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Green Chemistry Education at the Secondary School Level: A Bibliometric Analysis of Trends and Research Gaps

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Abstract
Green Chemistry Education (GCE) has become increasingly important in supporting sustainability-oriented chemistry learning at the secondary school level. This study aims to map research trends, identify dominant themes, and examine research gaps in GCE through a bibliometric analysis. The final dataset consisted of 43 articles retrieved from the Scopus and Web of Science databases for the period 2016–2025. Data were analyzed using VOSviewer through keyword co-occurrence and thematic mapping. The findings show a growing scholarly interest in GCE, reflecting the increasing relevance of sustainability principles in chemistry education. Keyword analysis indicates that existing studies are mainly centered on students, teachers, education systems, active learning, experimentation, and contextual learning approaches. The thematic development also shows a shift from foundational discussions of green chemistry principles toward curriculum integration, digital learning innovation, ethnochemistry, and alignment with the Sustainable Development Goals (SDGs). Despite this development, several gaps remain, particularly in long-term impact evaluation, students' behavioral change, teacher preparedness, and interdisciplinary implementation. This study contributes by providing a structured overview of the GCE research landscape in secondary education and by offering directions for educators, policymakers, and researchers to strengthen sustainable chemistry learning.

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INTRODUCTION

Global environmental challenges, including climate change, pollution, hazardous waste, and resource depletion, have increased the demand for science education that is not only conceptually rigorous but also responsive to sustainability problems. Chemistry is often associated with environmental risks because of its links to industrial production, synthetic materials, and chemical waste. However, chemistry also provides important scientific foundations for developing safer materials, reducing hazardous substances, and designing more sustainable processes. Within this context, green chemistry has emerged as a key framework for connecting chemical knowledge with sustainability-oriented problem solving (Carangue et al., 2021; Delaney et al., 2024; Lembens et al., 2022; Sunday et al., 2025; Teplá et al., 2025).

Green Chemistry Education (GCE) refers to the integration of green chemistry principles into chemistry teaching, curriculum design, laboratory activities, and contextual learning. Its relevance has grown alongside the global emphasis on Education for Sustainable Development (ESD) and the Sustainable Development Goals (SDGs), particularly SDG 4 on quality education, SDG 12 on responsible consumption and production, and other goals related to environmental protection and sustainable innovation (Hurst, 2020; Lathwesen &

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Eilks, 2024; Li & Eilks, 2021; Salsabila & Ayugea, 2025). Through GCE, chemistry learning can be positioned not merely as the transmission of disciplinary concepts but as a pedagogical space for developing scientific literacy, environmental awareness, systems thinking, and responsible decision-making.

The secondary school level is a particularly important context for GCE because students at this stage begin to form foundational scientific understanding, attitudes toward chemistry, and awareness of socio-scientific issues. Introducing green chemistry at this level can help students connect abstract chemical concepts with real-world environmental problems, laboratory safety, sustainable consumption, and technological innovation (Hoffman & Dicks, 2020; Karpudewan, 2020; Koulougliotis et al., 2024; Li & Eilks, 2021). Recent studies have shown that GCE at the secondary level has been developed through diverse approaches, including green laboratory practices, problem-based learning, project-based learning, ethnochemistry, digital learning tools, and curriculum integration (Aubrecht et al., 2019; Dewi & Listyarini, 2022; Lathwesen & Eilks, 2024; Putri et al., 2023; Wardani et al., 2023; Zidny & Eilks, 2022).

Despite this growing interest, the development of GCE at the secondary school level remains uneven. Much of the literature on green chemistry education has historically been concentrated in higher education, teacher education, or general sustainability education, while studies specifically addressing secondary school contexts are still relatively fragmented (Haack & Hutchison, 2016; Linkwitz & Eilks, 2020, 2022a; Zuin et al., 2021). Existing studies tend to focus on particular interventions, local curriculum contexts, laboratory modules, or specific pedagogical strategies. Although these studies provide valuable empirical and pedagogical insights, they do not yet offer a sufficiently systematic overview of how research on GCE at the secondary level has evolved, what themes dominate the field, and which areas remain underexplored.

Several reviews have discussed green chemistry, sustainable chemistry education, or sustainability-oriented chemistry learning more broadly (Chen et al., 2020; Salsabila & Ayugea, 2025; Sánchez Morales et al., 2024). However, many of these works are qualitative, conceptual, regionally limited, or not specifically focused on secondary school education. As a result, there remains a need for bibliometric evidence that can map the structure of research development, identify dominant and emerging themes, and clarify research gaps in GCE at the secondary school level. Such mapping is important because the field is increasingly connected to global sustainability agendas, curriculum reform, teacher preparedness, digital innovation, and interdisciplinary learning.

