (2024) highlighted the emerging application of ESD in chemistry education, while Anggraeni and Rohaeti (2026) reviewed the integration of sustainable development issues into chemistry concepts. However, existing reviews provide limited evidence regarding the explicit integration of specific Sustainable Development Goals (SDGs) within chemistry education. Consequently, it remains unclear which SDGs are most frequently incorporated into chemistry teaching, how they are connected with chemistry concepts, and which ESD-based pedagogical approaches are employed to facilitate their integration. This limitation may affect teachers' ability to align appropriate SDGs with chemistry topics, design meaningful sustainability-oriented learning experiences, and develop students' sustainability competencies. Furthermore, the absence of a comprehensive synthesis limits the availability of evidence that can inform curriculum development, instructional planning, and future research on SDG-oriented chemistry education.

Therefore, this study systematically synthesizes research on the integration of Sustainable Development Goals (SDGs) in chemistry education through the lens of Education for Sustainable Development (ESD). Specifically, it examines the SDGs integrated into chemistry education, the ESD-based pedagogical approaches employed, and the chemistry concepts or sustainability contexts in which SDGs are incorporated. Based on these objectives, the study addresses the following research questions:

1. What Sustainable Development Goals (SDGs) are commonly integrated into chemistry education?
2. What Education for Sustainable Development (ESD)-based pedagogical approaches are commonly used in chemistry education?
3. What chemistry concepts and sustainability contexts are commonly used for integrating SDGs into chemistry education?

LITERATURE REVIEW

Within the context of the younger generation, education plays a significant role in shaping both their character and social understanding. One approach that has increasingly gained global attention is the integration of the Sustainable Development Goals (SDGs) into education systems. The SDGs consist of 17 goals that aim to promote socially, economically, and environmentally sustainable development by 2030 (Maryanti *et al.*, 2022; Prieto-Jiménez *et al.*, 2021). In education, the SDGs provide a framework for developing students' social awareness, emphasizing that education should extend beyond the transmission of knowledge to include character formation and the development of values that promote sustainability and social responsibility (Huang *et al.*, 2024).

Despite these efforts, the global progress toward achieving the SDGs remains concerning. More than halfway through the 15-year period established to guide collective efforts toward addressing pressing socioeconomic and environmental challenges, the United Nations (2023) reported limited progress in more than half of the SDG targets, with some targets even experiencing regression (Padilla *et al.*, 2026). At the same time, global awareness of the SDGs remains insufficient (UNESCO, 2020). This situation may indicate gaps in the integration of the SDGs into school curricula and pedagogical practices, potentially limiting the development of the knowledge and competencies that the current generation needs to contribute meaningfully to sustainable development (Padilla *et al.*, 2026).

In this regard, science education can play an important role in supporting the attainment of the SDGs. Science is intrinsically connected to sustainable development because many science curriculum topics directly relate to SDG concerns, including climate change, resource efficiency, water management, and biodiversity (Ministry of Education of the People's Republic of China [MOE], 2022). Moreover, the interdisciplinary nature of science education enables learners to connect scientific knowledge and skills with real-world issues while developing values and attitudes relevant to sustainable development (Maryanti *et al.*, 2022). Science education also seeks to prepare learners to become critical and responsible citizens (Sjöström & Eilks, 2017), equipping them with the competencies to think critically, creatively, and ethically when addressing societal challenges shaped by science and sustainability (Zidny *et al.*, 2020).

Within science education, chemistry is particularly relevant to sustainable development because its concepts and applications are closely connected to many environmental, social, and economic challenges. This provides a basis for examining how SDGs can be incorporated into chemistry education and how Education for Sustainable Development (ESD) can provide appropriate pedagogical approaches for such integration.

Sustainable Development Goals (SDGs) and Education for Sustainable Development (ESD)

The breadth of the 2030 Agenda for Sustainable Development is simply astounding. At the heart of this global agenda are the 17 Sustainable Development Goals (SDGs), which serve as an important wake-up call for nations to address interconnected economic, social, and environmental challenges. The SDGs were established by the United Nations as a global framework to eradicate poverty and inequality, protect the environment, and promote equal access to justice, healthcare, and prosperity by 2030 (United Nations, 2015). Collectively, these goals provide a shared direction for countries to pursue development that is inclusive, equitable, and sustainable.

Sustainable development is generally understood as development that meets present needs without compromising the ability of future generations to meet their own needs (UNESCO, 2019). Within this perspective, the SDGs encompass goals aimed at improving the economic well-being of communities, protecting the social fabric of societies, conserving the environment, and promoting justice and good governance. More broadly, they seek to ensure that improvements in quality of life are sustained across generations. Thus, achieving the SDGs requires not only economic and technological advancement but also changes in the knowledge, values, attitudes, and behaviors of individuals and communities.

Due to the interconnected nature of the SDGs, efforts to achieve their targets have become a global development priority. This requires synergy in the formulation and implementation of policies at the national, provincial, district, and city levels (Ministry of National Development Planning/BAPPENAS [BAPPENAS], 2020). However, policy and institutional efforts alone are insufficient to achieve long-term sustainability. Individuals need to understand sustainability issues, recognize their interconnectedness, and develop the capacity to make informed and responsible decisions. In this regard, education becomes a critical mechanism for translating the principles and values of sustainable development into individual and collective action.

Education is widely recognized as one of the most effective means of promoting sustainable development and strengthening human capacity to respond to environmental and developmental challenges (Ferrer-Estévez & Chalmeta, 2021; Vilmala *et al.*, 2022; United Nations Educational, Scientific and Cultural Organization [UNESCO], 2014; Kopnina, 2020). As Khalid Malik *et al.* (2023) emphasized, education is one of the most essential pillars of sustainable development and serves as the foundation upon which sustainable development is built. Without adequate educational opportunities and quality learning, the world may face significant limitations in achieving its development goals. Consequently, the Earth Charter and UNESCO have emphasized the importance of education in advancing sustainable development.

