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Mapping Global Research on Sustainability and SDGs in Chemistry Higher Education

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Abstract

This paper examines how the Sustainable Development Goals (SDGs) have been brought into university-level chemistry education worldwide. Using a blend of bibliometric and systematic review methods, we analyzed 564 publications from Scopus and Web of Science (2001–June 2025), along with a closer look at 17 influential papers. Over the past twenty years, there's been a clear uptick in studies on this topic, largely shaped by global education policies and sustainability initiatives. The United States, Canada, China, and the UK stood out as the most active contributors. Our findings reveal that green chemistry, systems thinking, and hands-on learning are key themes. Different teaching approaches, like problem-based and authentic learning, have helped improve students' understanding of concepts, awareness of sustainability, and ethical outlook. Still, gaps remain, especially in how these ideas play out across cultures, their long-term effects, and how fully SDGs are woven into various chemistry programs. These insights point to the important role chemistry education can play in preparing graduates who are both scientifically grounded and ethically mindful. Looking ahead, future studies might benefit from broader data, longer-term designs, and cross-disciplinary efforts to keep pushing sustainable chemistry education forward.

Keywords: SDGs, chemistry education, green chemistry, higher education, bibliometric

1. Introduction

Higher education plays a pivotal role in shaping a sustainable society, with chemistry as a fundamental discipline at the forefront of global sustainability challenges. Chemistry not only drives innovations that enable sustainable solutions but also bears responsibility for its historical environmental impacts. Consequently, embedding sustainability principles and the Sustainable Development Goals (SDGs) into university-level chemistry curricula is imperative (M. Chen et al., 2020; Płotka-Wasylka et al., 2018). This integration seeks to equip students with a profound understanding of green chemistry principles, systems thinking, problem-solving skills, and ethical responsibility essential for addressing complex global issues kompleks (Anastas & Zimmerman, 2018; Mahaffy & Elgersma, 2022; Zuin et al., 2021). Future chemistry graduates must be capable of applying their knowledge to design processes and products that are safe, efficient, and environmentally benign, thus actively contributing to a more sustainable future (Ogodo & Abosede, 2025; Salsabila & Hernani, 2025; Sánchez Morales et al., 2024).

The 2030 Agenda adopted by the United Nations in 2015, with its 17 SDGs, has established an ambitious framework for sustainable global development, positioning higher education as a key agent in realizing these goals (Leal Filho et al., 2015; Molina et al., 2023). Initiatives such as Education for Sustainable Development (ESD), promoted by UNESCO, highlight the responsibility of universities to foster sustainability competencies among students, including critical thinking, environmental awareness, interdisciplinary collaboration, and anticipatory capacity (Burmeister et al., 2013; Filho et al., 2021; Zowada et al., 2022). This has driven higher education institutions worldwide to reorient their curricula, research, and operations in alignment with the global sustainability agenda, ensuring that graduates possess the relevant skills to tackle pressing social, economic, and environmental challenges (Borges, 2019; Lozano & Watson, 2013; Mitarlis et al., 2023).

Despite growing recognition of the importance of sustainability and the SDGs within higher education—particularly in the sciences—systematic mapping of global literature on the integration of these topics into chemistry higher education remains scarce. Existing bibliometric studies often focus on sustainability in education more broadly (Côrtes & Rodrigues, 2016), within the sciences in general (Maryanti et al., 2022), or address sustainability in higher education without specific attention to the chemistry discipline (Alejandro-Cruz et al., 2019; Gorski et al., 2023). There are also systematic reviews centered on green and sustainable chemistry training, yet these do not comprehensively cover all facets of sustainability and SDG integration across chemistry curricula and practices globally (Gunbatar et al., 2025). This gap underscores the need for an in-depth analysis that explicitly maps the global research landscape on integrating sustainability and the SDGs into chemistry higher education.

Accordingly, this study pursues several objectives. First, it conducts a comprehensive bibliometric analysis of literature concerning the integration of the SDGs into chemistry higher education, utilizing the combined coverage of the Scopus and Web of Science (WoS) databases. Second, it aims to evaluate the development of publications on this theme over the past two decades, thereby illustrating the evolution of research on SDG implementation in university-level chemistry education. Third, it seeks to identify the most prolific authors, journals, countries, and institutions contributing to this field. Fourth, the study maps bibliographic networks among authors, journals, and countries, examines the co-occurrence of frequently used keywords, and performs thematic analyses to reveal dominant research foci. Finally, by adopting the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework, this study also carries out a systematic review of relevant literature, discussing diverse pedagogical approaches and methodologies employed, while identifying determinants and implications of SDG implementation in chemistry higher education across various national contexts.

Based on these objectives, this study was designed to address five primary research questions. First (RQ1), what are the characteristics of research on the implementation of the SDGs in chemistry higher education in terms of contributing authors, journals, countries, institutions, and associated keywords? Second (RQ2), what patterns of bibliographic networks and keyword or thematic co-occurrences can be observed within this body of literature? Third (RQ3), what educational approaches and methods have been employed to integrate the SDGs into university-level chemistry instruction? Fourth (RQ4), what research gaps persist that warrant future investigation?

Through these aims, the study makes several significant contributions to the existing literature. To begin with, it offers a bibliometric analysis of 564 articles retrieved from the Scopus and WoS databases, which were subsequently synthesized to provide a comprehensive overview of research trends concerning the integration of the SDGs into chemistry higher education. By combining bibliometric analysis with a concrete systematic literature review (SLR), this study delivers a more nuanced understanding of the field.

Additionally, the bibliometric findings were visualized using the R-based bibliometrix package. This allowed for the depiction of the evolution of the literature over more than two decades, highlighting annual publication counts, total citations, and average citations. The study also identifies the most relevant journals, authors, countries, affiliations, and keywords, while mapping the bibliographic relationships among journals, authors, and countries, as well as patterns of keyword co-occurrence. Such analyses reveal the thematic dynamics within this research area over the past twenty years, thus facilitating the identification of emerging trends, focal topics, leading publication sources, and potential avenues for collaboration across authors, journals, and regions. Third, this study advances a systematic literature review guided by the PRISMA 2020 framework. Through this process, 17 relevant studies identified from the previously analyzed bibliometric dataset were subjected to in-depth content analysis. This examination focused on three principal dimensions: the theoretical frameworks underpinning the integration of the SDGs into chemistry education, the diverse pedagogical approaches and implementation methodologies reported, and the key issues arising in university-level practice. Fourth, the study identifies critical determinants and outcomes associated with the implementation of the SDGs in chemistry higher education, which are extensively emphasized within the empirical literature. In doing so, the research helps to illuminate methodological challenges and provides insights into the key drivers that support the successful integration of the SDGs within chemistry curricula. Fifth, this study synthesizes findings from prior research to pinpoint existing research gaps, complemented by visual classifications of the factors influencing and resulting from the implementation of the SDGs in chemistry higher education. Moreover, this investigation highlights the limitations of current studies and opens avenues for future research from three perspectives: theoretical foundations, contextual diversity, and methodological innovation. In light of the pressing global agenda for sustainable development, this combined bibliometric and systematic review serves as a vital reference point for designing chemistry education practices that are more relevant, sustainable, and directly aligned with the SDGs.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods employed in the study. The results of the bibliometric analysis are presented in Section 3. Section 4 elaborates on the findings of the systematic literature review (SLR). Section 5 discusses research gaps and formulates problem statements to guide future studies. Section 6 outlines the conclusions and key implications, while Section 7 addresses the study's limitations and offers recommendations for future research.