Responding to this gap, the present study conducts a bibliometric analysis of 43 articles on Green Chemistry Education at the secondary school level published between 2016 and 2025 and indexed in Scopus and Web of Science. By using VOSviewer to analyze publication trends, keyword co-occurrence, and thematic patterns, this study provides a structured overview of the intellectual landscape of GCE research in secondary education. The novelty of this study lies in its specific focus on the secondary school level and its attempt to connect bibliometric patterns with pedagogical and sustainability-related research gaps. Rather than merely describing publication growth, this study examines how research attention has shifted from foundational green chemistry concepts toward curriculum integration, active and experimental learning, digital innovation, ethnochemistry, and SDG-oriented education.

Based on this background, the study is guided by the following research questions:

1. How have research trends in Green Chemistry Education at the secondary school level developed from 2016 to 2025?
2. What dominant themes and keyword patterns characterize the research landscape of Green Chemistry Education at the secondary school level?
3. What research gaps and future directions can be identified to strengthen the implementation of sustainable Green Chemistry Education in secondary schools?

By addressing these questions, this study is expected to contribute to the literature in three ways. First, it provides a bibliometric mapping of GCE research at the secondary school level. Second, it clarifies the thematic concentration and underexplored areas within the field. Third, it offers evidence-informed directions for educators, policymakers, and researchers in

designing more contextual, practical, and sustainability-oriented chemistry education.

LITERATURE REVIEW

Concept and Principles of Green Chemistry in Education

Green Chemistry was introduced as an approach to designing chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Its principles emphasize waste prevention, safer chemical synthesis, energy efficiency, renewable feedstocks, and the design of less hazardous chemical products and processes (Haack & Hutchison, 2016; Sánchez Morales et al., 2024; Zuin et al., 2021). In education, these principles are not only treated as scientific content but also as a pedagogical framework for connecting chemistry learning with sustainability, safety, environmental responsibility, and socio-scientific decision-making.

Green Chemistry Education (GCE) has gradually developed from the introduction of safer laboratory practices into a broader educational agenda. Earlier studies emphasized the role of GCE in improving laboratory safety, modernizing chemistry curricula, and developing educational resources (Haack & Hutchison, 2016). More recent discussions highlight the importance of systems thinking, where students are encouraged to understand chemical concepts in relation to environmental impacts, life-cycle considerations, and sustainability challenges (Aubrecht et al., 2019). This development indicates that GCE is not merely an additional topic in chemistry education, but a way to reorient chemistry learning toward more responsible and sustainable scientific practice.

Green Chemistry Education at the Secondary School Level

The secondary school level is a crucial context for GCE because students begin to develop foundational chemical understanding, scientific literacy, and attitudes toward environmental issues. At this level, GCE can help students connect abstract chemistry concepts with real-life problems such as pollution, waste, resource use, climate change, and chemical safety (Ause, 2019; Hoffman & Dicks, 2020; Koulougliotis et al., 2024). Therefore, GCE at the secondary level has strong potential to make chemistry more contextual, meaningful, and relevant to everyday lives.

Previous studies show several dominant approaches in secondary-level GCE. Laboratory-based approaches focus on redesigning experiments to be safer, less hazardous, and more environmentally friendly. Karpudewan and Kulandaisamy (2018) found that green chemistry experiments were perceived by secondary school teachers as feasible, safe, relevant to the curriculum, and supportive of inquiry-based learning. Hoffman and Dicks (2020) further argue that greening the high school laboratory can shift students' understanding of experimental success from merely achieving high yield toward considering green chemistry metrics and sustainability criteria.

Another important approach is contextual and socio-scientific learning. Koulougliotis et al. (2021) show that context-based projects related to climate change and recycling can support students' awareness of green chemistry principles. Similarly, Koulougliotis et al. (2024) identify inquiry-based, hands-on, problem-based, context-based, and socio-scientific issue-based learning as common approaches in secondary green chemistry education. These studies suggest that GCE is more effective when students are invited to connect chemistry concepts with authentic environmental issues and social responsibility.