The central role of education is explicitly recognized within the SDGs through Target 4.7 of SDG 4, which calls for learners to acquire the knowledge and skills needed to promote sustainable development, including through education for sustainable development and sustainable lifestyles, human rights, gender equality, a culture of peace and non-violence, global citizenship, and appreciation of cultural diversity (UNESCO, 2020; United Nations, 2015). This target demonstrates that education is not merely a means of supporting sustainable development but is itself an essential component of the global sustainability agenda. It also highlights the need for educational systems to move beyond the transmission of disciplinary knowledge toward the development of competencies that enable learners to respond meaningfully to complex sustainability challenges.

In this context, Education for Sustainable Development (ESD) has emerged as an important educational approach for advancing the goals of the 2030 Agenda. ESD is an innovative paradigm that goes beyond knowledge acquisition by nurturing competencies needed to understand and address sustainability challenges, including systems thinking, anticipatory thinking, critical thinking, and other capacities for responsible decision-making (Araneo, 2024; Martín-Sánchez *et al.*, 2022; Olsson *et al.*, 2022; Soto-Solier *et al.*, 2023). Through ESD, learners are encouraged not only to understand sustainability issues but also to examine their causes and consequences, consider alternative futures, and participate in actions that contribute to sustainable development.

The contribution of education to sustainable development is further supported by Peeters (2021), who argues that quality education contributes to the preservation of human capital by equipping individuals with the knowledge and skills they need to become culturally and intellectually enriched, productive, and committed members of their communities. This perspective reinforces the connection between quality education and sustainability because individuals who are equipped with relevant knowledge, skills, and values are better positioned to contribute to the development of their communities while responding to emerging social, economic, and environmental challenges. Moreover, experiences in education across different contexts demonstrate that the success and implementation of educational reforms depend considerably on effective and clearly defined policies. Educational systems are responsible for preparing learners to apply knowledge to practical situations and to respond to the demands of a rapidly changing world. As Yang and Xiu (2023) noted, education involves specialists who connect knowledge with practical work to support growth in the modern information age. Therefore, schools need to operate within an educational philosophy that is responsive to global developments and societal needs. In this regard, sustainability and quality education are closely intertwined. Without sustained efforts to strengthen education and improve its quality and relevance, the broader objectives of sustainable development cannot be fully achieved.

The theoretical scope of ESD further demonstrates why it is particularly relevant to contemporary education. According to UNESCO, ESD requires countries to ensure that learners acquire the knowledge, skills, attitudes, and values necessary to promote sustainable development. These include learning related to sustainable lifestyles, human rights, gender equality, peace and non-violence, global citizenship, cultural diversity, and contributions to sustainable development. Thus, ESD is characterized by an interdisciplinary and holistic approach to education, rather than being confined to a single subject or area of learning. It encourages learners to examine the relationships among the three dimensions of sustainable development-economic, social, and environmental-and to understand how these dimensions interact across local, regional, and global contexts and across time (Ssosse *et al.*, 2021).

These three themes clearly establish the connection between SDGs, education, and ESD. SDGs represent the global vision and the goals of sustainable development, whereas education represents the mechanism by which individuals acquire the knowledge, skills, attitudes and values needed to attain such goals. In the case of ESD, it is the mechanism by which sustainable development can be taught in an interdisciplinary, contextualized and action-oriented manner. In other words, SDG goals cannot just be attained on the basis of an understanding of sustainability issues but need to be applied to the educational process itself. Therefore, the analysis of how ESD can be implemented in specific subjects like chemistry education becomes essential in this regard.

Integration of SDGs and ESD in Chemistry Education

In educational research, sustainable development and Education for Sustainable Development (ESD) have drawn a lot of attention, especially in reaction to growing social and environmental concerns. The importance of cultivating sustainable values and perspectives and bolstering the role of education in delivering ESD is highlighted by the growing need to protect the environment (Martín-Sánchez *et al.*, 2022). Therefore, education can be used to develop the values, skills, and attitudes that people need to contribute to sustainable development in addition to being a means of imparting knowledge.

In relation to the Sustainable Development Goals (SDGs), Sachs *et al.* (2022) argue that education provides a strong logical foundation for teaching in the 21st century. It primarily relies on inquiry-based processes that integrate teaching skills with disciplinary content, core competencies, and the cognitive habits that students need to effectively participate in achieving a sustainable future. From this perspective, ESD can be understood as a transformative learning process that equips both students and teachers with the thinking and teaching approaches needed to contribute to economic growth, social well-being, and environmental sustainability. Thus, ESD extends beyond the acquisition of information by preparing learners to apply knowledge and competencies to real-world sustainability challenges.

Despite the growing global awareness of sustainability and the importance of ESD, its implementation in educational settings remains inconsistent. Studies on teacher education for sustainable development indicate continuing challenges in translating sustainability-oriented knowledge and competencies into teacher preparation and classroom practice (Fischer *et al.*, 2022; Holst *et al.*, 2024). This suggests a gap between teachers' awareness of sustainability and their ability to translate such awareness into actual teaching practices. Similarly, a gap may persist between the sustainability objectives articulated in educational policies and curricula and their implementation through educator preparation and classroom practice (Holst *et al.*, 2024). These concerns highlight the need to strengthen teachers' capacity to integrate sustainability meaningfully into their subject-specific instruction.