2. Methods

The literature search related to studies on the integration of the SDGs into chemistry education was conducted using two primary databases: Scopus and Web of Science (WoS). The selection of these sources was based on several considerations. First, both databases offer extensive coverage across a wide array of reputable publishers and are widely recognized as leading repositories for indexing scholarly articles and various types of publications worldwide (Jabeen et al., 2021; Liu & Avello, 2021; Mongeon & Paul-Hus, 2016). Moreover, these platforms provide flexible search functionalities, enabling comprehensive searches across all fields as well as refined queries limited to titles, abstracts, and keywords—including controlled vocabulary and predefined terms (Linnenluecke et al., 2020; Sharif et al., 2019). For instance, Scopus stands as the largest abstract and citation database of peer-reviewed literature, offering broad, high-quality coverage along with complete bibliographic information for each record. In contrast, WoS is well known as a digital bibliometric platform that supplies high-quality metadata suitable for bibliometric analyses and encompasses a wide range of scientific disciplines (Gaviria-Marin et al., 2019).

Echchakoui (2020) cautions that relying solely on Scopus and WoS may limit the scope of understanding regarding knowledge structures and emerging trends within specific research domains. Comparative studies of these two databases have shown that neither platform holds an absolute advantage in the context of bibliometric analysis (Sánchez et al., 2017). Consequently, it is widely recommended to use both databases in tandem to achieve more comprehensive and accurate analytical results, as their respective strengths and limitations tend to complement one another (Mongeon & Paul-Hus, 2016). Accordingly, numerous recent bibliometric and systematic studies have employed these databases either independently or in combination (Dominković et al., 2022; Echchakoui, 2020; Qin et al., 2022).

This study adopted the PRISMA 2020 methodology introduced by the British Medical Journal (BMJ) in 2021. Identification criteria played a pivotal role in defining the scope of inquiry, developing the research workflow, and structuring the study protocol. This protocol encompassed critical elements such as search terms, selected databases, exclusion criteria, types of publications reviewed, and the specific time frame of the analysis. Detailed components of the research protocol are presented in Table 1.

Table 1.
Research Protocol

Databases	Scopus and Web of Science
Search Term:	
Group 1. Scopus: TITLE-ABS-KEY	Group 1: TITLE-ABS-KEY ("chemistry education" OR "chemical education" OR "teaching chemistry" OR "learning chemistry" OR "chemistry curriculum" OR "chemistry instruction") AND ("sustainability" OR "sustainable development" OR "green chemistry" OR "ESD" OR "education for sustainable development" OR "SDGs" OR "Sustainable Development Goals" OR "Agenda 2030" OR "global goal*") AND ("higher education" OR "university" OR "college" OR "tertiary education" OR "undergraduate" OR "postgraduate")
Group 2. Web of Science: All fields	Group 2: All Fields ("chemistry education" OR "chemical education" OR "teaching chemistry" OR "learning chemistry" OR "chemistry curriculum" OR "chemistry instruction") AND ("sustainability" OR "sustainable development" OR "green chemistry" OR "ESD" OR "education for sustainable development" OR "SDGs" OR "Sustainable Development Goals" OR "Agenda 2030" OR "global goal*") AND ("higher education" OR "university" OR "college" OR "tertiary education" OR "undergraduate" OR "postgraduate")
Language	English
Document type	Article, Review
Timeframe	2001 – Juni 2025
Software	Excel, R (RStudio and Biblioshiny), VOSviewer.
Method	Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA-2020) framework

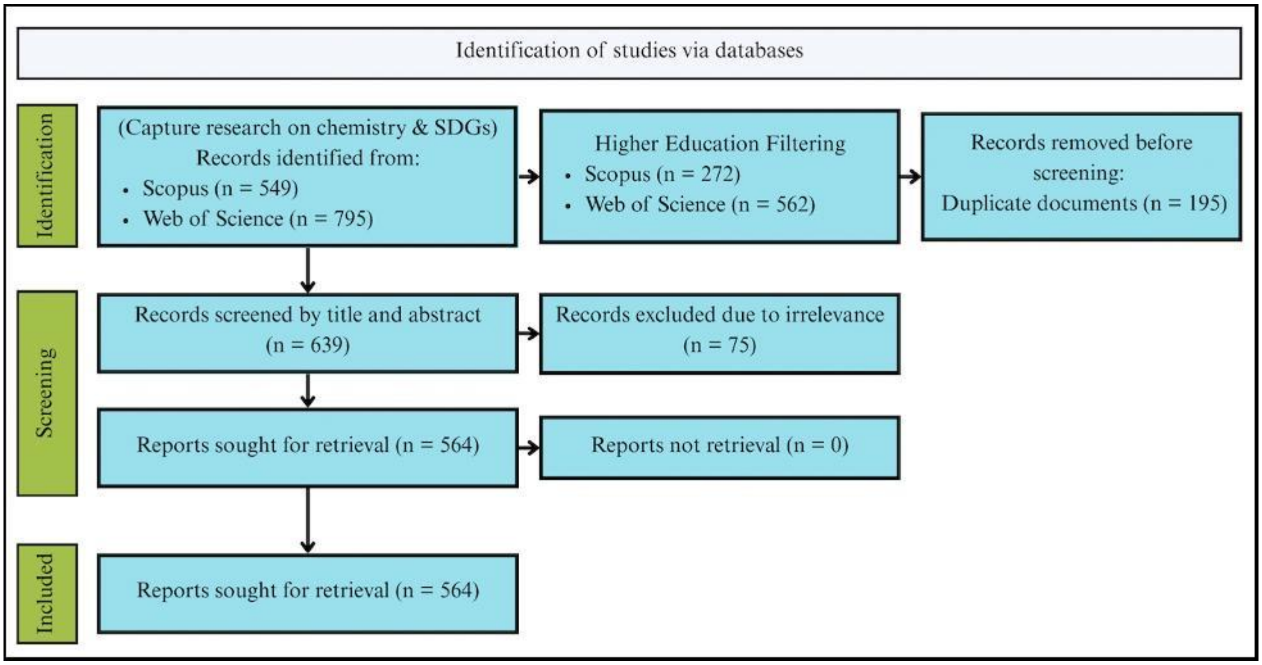
The data collection process was carried out systematically in three stages. In the initial stage, a literature search was conducted using a combined keyword string specifically designed to capture publications addressing both chemistry education and sustainability aspects. The primary keywords employed included: ("chemistry education" OR "chemical education" OR "teaching chemistry" OR "learning chemistry" OR "chemistry curriculum" OR "chemistry instruction") AND ("sustainability" OR "sustainable development" OR "green chemistry" OR "ESD" OR "education for sustainable development" OR "SDGs" OR "Sustainable Development Goals" OR "Agenda 2030" OR "global goal*"). This initial search retrieved 795 documents from WoS and 549 documents from Scopus.

In the second stage, to ensure that the retrieved publications were indeed relevant to the study's focus on higher education, an additional filtering step was performed using the keywords "higher education" OR "university" OR "college" OR "tertiary education" OR "undergraduate" OR "postgraduate." As a result, the number of documents was reduced to 562 in WoS and 272 in Scopus. The datasets from these two databases were then merged, during which 195 duplicate records identified as appearing in both databases were removed.

The third stage involved a manual screening process by reviewing the titles and abstracts of all remaining documents to confirm their specific relevance to chemistry education. This step led to the elimination of 75 documents that did not explicitly address chemistry education, yielding a final dataset of 564 documents for the bibliometric analysis. The overall selection and screening workflow is illustrated in Figure 1.

All documents were exported in BibTeX format and imported into the R programming environment for analysis. The bibliometric analysis was performed using Bibliometrix, an open-source R package designed to support comprehensive and transparent literature mapping (Aria & Cuccurullo, 2017). This package facilitates visualization for systematic reviews and enables the efficient processing of large datasets (Ghorbani, 2024). Furthermore, advanced analyses were conducted using Biblioshiny for Bibliometrix, an interactive web interface integrated with Bibliometrix that allows for more in-depth exploration of publication trends, author collaboration networks, and dynamic keyword analyses (Yao et al., 2024). Additionally, VOSviewer was employed for bibliographic coupling and keyword co-occurrence analyses, with datasets converted into RIS format to ensure compatibility and accurate network visualization.