Recent studies also indicate the growing role of local wisdom, ethnochemistry, and culturally relevant contexts in GCE. Zidny and Eilks (2022) demonstrate that ethnoscience can be used as an entry point for learning green and sustainable chemistry through local knowledge of pesticide use. Mashami et al. (2025) also show that integrating green chemistry with Indonesian local wisdom can improve high school students' scientific literacy. These findings suggest that GCE can be strengthened by linking sustainability principles with students' cultural and local contexts.

However, the implementation of GCE still faces several challenges. Teacher readiness remains a central issue because teachers may recognize the importance of GCE but have limited knowledge, resources, or confidence to integrate it into classroom practice. Carangue et al. (2021) found that senior high school chemistry teachers perceived GCE as important, but their prior knowledge and level of integration remained limited. This indicates that successful GCE

implementation requires not only curriculum support but also teacher professional development, validated teaching materials, and practical learning models.

Although research on GCE has increased, several gaps remain. Many studies focus on specific interventions, teaching materials, laboratory activities, or local curriculum contexts. Existing reviews have discussed green chemistry education more broadly, but fewer studies have specifically mapped research trends, keyword patterns, dominant themes, and underexplored areas in GCE at the secondary school level using bibliometric analysis. Therefore, a bibliometric study is needed to provide a structured overview of how this field has developed, what topics dominate the literature, and what future research directions are needed to strengthen sustainable chemistry education in secondary schools.

METHOD

Research Design

This study employed a descriptive bibliometric approach to map the development of research on Green Chemistry Education (GCE) at the secondary school level. Bibliometric analysis was selected because it allows researchers to examine publication trends, keyword patterns, thematic structures, and research gaps within a specific field of study (Donthu et al., 2021). In this study, the bibliometric approach was used to identify how secondary-level GCE research has developed, what themes dominate the literature, and which areas remain underexplored.

Data Sources and Search Strategy

The data were retrieved from Scopus and Web of Science, two databases widely used in bibliometric studies because they provide indexed publication metadata, including titles, abstracts, keywords, author information, affiliations, publication years, and citation records. The use of these two databases was intended to improve the coverage and reliability of the dataset while maintaining the quality of indexed publications.

The search was limited to the period 2016–2025 to capture the development of GCE research over the last decade. This period was selected because it reflects recent changes in sustainability-oriented chemistry education, curriculum reform, Education for Sustainable Development (ESD), and SDG-related educational discourse.

The search strategy used combinations of keywords related to green chemistry education and secondary education. The search string was formulated as follows:

("green chemistry education" OR "sustainable chemistry education") AND ("high school" OR "secondary education" OR "secondary school" OR "K-12")

Article Selection Procedure

The article selection process consisted of identification, duplicate removal, screening, eligibility assessment, and final inclusion. At the identification stage, 480 records were identified from Scopus and Web of Science. After removing 357 duplicate records, 123 records remained for screening. These records were screened based on titles and abstracts to determine their relevance to Green Chemistry Education and secondary school education. At this stage, 60 records were excluded because they did not match the focus of the study.

The remaining 63 full-text articles were assessed for eligibility based on the inclusion and exclusion criteria. The inclusion criteria were: (1) articles or review articles published between 2016 and 2025; (2) studies related to Green Chemistry Education or sustainable chemistry education; (3) studies focusing on, or having clear relevance to, secondary school education; and (4) publications with sufficient bibliographic information for bibliometric analysis. The exclusion criteria were: (1) editorials, news articles, short reports, and non-scholarly documents; (2) studies focusing exclusively on higher education without relevance to secondary education; and (3) articles that did not provide sufficient information related to the research focus. After the eligibility assessment, 20 articles were excluded for not meeting the inclusion criteria. As a result, 43 articles were included as the final dataset for bibliometric analysis.

Data Preparation and Cleaning

The bibliographic data from the selected articles were exported from Scopus and Web of Science in compatible formats for bibliometric analysis. The data were then organized and checked to ensure consistency across records. Data cleaning was conducted by removing duplicate entries, checking incomplete bibliographic information, and standardizing relevant terms where necessary, particularly

author keywords and recurring conceptual terms. This stage was important to reduce data bias and ensure that the visualization results accurately represented the structure of the literature.

Data Analysis

The cleaned dataset was analyzed using VOSviewer. The analysis focused on keyword co-occurrence to identify dominant themes, conceptual relationships, and emerging research directions in GCE at the secondary school level. Keyword co-occurrence analysis was used because it can reveal the thematic structure of a research field by showing how frequently certain keywords appear together in the literature.