In this regard, ESD provides a framework for developing the knowledge, skills, values, and attitudes necessary for sustainable living and responsible participation in society (Holfelder, 2019; Novidsa *et al.*, 2020; Violanda & Madrigal, 2021; Glavič, 2020). ESD addresses a broad range of sustainability-related concerns, including disaster risk reduction, climate change, biodiversity, poverty reduction, and sustainable consumption (Husamah, 2022). These areas demonstrate the close relationship between ESD, environmental education, and environmental awareness. However, effective ESD requires more than simply introducing sustainability topics into lessons. Students also need opportunities to engage in pedagogical approaches that encourage active participation and meaningful transformation. In this regard, active learning and transformative education are among the important pedagogical principles associated with ESD (Bezeljak *et al.*, 2020). Such approaches enable learners to connect knowledge with experience, reflect on sustainability issues, and participate in actions that may contribute to positive change.

The multi-disciplinary character of ESD implies that ESD implementation in various subjects becomes especially crucial. Instead of considering sustainability as an independent subject, ESD encourages teachers to relate sustainability-related issues to notions and practices which are inherent to the particular subjects. The relevance of such an approach to science education lies in the fact that numerous environmental, social and economic problems which SDGs are concerned about have much in common with the sphere of science. Since the processes and products of chemical nature are involved into people's lives to a great extent and have close relation to the mentioned above spheres, chemistry plays an especially significant role among sciences.

Chemistry education is therefore central to achieving the United Nations Sustainable Development Goals (UN SDGs) by promoting resource efficiency, reducing environmental impacts, and embedding sustainable practices into learning. Sustainability has consistently been an important theme in chemistry education, reflecting the significance of chemistry in addressing contemporary societal and environmental challenges (Mahaffy *et al.*, 2019). Through chemistry instruction, teachers can emphasize concepts and practices such as green chemistry, which promotes the reduction or elimination of hazardous substances and encourages greater atom efficiency in chemical processes (Etzkorn & Ferguson, 2023; Widyantoro *et al.*, 2025). Integrating these principles into chemistry education can help learners understand that chemistry is not only concerned with chemical concepts and laboratory procedures but also has an important role in addressing sustainability challenges.

Furthermore, connecting theoretical chemistry concepts taught in the classroom with real-world applications can increase the relevance and meaningfulness of chemistry learning. Examples such as clean energy, biodegradable materials, waste reduction, and sustainable chemical industries provide opportunities for students to recognize how chemistry contributes to addressing contemporary sustainability concerns. Through such connections, students can develop a broader understanding of chemistry and recognize its relationships with other scientific and non-scientific fields. The integration of sustainability into chemistry education can therefore help students see chemistry as a discipline that has practical implications for environmental protection, economic development, and societal well-being.

Consequently, contemporary trends in chemistry education increasingly emphasize approaches that are grounded in sustainability problems, green chemistry, and the practical application of these principles. Modern chemistry education requires instructional models that can bring together disciplinary chemical knowledge and sustainable development. In this regard, project-based and other student-centered approaches provide opportunities for learners to explore sustainability issues while applying chemistry concepts to authentic situations. Poya (2026), for instance, highlights the use of project work aligned with the UN SDGs as a means of enhancing students' knowledge of sustainability. Such approaches demonstrate how chemistry education can move beyond the traditional transmission of content toward learning experiences that connect chemical knowledge with sustainability challenges and encourage students to consider their role in contributing to the achievement of the SDGs.

Given all these factors, it can be concluded from the available literature that the integration of ESD in chemistry education will provide an important mechanism for making connections between educational knowledge and the broader objectives of sustainable development. For teachers to effectively integrate sustainability into their chemistry classes, it is essential for them to have the relevant knowledge, pedagogical skills, and support, as evident from the identified gap between sustainability awareness and instruction. Therefore, the importance of examining how chemistry teachers perceive and integrate SDGs and ESD cannot be overemphasized.

MATERIALS AND METHODS

This study employed a systematic literature review (SLR) methodology to systematically identify, evaluate, and synthesize existing research on the integration of Sustainable Development Goals (SDGs) in chemistry education through the lens of Education for Sustainable Development (ESD). Specifically, the review focused on identifying the specific SDGs integrated into chemistry education, the ESD-based pedagogical approaches employed, and the chemistry concepts or content areas in which SDGs are incorporated. The SLR approach was selected because it provides a rigorous, transparent, and replicable process for synthesizing evidence from existing literature (Chien & Knoble, 2024).

Relevant studies were retrieved from the ERIC, ScienceDirect, Google Scholar, and Scopus databases using combinations of keywords such as "Sustainable Development Goals" or "SDGs", "Education for Sustainable Development" or "ESD", "chemistry education", "chemistry teaching", "chemistry learning", "chemistry curriculum", "SDGs integration", "ESD-based pedagogical approaches", and "sustainable chemistry". This was conducted utilizing a software named Publish or Perish as a tool in filtering articles needed for the systematic literature review.

Furthermore, the studies was then continuously selected though inclusion and exclusion criteria. Included were both international and national peer-reviewed journal articles that met the predetermined inclusion criteria: (1) articles published between 2020 and 2026; (2) studies focusing on the integration of Sustainable Development Goals (SDGs) in chemistry education through Education for Sustainable Development (ESD); (3) studies reporting ESD-based pedagogical approaches and/or chemistry concepts or sustainability contexts in which SDGs were integrated; (4) samples used were secondary high school students, chemistry teachers, and higher education students; and (5) articles published in the English language. In contrast, the exclusion criteria include non-peer-reviewed publications, conference abstracts without full papers, and studies that are not aligned with the objectives of this review. The filtering process yielded 26 synthesized articles. The database search process is summarized in the framework shown in Figure 1.