Figure 1
PRISMA Flowchart of Literature Screening and Selection Process



3. Result and Discussion

3.1. Bibliometric Results

The bibliometric analysis encompassed 564 publications, examining them by year of publication, journal, author, country, and keyword. This study provides insights into research interests, scholarly attention, and emerging trends concerning the integration of the SDGs within chemistry education.

3.1.1. Main Information and Publication Trends on SDGs and Chemistry Education

As summarized in Table 2, the analysis included 564 documents published between 2001 and 2025, originating from 50 distinct sources comprising journals, books, and other scholarly outlets. The annual growth rate of publications was recorded at 16.1%. The average document age was 6.18 years, with a mean of 12.56 citations per document. The dataset contained 1,022 Keywords Plus and 854 author-supplied keywords.

A total of 2,045 authors contributed to this body of literature, with 64 identified as single authors. The collaboration level was notably high, indicated by an average of 4.23 authors per document and an international co-authorship rate of 12.06%. In terms of document types, journal articles predominated (514), followed by early access articles (26), conference proceedings (22), and combined article-proceedings (2).

Table 2.
Main Information on Publication

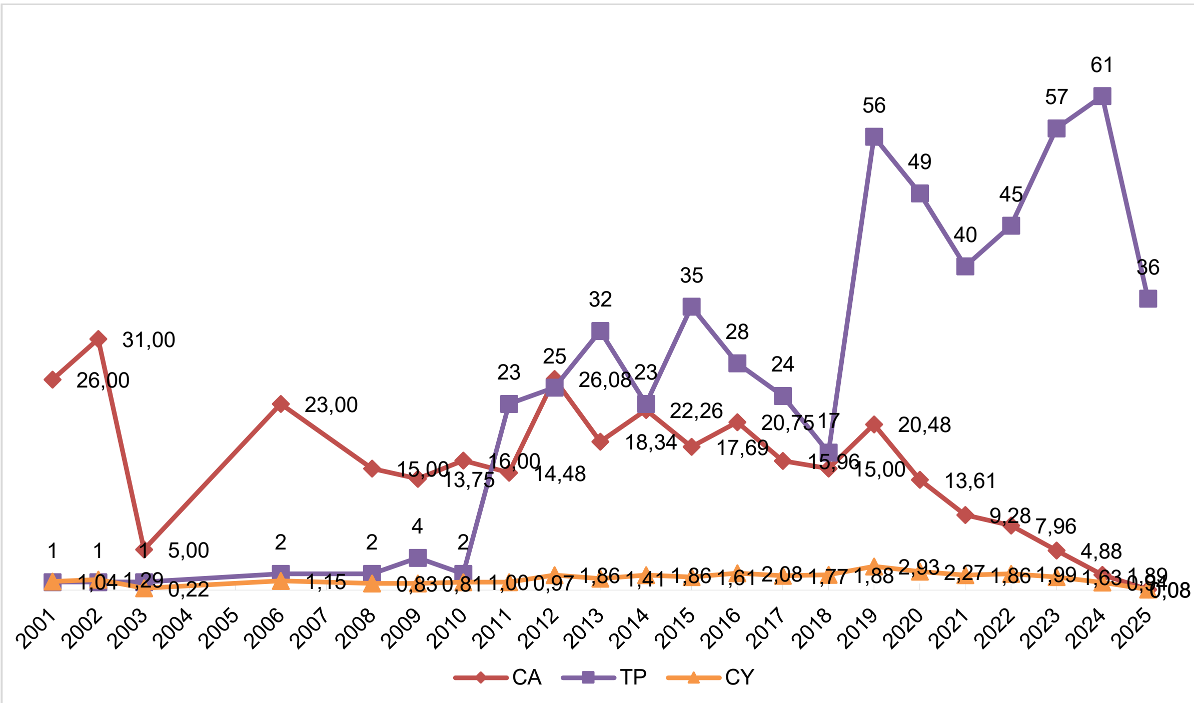
Description	Results
Main Information About Data	
Timespan	2001:2025
Sources	50
Documents	564
Annual Growth Rate %	16.1
Document Average Age	6.18
Average citations per doc	12.56
Document Contents	
Keywords Plus (ID)	1022
Author's Keywords (DE)	854
AUTHORS	
Authors	2045
Authors of single-authored docs	64
Authors Collaboration	
Single-authored docs	67
Co-Authors per Doc	4.23
International co-authorships %	12.06
Document Types	
article	514
article; early access	26
article; proceedings paper	2
proceedings paper	22

Source: Authors' calculation using R

3.1.1. *Trends in Publications Per Year*

Figure 2 illustrates the publication trends on the SDGs within chemistry education, highlighting total publications (TP), total citations per year (CY), and average citations per article (CA) from 2001 to 2025. Overall, there has been a substantial increase in TP, particularly after 2011, marking a growing scholarly interest in this topic. The peak occurred in 2024, with 61 articles published. The sharp rise in publications between 2011 and 2012 directly corresponds with global discussions that culminated in the Rio+20 conference in 2012, where the concept of the SDGs was formally introduced (UNDP, n.d.). This trend aligns with the official adoption of the 2030 Agenda in 2015 and UNESCO's launch of the ESD for 2030 framework in 2019/2020 (Guo et al., 2024).

Figure 2
Trends of TP, CA, and CY.



Note: TP = Total publication, CA = Average citation per article, CY = Total citation per year. Source: Authors' calculation.

There is increasing recognition that chemistry education plays a critical role in advancing sustainable development, with science teachers including chemistry educators expected to guide learners toward building a commitment to sustainability (Quiroz-Martinez, 2024). The importance of teaching green chemistry to cultivate a new generation of scientists who are both responsible and highly motivated to implement sustainable development has also been underscored (Wang & Surif, 2024). This field is thus viewed as a vital framework for addressing global sustainability challenges and advancing the UN SDGs (Ogodo & Abosede, 2025). It implies a growing demand for pedagogical research and curriculum development within this domain. These patterns collectively indicate a strong causal relationship whereby global policy initiatives and frameworks directly stimulate academic research outputs in related areas.

The CA and CY values do not exhibit a significant upward trend, which can be attributed to several factors. First, there is an inherent citation lag; newly published articles (particularly from 2023–2025) have not been available long enough to accumulate citations. As noted by Yang et al. (2024), articles are less likely to be cited if they fail to receive citations within 24 months of publication. Second, variability in article quality results in many publications having low or even zero citations, thereby reducing average values. Third, studies with a predominantly local or regional focus tend to be less integrated into the global discourse, which restricts their citation reach. Fourth, a lack of convergence across topics has limited the formation of robust citation networks. Prior research indicates that multidisciplinary convergence can foster dense, interconnected citation structures, underscoring the importance of topic interlinkages for citation growth (Akerlof et al., 2022). Finally, the scarcity of review articles or landmark papers in this area further contributes to the stagnation observed in both CA and CY growth.

Table 3.