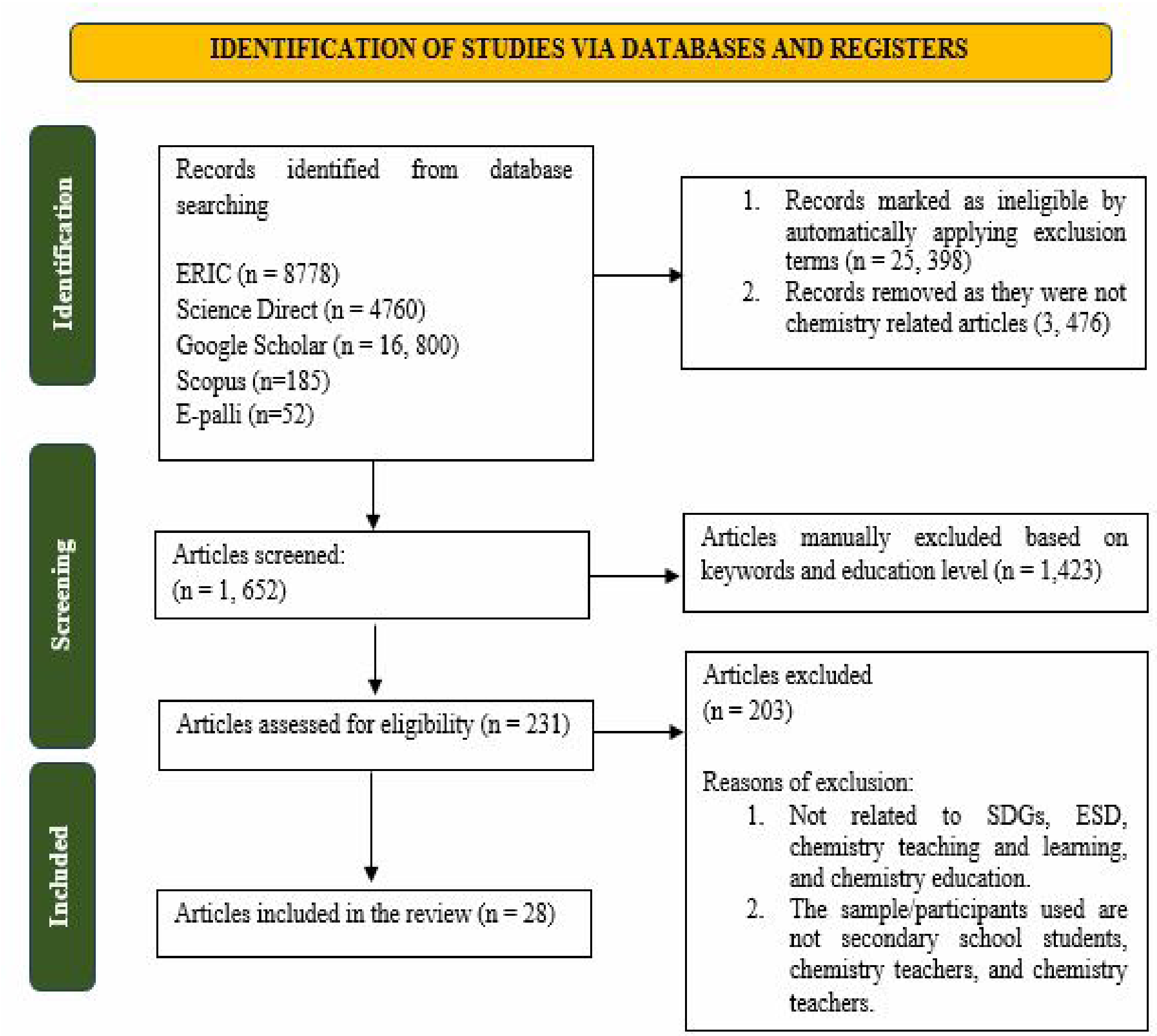

Figure 1: The Search Strategy Flow Diagram

RESULTS AND DISCUSSION

Based on the systematic review, it has synthesized 26 studies included in the final thematic dataset. With the findings consisting of empirical classroom studies, curriculum analyses, systematic reviews, conceptual papers, and chemistry education frameworks. Across the studies, three interrelated dimensions of SDG integration emerged as guided by the research questions: (1) the SDGs integrated in chemistry education, (2) the ESD-based pedagogical approaches used to facilitate integration, and (3) the chemistry concepts and sustainability contexts used as entry points for connecting chemistry with the SDGs.

Sustainable Development Goals (SDGs) Integrated into Chemistry Education

The results of the article review found 17 codes which are all the SDGs appeared on the theme of SDGs integrated into Chemistry education. With the synthesis showed that SDG 12 - Responsible Consumption and Production was the most frequently identified SDG, appearing in 14 of the 26 studies (53.8%). This was followed by SDG 13 – Climate Action, identified in 13 studies (50.0%), and SDG 4 – Quality Education, identified in 12 studies (46.2%).

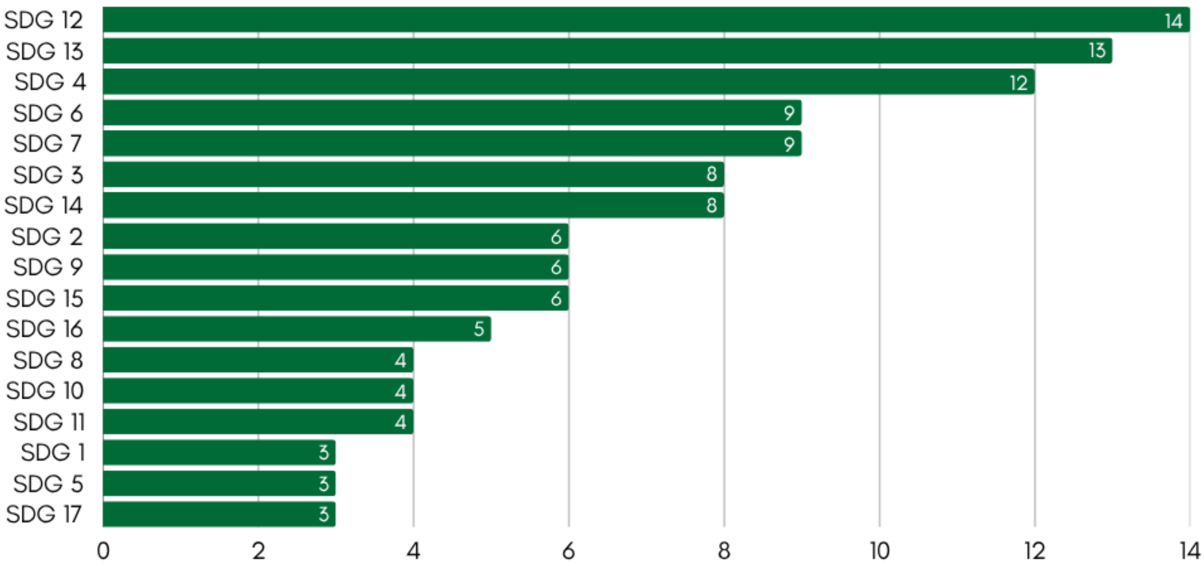

Figure 2: SDGs integrated in Chemistry Education based on the 26 articles

Based on the significance of SDGs 12 and 13, it seems that environmental sustainability would be the easiest SDG to incorporate into chemistry education. This conclusion makes sense since the creation, modification, utilization, and disposal of matter and energy are all directly related to chemistry. Since concepts like waste prevention, safe solvents, energy efficiency, renewable feedstocks, and pollution prevention can be associated with general sustainability goals, green chemistry is a particularly straightforward connection. For instance, SDGs 12 and 13 were connected to waste prevention, safer solvents, energy efficiency, renewable feedstocks, catalysis, degradable materials, and pollution prevention by Mitarlis *et al.* (2023).

Another highly recurrent SDG is the SDG 4 – Quality Education. In the studies reviewed, it has been noted that SDG 4 often acted as the educational approach by means of which other SDGs were realized. Research conducted on such issues as micro-scale chemistry, culturally responsive teaching, laboratory-based instruction, and more general ESD implementation linked chemistry education with quality, inclusive, learner-centered, and transformative education. Such as the study by Siregar *et al.* (2026) which is concerned with SDG 4 using the methods of culturally responsive teaching and differentiated learning, and the research by Chama (2025) emphasizes learner-centered pedagogy and transformative learning to improve ESD implementation in secondary chemistry.

From this perspective, SDG 4 in chemistry education has a dual nature: it is not just one of the goals that can be addressed, but also one of the means to realize other goals. In particular, it seems that for the integration of SDGs in chemistry education to be meaningful, it is necessary not only to introduce some sustainability issues into lessons of chemistry but also transform the educational approach used in it.

Moreover, the literature also demonstrated significant integration of SDGs 7 - Affordable and Clean Energy, 6 - Clean Water and Sanitation, 3 - Good Health and Well-Being, and 14 - Life Below Water. Concrete chemistry problems were often linked to these objectives. For instance, D'eon and Silverman (2023) used atom economy, combustion, fuel efficiency, and energy-related contexts to incorporate SDGs 7 and 13 into stoichiometry.

Similarly, SDG 6 was addressed through water pollution and purification, including research on hydrogels and biomaterials for treating pesticide-contaminated water. The SDG-focused Global Classroom study linked SDGs 2, 3, and 6 to agricultural chemistry, pesticides, food systems, pharmaceutical chemistry, and water purification. Analytical chemistry also provided connections to SDGs 2, 3, 6, 10, 12, 13, 14, and 16 through water depollution, environmental contaminants, pharmaceuticals in aquatic ecosystems, soil phosphorus, and sustainable analytical methods.

These findings demonstrate that SDG integration becomes broader when chemistry is presented through authentic sustainability problems. Rather than treating SDGs as additional topics,. The reviewed studies used issues such as energy, water pollution, food security, environmental contamination, and health as contexts through which chemistry concepts could be learned.

Similarly, the studies of hydrogels and biomaterials for the purpose of cleaning pesticide polluted water were considered as an approach to solving SDG 6 via water pollution and water purification. The interconnections between SDGs 2, 3, and 6 were analyzed via food systems, agricultural chemistry, pesticides, pharmaceutical chemistry, and water purification in the SDG-oriented Global Classroom project. Analytical chemistry, in turn, provided connections to SDGs 2, 3, 6, 10, 12, 13, 14, and 16 via soil phosphorus, pharmaceuticals in aquatic ecosystem, water pollution, environmental contaminants, and sustainable analytical methods.

It can be stated that the involvement of SDGs into chemistry through the issues of sustainability makes their integration broader. In particular, the studies analyzed above considered energy, water pollution, food security, environmental contamination, and health as contexts for learning chemistry.

Another important, yet smaller number of papers concentrated on several, or even all 17. According to Hoffman & Dicks (2023), it is advisable to include the Green Chemistry Principles and all 17 SDGs into chemistry education at the high school level. Mansour *et al.* (2026) proposed to introduce the SAMI (Sustainability of Analytical Methods Index), a SDG-based tool for evaluating analytical methods,. While Marteel-Parrish (2026) integrated all 17 SDGs into an interdisciplinary course using system thinking approach.

Among those SDGs that have been found to be dominant orientations in chemistry education are SDGs 12, 13, 4, and 7, based on the literature review. Followed by SDGs related to water, health, innovation, and sustainable communities. Nevertheless, there is no equal distribution of SDG focus. While some researches mentioned certain SDGs explicitly, others have only mentioned sustainability or SDGs in general terms. Thus, the integration of SDGs into chemistry education is selective.