Milestones in the Development of SDGs and ESD and Their Potential Impact on Publications

Year	Event	Description	Observed Impact on TP
2011	Initial Growth in SDG Discussions	The early period of global discussions that led to the SDG concept.	A notable rise in TP from 10 (2010) to 23 (2011), marking initial academic interest.
2012	UN Conference on Sustainable Development (Rio+20)	The SDGs were "born" at Rio+20, signaling a shift from the MDGs to a more comprehensive sustainable development agenda.	TP continued to rise to 25, reflecting an early response by the academic community to this global policy shift.
2013	First Meeting of the Open Working Group (OWG)	The OWG began designing the post-2015 agenda.	TP increased to 32, indicating sustained research interest alongside the evolving SDG framework.
2014	OWG Final Draft with 17 Proposed Goals	The OWG released its final draft of the SDGs.	TP reached 35, demonstrating strong anticipation of the formal SDG adoption.
2015	Adoption of the 2030 Agenda and SDGs by the UN	Formal adoption of the 17 universal SDGs.	TP slightly decreased to 28 but remained well above pre-2011 levels, suggesting consolidation following formal adoption.
2019	Adoption of UNESCO's ESD for 2030 Framework	A new global framework emphasizing ESD as crucial for achieving all SDGs.	TP began to accelerate markedly (from 49 in 2019, leading toward a peak).
2020	Publication of UNESCO's ESD for 2030 Roadmap	A guide for implementing the ESD for 2030 framework.	TP experienced a slight decline to 40, yet remained within a high-growth trend.

2021	UNESCO World Conference on ESD	The conference provided momentum to strengthen ESD in education policies and practice.	TP rose again to 45.
2022	Launch of the Global Network on ESD for 2030 (ESD-Net 2030)	A network established to accelerate progress through knowledge sharing, advocacy, and collaboration.	TP reached 57, nearing its peak, indicating the impact of institutional support and networking.
2023	Publication Peak	TP peaked at 61.	Highlighting the apex of research responses to increasingly mature SDG and ESD frameworks.

3.1.2. *Publications by Sources, Authors, Countries, Affiliations, and Keywords*

Table 3 highlights the top 10 journals and authors based on publication quantity and citations. The results also present the H-index, G-index, and M-index of these prolific sources and authors. The H-index is an individual-level metric that captures both the productivity and impact of a researcher by accounting for their number of citations (Hirsch, 2005). The G-index places greater weight on highly cited publications, indicating the highest number g such that the top g publications collectively have at least g^2 citations (Egghe, 2006). Meanwhile, the M-index reflects the average citation count per publication within the h-core—the set of papers that constitute a scholar's H-index (Bornmann et al., 2008). Together, these three indices (H, G, and M) provide a comprehensive assessment of the productivity and impact of the journals and authors listed in Table 3.

The analysis revealed that the top 10 journals accounted for 82.8% of the total publications in this study. The *Journal of Chemical Education* ranked first with the highest number of publications, totaling 467 articles and accumulating 6,376 citations. Its influence is further demonstrated by achieving the highest H-index (36) and G-index (46) on this topic. Other prominent journals include *Chemistry Education Research and Practice*, with 12 articles and 2,140 citations, as well as an H-index of 7 and a G-index of 11. The lower panel of Table 3 presents the top 10 authors based on publication count. The most prolific contributor was Dicks AP, who authored nine articles garnering 173 citations and recorded an H-index of 8 and a G-index of 9, making him the most impactful author in this dataset. He was followed by Hurst GA, who published 11 articles with a total of 203 citations, achieving an H-index of 8 and a G-index of 11. Together, these two authors demonstrated substantial influence within the literature on this subject.

Table 3.
Top 10 Journals and Authors with Impact

	Articles	H-Index	G-Index	M-Index	TC
Journal of Chemical Education	467	36	46	1.5	6376
Chemistry Education Research And Practice	12	7	11	0.5	140

Green Chemistry Letters and Reviews	5	4	5	0.444	50
Sustainability	7	4	7	0.364	57
Quimica Nova	6	3	4	0.176	23
Sustainable Chemistry And Pharmacy	5	3	5	0.5	35
Acs Sustainable Chemistry & Engineering	2	2	2	0.167	73
Green Chemistry	2	2	2	0.087	12
International Journal Of Sustainability In Higher Education	3	2	3	0.286	23
Science & Education	2	2	2	0.154	91
Authors					
Dicks AP	9	8	9	0.571	173
Hurst GA	11	8	11	0.889	203
Wissinger JE	10	8	10	0.533	225
Wentzel MT	9	7	9	0.583	149
Hudson R	7	6	7	0.545	115
Mahaffy PG	8	6	8	0.462	216
Vosburg DA	7	6	7	0.4	93
Eilks I	9	5	9	0.455	183
Ribeiro Mgtc	7	5	7	0.333	140
Abraham L	5	4	5	0.667	28

*Note: Sources and rank of authors are arranged as per the number of publications. Source: Authors' calculation using R.

3.1.3. Most Productive Countries and Affiliations

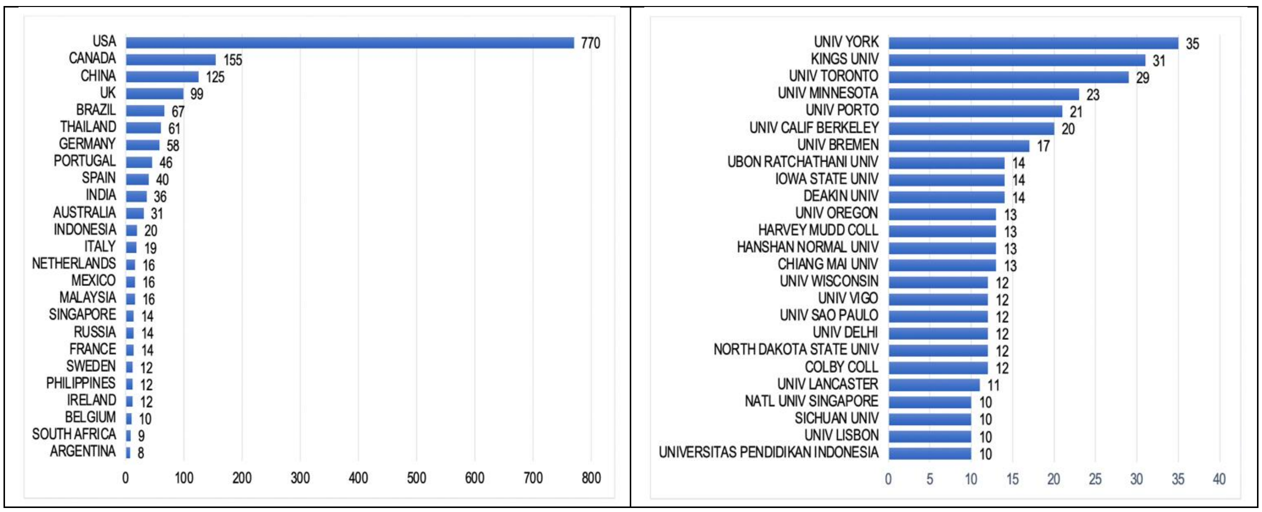
The contributions of leading authors such as Dicks A.P. (University of Toronto, Canada), Hurst G.A. (University of York, United Kingdom), and Wissinger J.E. (University of Minnesota, United States) have significantly enhanced the productivity and visibility of their respective institutional affiliations. These three universities are among the top institutions with high publication and citation counts in the field of chemistry education integrated with the SDGs. The active engagement of these researchers not only strengthens their institutions' standings on the list of most prolific affiliations but also positions their home countries as major contributors to global publications. This relationship between individual productivity and institutional affiliation underscores the strategic role of universities in supporting sustainable research initiatives. Consequently, the reputation of academic institutions is closely tied to the contributions of key scholars within their disciplines.

The five leading countries in publishing articles on this topic are the United States (770 articles), Canada (155 articles), China (125 articles), the United Kingdom (99 articles), and Brazil (67 articles). These nations have made substantial contributions to advancing the discourse on chemistry education integrated with the SDGs. Their high level of involvement in scientific output reflects both a significant interest in this area and a strong commitment to embedding sustainability issues within science curricula and teaching practices.