ESD-based Pedagogical Approaches Used in Chemistry Education

The most frequently occurring theme was interdisciplinary learning, identified in 8 studies, followed by experiential/hands-on/laboratory learning with 8 studies. While systems thinking had 7 studies. Moreover, Problem-/Project-Based Learning appeared in 6 studies, and context-based learning. Also, collaborative learning appeared in 5 studies each.

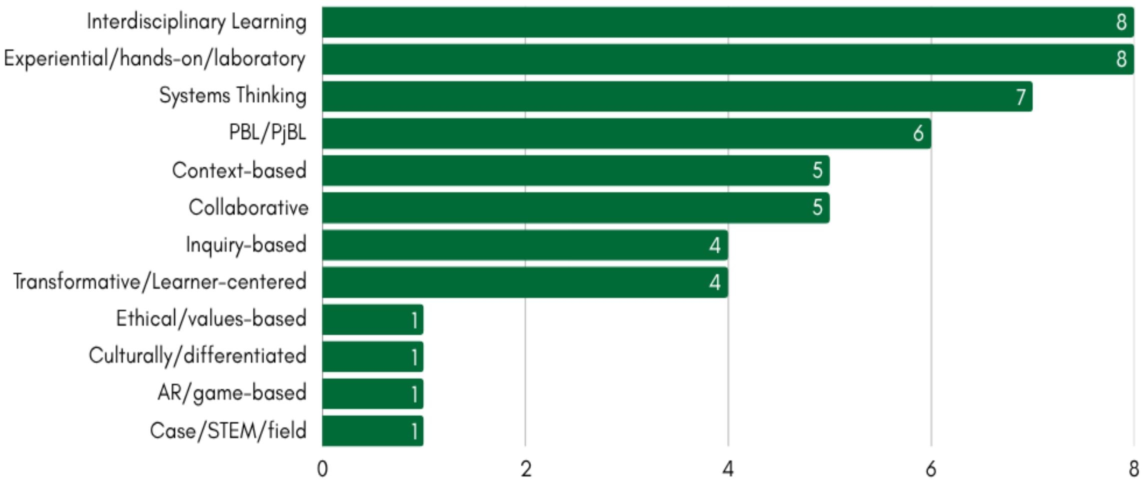

Figure 3: ESD-based Pedagogical Approaches Utilized in Chemistry Education based on the 26 articles

Upon systematically reviewing the articles, one of the strongest patterns that emerged as a central ESD-based pedagogical approach was the use of interdisciplinary learning. Sustainability issues were used to situate chemistry within agriculture, health, environmental science, engineering, industry, and community contexts. Wissinger *et al.* (2021), for instance, advocated cross-disciplinary learning and sustainability-contextualized chemistry education.

Additionally, by systems thinking to connect chemistry concepts with broader sustainability issues. D'eon and Silverman (2023) used systems thinking and backward design to connect reaction stoichiometry with SDGs 7 and 13. Wissinger *et al.* (2021) similarly proposed using systems thinking, the SDGs, and the Planetary Boundaries framework to position chemistry within physical, biological, ecological, technological, and social systems.

Since sustainability issues rarely have a single cause or solution, the significance of systems thinking is especially relevant to ESD. Carbon cycles, chemical reactions, energy transformations, and material flows are examples of chemistry concepts that can be viewed as parts of interrelated systems. Nguyen *et al.* (2026) reported that after five ESD-integrated chemistry lessons, students' systems-thinking abilities improved, further demonstrating this orientation.

On the other hand, problem-based and project-based learning were among the most prominent student-centered approaches. These approaches positioned students as active participants in addressing authentic sustainability problems rather than passive recipients of sustainability information. For example, Poya (2026) discovered that SDG-related interventions enhanced interdisciplinary skills and sustainability literacy and engagement. The interventions were resource management, water security, and renewable energy. In a similar manner, the Global Classroom project used SDG-related PBL to engage chemistry students in interdisciplinary projects concerning agricultural chemistry, pesticides, water purification, and biomaterials.

The use of hands-on inquiry-based learning was yet another recurring theme. As part of the drive to promote scientific literacy and sustainability education, Poya (2026) incorporated inquiry-based learning, experiential learning, and systems thinking into various topics including climate change, ocean acidification, soil/water quality, nutrient cycling, biodiesel synthesis, and green chemistry.

In addition, lab-based learning was particularly relevant in this case since it allowed for the application of sustainability principles to actual chemical processes. Whereas green analytical chemistry enabled students to look at lab procedures through the "green lens" and think of ways to make lab work more sustainable, micro-scale chemistry reduced the amount of chemicals used and wasted.

While the addition of Pevida *et al.* (2026) strengthens the experiential learning theme. The study used Experiential Learning Theory as its main theoretical framework and emphasized active engagement and interaction with nature as ways of developing environmental awareness and responsible environmental roles. However, its findings also showed that sustainability development education had only a weak relationship with environmental literacy, suggesting that exposure to sustainability education alone may not be sufficient to produce strong environmental literacy outcomes.

Furthermore, context-based learning also emerged quite commonly from the literature. The context of chemistry was made from agriculture, health, environmental sciences, engineering, industry, and communities in relation to sustainability issues. For instance, Marteel-Parrish (2026) introduced concepts of systems thinking, project-based learning, community-based education, green chemistry, life cycle assessment, AI, environmental sciences, and engineering.

There were also clear ethical and socioscientific approaches. While Rahmawati *et al.* (2022) employed an Ethical Dilemma-STEAM model to foster ethical reasoning, environmental awareness, and cooperative decision-making. Anggraeni and Rohaeti (2026) identified socio-scientific issues and green experiments as ESD implementation strategies.

These results demonstrate how ESD-oriented chemistry instruction is progressively shifting from isolated lab exercises to real-world, multidisciplinary and socially relevant learning opportunities.

Chemistry Concepts and Sustainability Contexts Used to Integrate SDGs

The most evident theme related to sustainability contexts was green chemistry and sustainable laboratory practices in 12 studies (46.2 %). This finding demonstrates the strong compatibility between green chemistry and SDG integration because its principles directly address issues of resource efficiency, waste prevention, safer chemicals, energy use, and environmental protection.

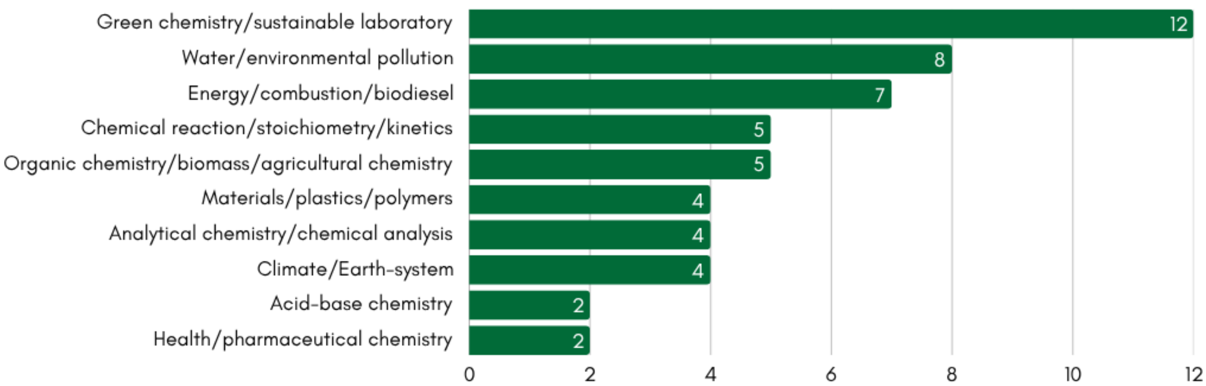

Figure 4: Chemistry Contents and Sustainability Contexts in SDGs

Mitarlis *et al.* (2023) demonstrated how learning based on green chemistry principles can facilitate the achievement of SDGs through laboratory activities and project-based assignments. Their study emphasized waste prevention, safer solvents, energy efficiency, and sustainable laboratory practices. Similarly, Hoffman and Dicks (2023) proposed integrating the SDGs with Green Chemistry Principles in secondary school chemistry curricula to strengthen sustainability literacy.

Sustainability was also successfully linked to basic chemistry concepts. The integration of SDGs 7 and 13 with stoichiometry, atom economy, reaction efficiency, combustion, thermochemistry, and energy efficiency is the most obvious example. Sustainability can be integrated into required chemistry content without taking the place of the intended chemistry learning outcomes, as D'eon and Silverman's (2023) study showed.

Organic and materials chemistry also provided important contexts for sustainability. Czok *et al.* (2023), for example, addressed microplastics, nanoplastics, polymer characteristics, plastic consumption, waste, recycling, and alternative materials through an ESD-oriented learning context. Rohiat *et al.* (2025), meanwhile, used micro-scale experiments in organic chemistry, demonstrating how reducing chemical quantities and laboratory waste can connect organic chemistry learning with SDGs 4 and 12. Further studies were made in macromolecules, plastics, biodiesel, and biomass chemistry, indicating links between resource use, waste management, alternate materials, and renewables in terms of chemistry. Anggraeni and Rohaeti

(2026), for example, pointed out that the chemistry and sustainability concepts involved in the implementation of ESD include macromolecules, biodiesel, plastics, and water pollution.

Analytical chemistry and environmental chemistry emerged as particularly useful areas for connecting chemistry with real-world sustainability problems. Dicks (2023) identified water depollution, environmental contaminants, pharmaceuticals in aquatic ecosystems, soil phosphorus, organic carbon, green solvents, catalysis, spectroscopy, chromatography, and electroanalysis as contexts for sustainable analytical chemistry.

Climate change, carbon cycle, nutrient cycles, water cycle, ocean acidification, soil quality, biodiversity, and planetary boundaries are among broader contexts incorporated. Wissinger *et al.* (2021) emphasized the use of systems thinking, the SDGs, and the Planetary Boundaries framework to situate chemistry within broader physical, biological, ecological, technological, and social systems. Their work connected chemical processes and products, chemical reactions, carbon cycles, nutrient cycles, water cycles, climate change, and planetary boundaries with sustainability-oriented chemistry education.

Poya (2026) has used some similar contexts in the case of inquiry-based experiential chemistry education for climate change, ocean acidification, soil and water quality, nutrient cycles, biodiesel production, and green chemistry. Lastly, Pevida *et al.* (2026) highlights issues such as climate change, depletion of resources, loss of biodiversity, plastic pollution, solid waste, water, and air quality issues, greenhouse gases, energy conservation, and sustainable development. Similarly, Kathyole *et al.* (2025) mentions the importance of ecological conservation, environment stewardship, sustainability, ecological justice, biodiversity, climate change, energy, water, and responsible resource management.

Integrated Discussion

The results of the article review from this study are also intended as an effort to curriculum developers and teachers to overcome difficulties in integrating sustainable development goals into different chemistry concepts utilizing appropriate ESD-based pedagogical approaches within sustainability contexts. The following are the results of the review of various SDGs that can be integrated into chemistry concepts through pedagogical approaches presented in Table 1.