Figure 3 also presents the top 25 countries by publication count along with the 25 most prolific institutional affiliations. The h, g, and m indices can be used to identify the most productive countries and institutions (Donthu et al., 2022). This study thus serves as a valuable reference point for exploring research policies and scientific incentive structures implemented by these countries and their affiliated institutions. However, given that this study relies on bibliometric data and does not specify the software used, future research could optimize performance analyses by consistently employing a single primary database as the basis for such evaluations.

Figure 3

Top 25 Countries' Publications and Authors' Affiliations.



Source: Authors' calculation in R

3.1.4. Keyword Trends in SDG-Oriented Chemistry Education

The bibliometric databases used in this study generated two types of keywords: Authors' Keywords and Keyword Plus. Authors' Keywords are terms directly selected by the authors to represent the content and topical relevance of their articles (Romo-Fernández et al., 2013). In contrast, Keyword Plus is automatically generated by the indexing system through specific algorithms that identify frequently occurring words in the titles of an article's cited references (Bhatnagar & Sharma, 2022). As a result, Keyword Plus may include terms not explicitly provided by the authors. In this study, greater emphasis was placed on Authors' Keywords, as they are considered to more accurately capture the substance and focus of the articles compared to Keyword Plus (Zhang et al., 2016).

Figure 4 presents a word cloud illustrating the most frequently used keywords in publications on this topic. The size of each term in the visualization indicates its frequency within the literature. "Green chemistry" clearly dominates at the center of the graphic, reflecting the highest occurrence. Other common keywords include "systems thinking," "chemistry education," "sustainable development," "chemistry laboratory," and "organic chemistry."

Furthermore, Figure 5 depicts the temporal growth of these keywords. Notably, the term "green chemistry" demonstrates the most substantial increase in use over recent years, highlighting a growing research focus in this area.

Figure 4
Word Cloud Publication (Source: Authors' calculation in R)

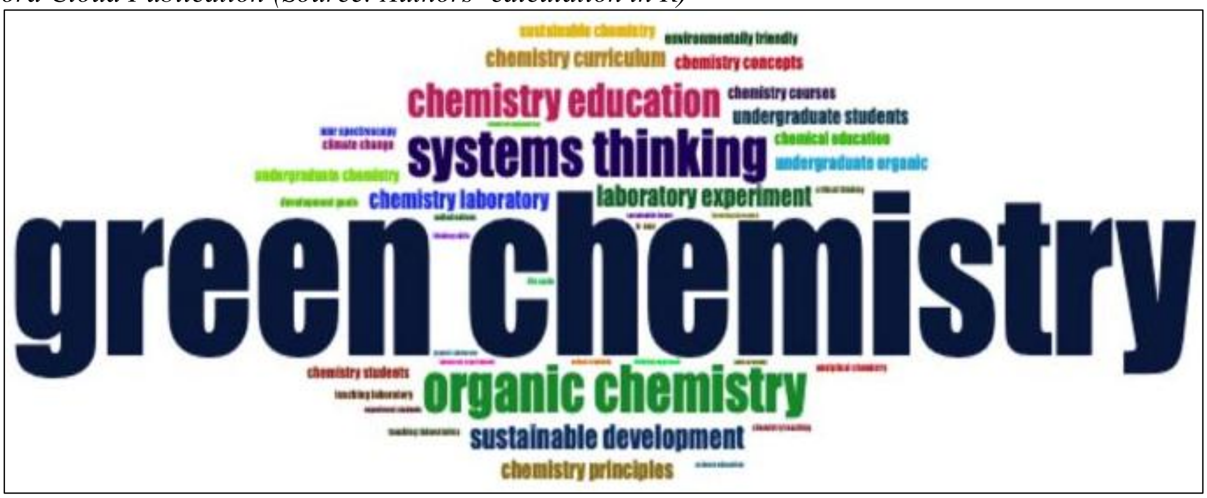
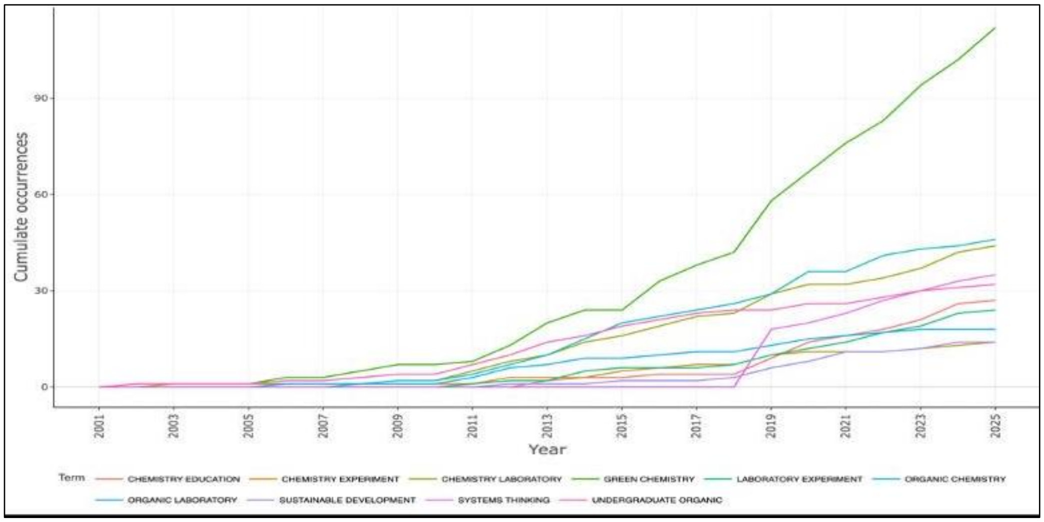


Figure 5
Word Growth of Research. (Source: Authors' calculation in R)



3.1.5. *Bibliographic coupling of authors and co-occurrence of keywords*

Bibliographic coupling describes the degree of similarity between documents based on the number of shared references they cite. The more references two documents have in common, the stronger their linkage. This type of analysis reveals substantive similarities across documents in terms of content, sources, authors, institutions, or countries of origin (Sahu, 2021). Unlike co-citation analysis, which relies on documents being cited together by subsequent works, bibliographic coupling was employed in this study due to limitations inherent in the merged dataset, which only allowed identification of two publications cited together within a single article. Using VOSviewer, analyses were conducted to map the connections among authors and keywords. The results showed the formation of clusters reflecting thematic affinities among components within the examined literature network.

Figure 6 illustrates the bibliographic coupling among authors in this body of research. Applying a threshold of at least two documents and one citation per author, the analysis identified 17 interconnected authors forming a large collaborative group. The visualization highlights four distinct clusters represented by different colors. Mahaffy, Holme, and Matlin are tightly linked within one cluster, indicating strong collaboration on specific topics. Wissinger and Wentzel appear in the blue cluster, directly connected to Kubo and Schneiderman, suggesting similar research foci. Hurst, along with Clark and Matharu, forms the yellow cluster, while Hudson is linked to Katz and Bishop in the green cluster. These patterns underscore a supportive research network in the field of sustainable chemistry education.

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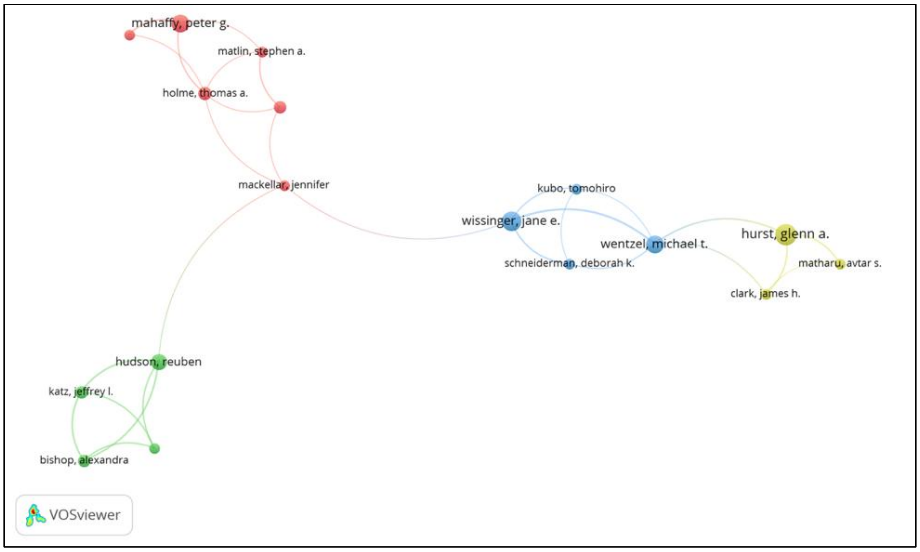
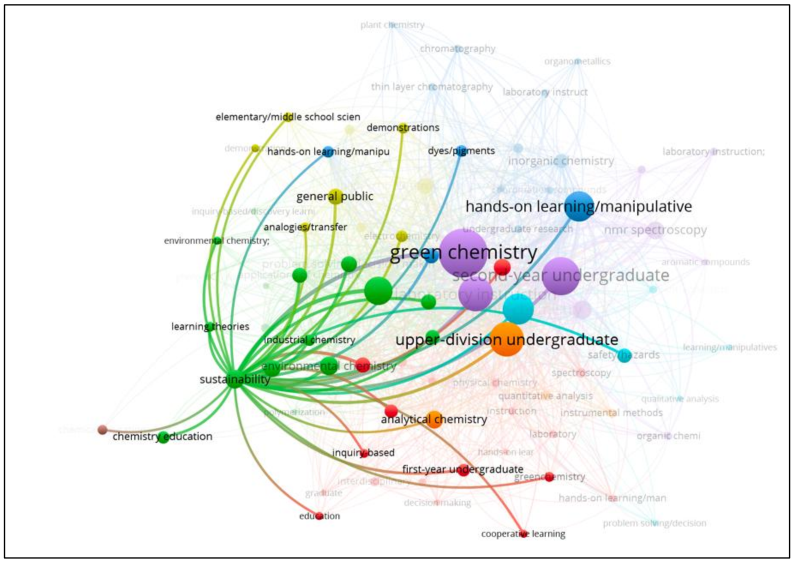
Figure 6
Bibliographic Coupling of Authors (Source: Authors' calculation in VOSviewer)



Meanwhile, Figure 7 presents a co-occurrence map of keywords found in publications on chemistry education integrated with sustainability issues. Keywords such as "green chemistry," "sustainability," and "upper-division undergraduate" emerge as central nodes with extensive connections, signaling their pivotal role within the literature network. The green cluster centers around "sustainability," closely tied to "environmental chemistry" and "learning theories," reflecting an emphasis on environmentally conscious education. The purple and blue clusters highlight practice-oriented learning approaches, such as "hands-on learning/manipulative," particularly at the undergraduate level. In contrast, the red cluster concentrates on introductory learning themes, such as "first-year undergraduate" and "inquiry-based" approaches. These interconnections demonstrate a robust integration between pedagogical strategies and sustainability topics in the advancement of SDGs-oriented chemistry education.

Figure 7
Co-occurrence of Keywords (Source: Authors' calculation in VOSviewer)



As the final component of the bibliometric analysis, a Sankey diagram (Figure 8) was employed to visualize the connections among the top 14 countries (AU_CO), 19 primary keywords (DE), and the four most productive journals (SO) in the field of chemistry education integrated with the Sustainable Development Goals (SDGs). This diagram illustrates the flow of academic literature across three critical dimensions: journals as publication sources, keywords as thematic representations, and countries as the institutional origins of authors. The visualization reveals that the *Journal of Chemical Education* stands out as the dominant journal, consistently contributing to key topics such as green chemistry, laboratory instruction, and upper-division undergraduate education. Thematically, "green chemistry" emerges as the most prominent keyword, most frequently associated with publications from the United States, followed by Canada, China, and the United Kingdom. Other countries, including Brazil, Indonesia, and Germany, have also increasingly engaged in advancing research on sustainability-oriented chemistry education.

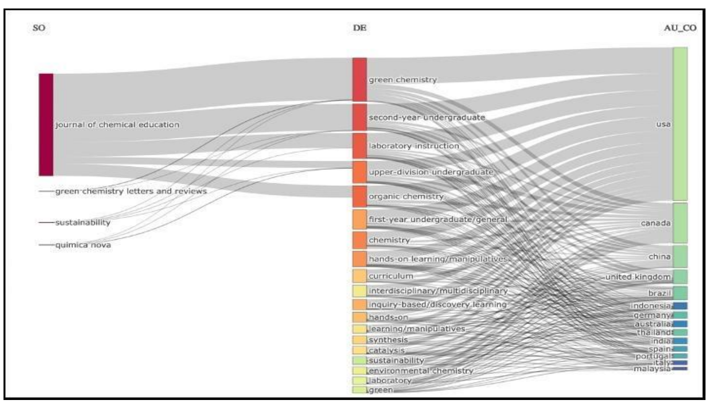
Overall, the bibliometric analysis in this study successfully maps the evolution of the global literature on chemistry education aligned with the SDGs. Since the early 2000s, publications with this focus have shown a marked upward trend. This study identifies the most productive countries in this field—namely the United States, Canada, China, and the United Kingdom—which have significantly shaped the discourse on sustainable chemistry education at the international level. Furthermore, reputable journals such as the *Journal of Chemical Education* and the *Journal of Cleaner Production* have served as primary publication outlets, supported by active authors from leading academic institutions.

Through the application of keyword co-occurrence and bibliographic coupling analyses, this research highlights several central keywords—such as green chemistry, sustainability, hands-on learning, and inquiry-based learning—that are closely linked within networks of authors, journals, and countries. These findings also demonstrate thematic evolution in the literature, with a principal focus on the implementation of green chemistry and active learning strategies in higher education, particularly at the undergraduate level. The Sankey diagram reinforces this analysis by illustrating the interconnections among the main elements driving global literature production. Topics such as sustainability and laboratory instruction serve as key nodes in research networks that span countries and journals.

This bibliometric evidence not only provides a quantitative overview of the direction and focus of publications in SDGs-based chemistry education but also establishes a foundation for deeper exploration through a systematic approach. Accordingly, the next section presents the results of the Systematic Literature Review (SLR), offering more nuanced insights into the conceptual and methodological aspects, key determinants, and impacts of implementing sustainable chemistry education across diverse educational contexts worldwide.

Figure 8

Three-field Analysis of Research (Source: Authors' calculation in R)



3.2. Systematic Literature Review (SLR)

This section presents a content analysis of relevant literature to explore both the conceptual and practical dimensions of integrating the Sustainable Development Goals (SDGs) into chemistry education. The review focuses on mapping the objectives, methods, strategies, study outcomes, and their connections to Education for Sustainable Development (ESD).

In an effort to gain a comprehensive understanding of research developments in the field of chemistry education aligned with sustainability principles, an in-depth examination of key literature was undertaken. Accordingly, this study systematically reviewed 17 selected articles, comprising the ten most highly cited publications and seven of the most recent studies. These articles were chosen based on their topical relevance, theoretical and methodological contributions, and direct linkage to sustainable education.

The selection of highly cited articles was grounded in the bibliometric principle that citation counts serve as a primary indicator of a work's scientific impact within the academic community (Bornmann & Daniel, 2008). Such articles reflect significant theoretical and empirical contributions and often serve as foundational references in advancing the field of sustainable chemistry education. Moreover, high citation counts indicate that these works have been widely recognized, utilized, and further developed by other researchers (Garfield, 2006), underscoring their importance in understanding dominant conceptual frameworks in the literature.