Table 1: Thematic Synthesis of SDG Integration in Chemistry Education through Education for Sustainable Development

SDGs	Sustainability Contexts	ESD-BasedPedagogical Approaches	Chemistry Concepts	Cited Study
SDG 7 SDG 13	Clean energy, Combustion, Climate change	Systems thinking, Contextual learning	Stoichiometry, Atom economy, Combustion, Reaction efficiency	D'eon & Silverman (2023) Poya (2026) Wissinger *et al.* (2021) Dicks (2023)
SDG 12 SDG 13	Waste reduction, Sustainable chemical production	Green chemistry learning, Laboratory learning, Project-based Learning	Safer solvents, Energy efficiency, Waste prevention	Mitarlis *et al.* (2023) Hoffman & Dicks (2023) Marteel-Parrish (2026) Moniz & Sarraguça (2026) Rohiat *et al.* (2025)
SDG 6	Pesticide-Contaminated water	Problem-based Learning, Interdisciplinary learning, Research-based learning	Water purification, Hydrogels, pesticides, Environmental chemistry	Radhakrishnan *et al.* (2026) Poya (2026) Dicks (2023)
SDG 12 SDG 14	Plastic Microplastic pollution	Augmented Reality, Contextual Learning, Experiential Learning	Polymers, Plastics, Material properties, Recycling	Czok *et al.* (2023) Anggraeni & Rohaeti (2026)
SDG 2 SDG 6	Food security, Agriculture, Pesticide Contamination	Interdisciplinary Problem-based Learning	Agricultural Chemistry, Pesticides, Biomaterials	Radhakrishnan *et al.* (2026) Dicks (2023) Poya (2026)

SDG 3	Health and Pharmaceutical Access	Interdisciplinary Problem-based Learning	Pharmaceutical/Health Chemistry	Radhakrishnan *et al.* (2026) Dicks (2023) Wissinger *et al.* (2021) Poya (2026)
SDG 4	Quality, Inclusive Chemistry Education	Culturally Responsive, Differentiated, Learner-centered Learning	Chemistry concepts contextualized through students' cultural and learning contexts	Siregar *et al.* (2026) Rohiat *et al.* (2025) Rahmawati *et al.* (2022) Chama (2025) Gericke & Torbjörnsson (2022)

These patterns indicate that the identification of SDG in a lesson on chemistry is not sufficient for effective integration of SDG. On the contrary, the studies reviewed have tended to first relate SDG to a concrete sustainability problem, secondly find a pedagogy that focuses on ESD and is appropriate for addressing that problem, and thirdly contextualize the learning within a chemistry topic. SDGs 7 and 13 have been tied to the concept of systems thinking that was operationalized in topics such as stoichiometry, atom economy, combustion, efficiency of reactions, and efficiency of energy in the case of D'eon and Silverman (2023).

Similarly, Radhakrishnan *et al.* (2026) used SDG-focused interdisciplinary problem-based learning in a Global Classroom involving Chemistry students, with projects addressing sustainability contexts such as water pollution, food insecurity, vaccine access, water purification, pesticides, hydrogels, agricultural chemistry, and health-related chemistry.

From the combined findings, it can be noted that contextualized chemistry, active learning, and environmental sustainability are the key elements of SDG integration in chemistry education. Although the pedagogical analysis reveals a bias towards interdisciplinary learning, systems thinking, experiential learning, and Problem-based and Project-based Learning, the quantified findings explicitly concentrate on SDGs 12, 13, 4, 6, and 7. Entry points to SDG integration in chemistry content include green chemistry, environmental pollution, water, energy, chemical reactions, organic chemistry, and materials.

However, despite having several literatures that makes the synthesis strong, several gaps are evident. One gap identified is the uneven distribution of SDGs. Studies heavily focuses on SDG 12, 13, 4, 6, and 7, whereas other SDGs have significantly lower importance. This implies a chance to study the ways in which chemistry education can help achieve SDGs which have been less frequently represented across curriculums or contents without making unnecessary associations.

Another one is that there is a limited alignment among SDGs, chemistry competencies, and pedagogies. Which is an important area for curriculum and teacher-training development.

While on sustainability contexts, green chemistry is the strongest bridge between chemistry and sustainability. But reliance on green chemistry alone may limit the range of chemistry concepts used for SDG integration. More studies are needed on how acid-base chemistry, thermochemistry, kinetics, periodic trends, equilibrium, electrochemistry, macromolecules, and other foundational concepts can be meaningfully connected to the SDGs.

The literature also suggests that successful integration depends on teachers' knowledge, confidence, curriculum support, resources, and professional development. This is particularly relevant since curriculum integration cannot be sustained when teachers recognize the importance of SDGs but lack the capacity to identify appropriate SDG–chemistry connections or design suitable ESD learning experiences.

CONCLUSION

The systematic review demonstrates differences in SDGs incorporated into chemistry education, the ESD-based approaches applied, and the chemistry concepts and sustainability contexts used. The three most common SDGs are SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 4 (Quality Education), followed by SDGs linked to water, energy, health, and aquatic ecosystems. This is a clear indication of strong links between chemistry education and consumption of resources, protection of environment from pollution, and provision of energy.

The most common chemistry contexts are green chemistry and sustainable laboratories, which provide clear links to sustainability through reduction of wastes, safer chemicals, energy savings, renewable sources of energy, and pollution prevention. The other sustainability contexts are water and environmental pollution, energy and combustion, biodiesel, chemical reactions, agriculture, plastics and polymers, and analytical chemistry.

Finally, it was found that interdisciplinary, systems thinking, experiential, problem-based, project-based, inquiry-based, and contextual learning promote successful ESD integration. In general, chemistry education can be regarded as an area that provides many chances for promoting sustainable development. Further research is needed to develop teachers' ability to recognize links between SDGs and chemistry and apply ESD-based approaches to instruction and assessment of sustainability competencies.

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