Conversely, articles published in recent years capture current research trends, innovative approaches, and responses to evolving global dynamics, including educational policy shifts, technological advancements, and the integration of SDGs (Donthu et al., 2021). Including these recent studies enables this review to identify forward-looking trajectories and potential updates to theories and practices in sustainability-oriented chemistry education. By combining the most frequently cited works with the latest publications, this study achieves a balanced perspective—integrating influential foundational studies with contemporary insights that reflect present and future needs. This selection strategy aligns with systematic literature review and mapping review approaches that advocate blending influential knowledge with emerging insights (Snyder, 2019).

The primary aim of this analysis is to identify the theoretical approaches, instructional strategies, and current research trends that support the achievement of the SDGs within the context of chemistry education. This approach facilitates a sharper mapping of global research dynamics and highlights gaps that warrant further exploration in advancing sustainable chemistry education practices.

Table 4.
Overview of Selected Articles on Sustainable Chemistry Education: Objectives, Methods, Strategies, and Links to ESD

Authors & Year	Objective	Methodology	Teaching Strategy	Key Findings	Link to ESD
(Sharma et al., 2012)	To teach green chemistry principles via gold nanoparticle synthesis using tea as a natural reducing agent.	Synthesized AuNPs using tea extract (green synthesis).	Laboratory-based, hands-on experiential learning.	Successfully produced AuNPs through an environmentally friendly process; color change easily observed by students.	Promoted green chemistry practices in educational labs, fostering environmental awareness and scientific attitudes through contextual, sustainable experiments.
(Mahaffy et al., 2017)	To enhance understanding of basic chemistry concepts via climate change contexts using visual and systemic approaches.	Integrated climate literacy with basic chemistry via interactive modules.	Context-based learning & digital case studies.	Improved understanding of chemistry concepts and climate issues through progressive assessments.	Advanced climate literacy and systems thinking skills in early chemistry education.
(Mahaffy et al., 2019)	To integrate molecular-level sustainability concepts	Embedded molecular sustainability concepts using systems thinking.	Systems-based learning and cross-concept integration.	Improved student understanding of links between chemistry	Fostered cross-scale understanding from molecules to global

	into basic chemistry via systems thinking.			concepts and sustainability.	systems in introductory chemistry.
(Aubrecht et al., 2019)	To develop students' systems thinking, lab safety, and sustainability skills by integrating green chemistry into the curriculum.	Integrated green chemistry via systems, safety, and sustainability approach.	Project-based learning with lab practice integration.	Enhanced systems thinking, safety awareness, and concern for sustainability.	Encouraged 21st-century skill development via chemistry education tied to global issues and ethical lab practices.
(Mercer et al., 2012)	To train students in evaluating environmentally friendly syntheses using quantitative green metrics.	Evaluated synthesis routes based on quantitative green metrics.	Comparative case studies and data-driven analysis.	Students assessed efficiency and sustainability of various chemical syntheses.	Supported data-based decision-making in green chemistry and awareness of environmental synthesis impacts.
(Sjostrom et al., 2016)	To promote ecologically reflective science education via green chemistry.	Critical reflective literature review.	Contextualized chemistry through social, ethical, and environmental issues.	Green chemistry fostered critical awareness and students' ecological responsibility.	Strengthened value education, systems thinking, and social responsibility in science learning for sustainability.
(Haack & Hutchison, 2016)	To review 25 years of green chemistry education and outline a roadmap for the next 25 years.	In-depth literature review and policy analysis.	Infused green chemistry into undergraduate curricula, developed teaching materials.	Significant advances in lab safety, curriculum modernization, and global educator networks.	Integrated sustainability and safety principles into science education via sustained systemic approaches.
(Eilks, 2015)	To analyze justifications, models, practices, and perspectives of integrating ESD into science education.	Theory-based review and case studies from University of Bremen.	Socioscientific issue approaches and ESD integration in science; cross-topic collaboration.	Integrated science–ESD models effectively built student competencies and ecological awareness.	Reinforced science education's critical role in fostering scientific, ethical, and systemic literacy aligned with ESD.
(Kennedy, 2016)	To design and implement a dynamic, sustainable undergraduate green chemistry course.	Curriculum designed on green chemistry principles and continuous reflection.	Combined interactive lectures, case studies, collaborative projects, and reflective discussions.	Students improved understanding of green chemistry principles, systems thinking, and social responsibility.	Promoted sustainability principles through critical, systemic, contextual chemistry learning; supported ESD goals in higher education.
(Graham et al., 2014)	To develop student-designed organic lab projects focused on green chemistry applications.	Multi-week projects: students redesigned synthetic routes to be greener, replicated and modified under faculty guidance.	Student-designed projects and critical reflection via comparative data reports.	Students independently designed and compared green syntheses, gaining insight into scientific inquiry.	Encouraged autonomy, sustainability-based decision-making, and practical science skills in line with ESD principles in the lab.
(Widyantoro et al., 2025)	To prepare pre-university chemistry teachers to integrate sustainability and green chemistry into teaching.	Workshops and field visits (e.g., Semakau landfill), followed by classroom CBL implementation.	Experiential case-based learning (CBL), feedback, and collaborative strategy development.	Modules effectively improved teachers' preparedness and application of sustainability principles.	Supported transformation of chemistry education via real-world contextual learning, professional engineering, and stakeholder collaboration aligned with ESD.
(Alhazmi & Almashhour, 2025)	To examine market-based policy influences on integrating green chemistry into Saudi higher education.	Grounded theory with in-depth interviews (22 participants).	Critical reflection and policy dialogues among academics, practitioners, and policymakers.	Market-driven policies prioritized short-term profit, hindering green chemistry adoption; curriculum reform and policy incentives offered opportunities.	Advocated educational policy transformations to support sustainable science education and cross-stakeholder collaboration in line with ESD.
(Vaz et al., 2025)	To analyze the impact of PBL on students'	Case-based PBL project (8 students), covering two industrial cases and	Group discussions, case-based PBL; assessments via	PBL improved students' grasp of green chemistry; some concepts (atom	Fostered critical thinking, real-world GC applications, and

	understanding of green chemistry principles.	acetanilide synthesis, with pre/post analysis.	quizzes, discussions, written reflections.	economy, catalysis) remained challenging; students compared green methods and analyzed trade-offs.	sustainability awareness in chemistry learning aligned with ESD and 21st-century competencies.
(Lai & Li, 2025)	To provide a green pyrrole synthesis method while introducing green chemistry to introductory organic students.	Synthesized pyrrole from 2,5-hexanedione & 4-tert-butylaniline without solvent/catalyst; UV-Vis & green metric analysis.	Hands-on lab (experiential learning) plus concept discussions & green metric calculations.	Efficient synthesis with high yield & optimal atom economy; students improved experimental skills & GC understanding.	Integrated green chemistry into introductory organic labs, cultivating environmental awareness & sustainable lab skills aligned with ESD.
(A. Z. Chen et al., 2025)	To introduce first-year chemistry students to systems thinking via green chemistry concepts.	Trimester-long intervention; mixed-method (motivation survey, interviews, student task thematic analysis).	Authentic learning via real-world problem-based green chemistry activities.	Students showed high motivation & systems thinking skills in sustainability contexts; better understood chemistry's role in solving global challenges.	Advanced sustainability literacy & critical competencies via green curricula aligned with global environmental challenges & ESD.
(Reynders et al., 2025)	To build first-year students' systemic skills through group activities on detergents.	Contextual intervention in large general chemistry course using mixed methods (SOCME concept maps & reflections).	Authentic group tasks: molecular & systemic detergent analysis; SOCME maps.	Students identified system components, boundaries, causality; motivation & sustainability awareness increased.	Promoted systems thinking, scientific literacy, & environmental sensitivity through real-world contexts & systems-based learning aligned with ESD.
(Breen et al., 2025)	To provide students with a co-curricular research experience analyzing biochar as a green material.	Experimental biochar analysis (Boehm titration, FTIR, UV–Vis).	Collaborative student research outside core curriculum.	Students developed analytical chemistry skills, biochar structural understanding, & sustainability relevance.	Integrated sustainability in green material development & enhanced students' scientific competencies.

The SLR of 17 articles comprising the 10 most highly cited publications and 7 of the most recent studies illustrates the directions and evolving landscape of research on chemistry education integrated with the SDGs. Overall, the core emphases identified include strengthening the principles of green chemistry, fostering systems thinking skills, and utilizing global issues such as climate change as contextual frameworks for teaching chemistry.

Various instructional approaches were employed across these studies, including experiential learning, authentic learning, problem-based learning (PBL), student-designed projects, and case-based learning (CBL). These strategies have consistently proven effective in enhancing students' conceptual understanding, environmental awareness, and sustainability literacy.

From a methodological perspective, the articles demonstrate diverse analytical techniques, ranging from experimental quantitative studies and critical reflections to qualitative analyses through interviews and observations, as well as mixed-methods approaches. The learning strategies developed actively engaged students through environmentally friendly laboratory practices, integrated projects, and reflective discussions. The main outcomes indicate notable improvements in students' mastery of chemistry concepts, systems thinking capabilities, and awareness of the social and environmental implications of chemical practices. Several studies further highlighted the importance of transdisciplinarity and collaboration among academics, practitioners, and policymakers to create learning environments that advance sustainability.

Collectively, these findings reveal that the integration of SDG principles into chemistry education is increasingly robust, achieved through innovative approaches such as contextual learning, green chemistry, systems thinking, and experiential learning. Embedding the SDGs within the chemistry curriculum not only strengthens students' cognitive dimensions but also significantly nurtures affective and social aspects, such as ethical responsibility, environmental empathy, and sustainability-informed decision-making.

The studies analyzed consistently underscore the importance of developing 21st-century skills, sustainability literacy, and critical awareness of global issues such as climate change, pollution, and overconsumption. In this context, chemistry education emerges as a transformative platform that goes beyond imparting scientific concepts, preparing students to become global citizens who are conscious of ecological challenges and equipped to contribute to sustainable development.

Ultimately, the key to the effectiveness of this integration lies in students' active participation in the learning process and the role of educators as facilitators who create reflective, collaborative, and meaningful learning spaces. These findings reinforce the argument that integrating the SDGs particularly SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production) into chemistry education is not merely conceptual but has evolved into an operational framework that is relevant, applicable, and significantly impactful in strengthening scientific competencies and sustainability values in higher education.

3.3. Research Gap and Directions for Future Studies

The combined bibliometric and systematic literature analysis conducted in this study reveals that the integration of sustainability principles and the SDGs into tertiary chemistry education has advanced significantly over the past two decades. This is reflected in the prominence of topics such as green chemistry, systems thinking, and experiential learning, alongside increasingly expansive networks of author and country collaborations. However, these findings also highlight several critical research gaps that warrant attention for shaping future research agendas.

First, existing studies are predominantly concentrated in developed countries, with most research emerging from the United States, Canada, the United Kingdom, and China. This indicates a lack of empirical contributions from developing contexts, including Southeast Asia. Yet integrating the SDGs into chemistry education demands context-sensitive adaptations that consider local challenges such as limited resources, diverse educational policies, and varying levels of environmental awareness. Second, many studies tend to focus on strengthening a single pedagogical approach such as green chemistry or problem-based learning without constructing comprehensive pedagogical frameworks that integrate multiple strategic approaches. Literature suggests, however, that fostering sustainability literacy requires a synthesis of conceptual mastery in chemistry, multi-scale systems thinking, and social skills through collaborative, real-world projects. Third, the reviewed studies show that evaluations of SDG integration in chemistry education primarily emphasize cognitive outcomes (understanding of chemical concepts and green chemistry principles). In contrast, affective and social dimensions such as ethical commitment, reflective attitudes toward environmental issues, and sustainable decision-making remain underexplored and rarely assessed using robust, validated instruments. Fourth, there is a near absence of longitudinal studies that trace the evolution of students' sustainability literacy over time, including how these competencies influence their professional practices post-graduation. Yet sustainability, as a competence, inherently requires processual and sustained reinforcement. Fifth, from a methodological standpoint, this review finds that there is still a notable lack of quasi-experimental or experimental controlled studies capable of providing strong causal evidence for the effectiveness of SDG-oriented learning approaches in chemistry education. Most existing research remains descriptive, case-based, or employs pre-experimental designs with relatively low internal validity.

These gaps present substantial opportunities for further research, not only to enrich the scientific discourse but also to provide a stronger empirical foundation for policymaking and curriculum development in higher chemistry education. Based on these identified gaps, a central research problem can be articulated as follows: While global literature shows a significant rise in integrating SDGs into chemistry education, comprehensive studies that design, implement, and evaluate integrated pedagogical models combining green chemistry principles, systems thinking, problem-based learning, and project-based learning in higher education, especially within developing countries—remain extremely limited. Moreover, few studies have investigated, either longitudinally or experimentally, the impact of such approaches on students' sustainability literacy across cognitive, affective, and social dimensions.
In light of this, future research is needed to:

1. Develop and validate contextually relevant, integrative SDGs-based chemistry learning models.
2. Examine their effectiveness through quasi-experimental or experimental designs in enhancing students' sustainability literacy.
3. Explore the longitudinal dynamics of competency transformation, including the extent to which these outcomes are retained and applied in professional practice post-graduation.
4. Broaden the research context to encompass developing countries, thereby offering empirically grounded insights that meaningfully contribute to the globalization of sustainable education.

4. Conclusion

This study presents a comprehensive bibliometric and systematic literature review of global research on the integration of sustainability and the SDGs into higher chemistry education. The findings indicate a substantial growth in scholarly attention over the past two decades, particularly following global initiatives such as the adoption of the 2030 Agenda for Sustainable Development and UNESCO's Education for Sustainable Development (ESD) framework. Bibliometric analyses reveal that this research landscape is predominantly shaped by contributions from countries such as the United States, Canada, China, and the United Kingdom, with leading journals like the *Journal of Chemical Education* serving as primary publication outlets. Thematic mapping underscores the centrality of topics such as green chemistry, systems thinking, and experiential learning in advancing sustainability-oriented chemistry education.

The systematic review further highlights that diverse pedagogical approaches—including problem-based learning, authentic learning, case-based learning, and student-designed projects—have been effectively implemented to enhance students' conceptual understanding, systems thinking skills, and environmental awareness. These approaches not only reinforce cognitive competencies but also cultivate ethical responsibility, critical reflection, and decision-making aligned with sustainability principles.

Overall, this review affirms the strategic role of chemistry education in equipping future graduates with the competencies needed to address complex sustainability challenges. By systematically mapping existing research and identifying key theoretical, contextual, and methodological gaps, this study provides a robust foundation for future inquiries. It also encourages deeper interdisciplinary collaboration, expanded empirical studies across diverse sociocultural contexts, and innovative curriculum designs that fully embed the SDGs into chemistry education. In light of the pressing global sustainability agenda, these findings carry significant implications for educators, policymakers, and researchers striving to transform chemistry education into a catalyst for achieving the SDGs. Moving forward, sustained scholarly engagement and strategic educational reforms are essential to develop scientifically literate, ethically grounded, and sustainability-minded graduates who can meaningfully contribute to building a resilient and just future.

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