The visualization results were interpreted by considering keyword size, link strength, cluster formation, and temporal patterns. Keyword size indicated the frequency of occurrence, link strength represented the relationship between keywords, and clusters reflected thematic groupings within the literature. In addition, descriptive analysis was used to examine publication trends across the selected period. The results were then interpreted in relation to curriculum integration, pedagogical approaches, teacher readiness, contextual learning, sustainability education, and future research gaps in secondary-level Green Chemistry Education.

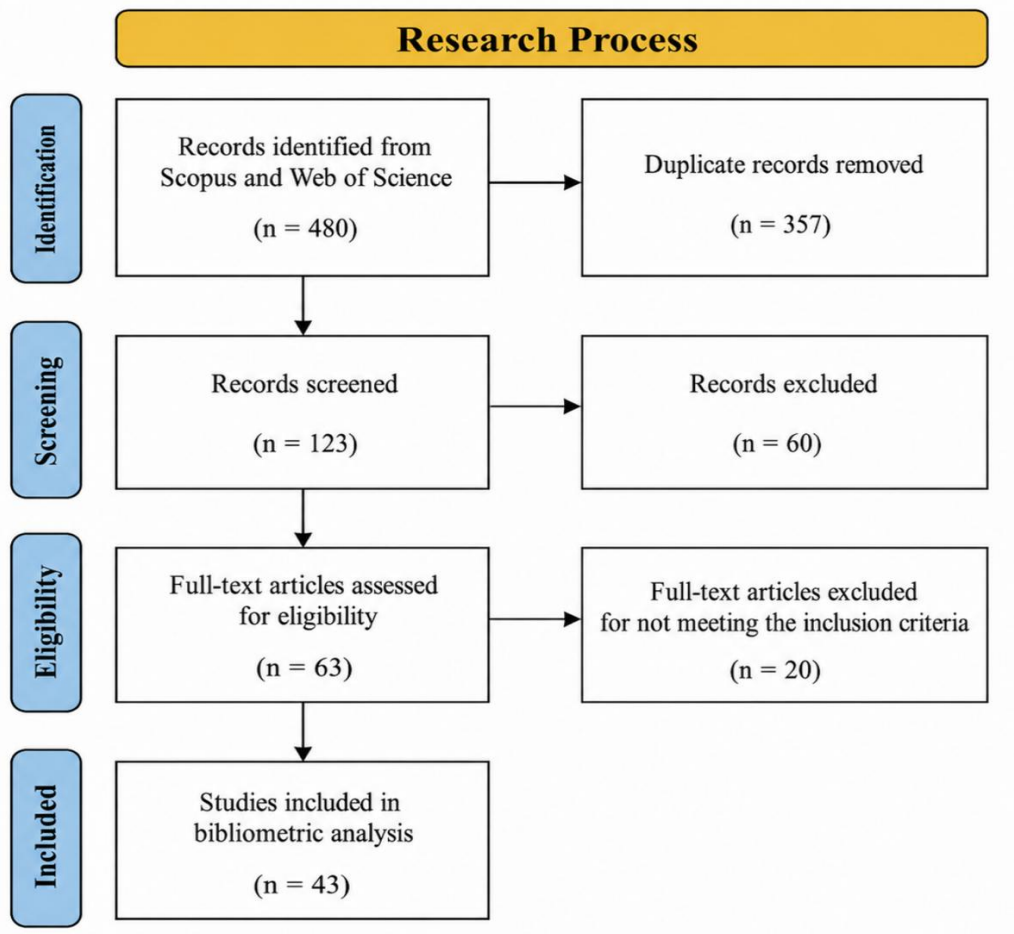


Figure 1. Flow Diagram of Article Identification, Screening, Eligibility, And Inclusion.

RESULTS AND DISCUSSION

Results

The bibliometric analysis was conducted on 43 articles related to Green Chemistry Education (GCE) at the secondary school level published between 2016 and 2025. The results are presented in two main forms: keyword co-occurrence mapping and trend analysis. Keyword co-occurrence mapping was used to identify the dominant concepts and relationships among research themes, while trend analysis was used to examine the development of GCE research across the selected period.

Figure 2 shows the keyword co-occurrence network generated using VOSviewer. The size of each node indicates the frequency of keyword occurrence, while the connecting lines represent the strength of relationships among keywords.

The visualization indicates that the keyword "student" occupies the most central position in the network. This suggests that research on GCE at the secondary school level is primarily centered on students as the main subjects of learning, particularly in relation to classroom activities, conceptual understanding, environmental awareness, and learning outcomes.

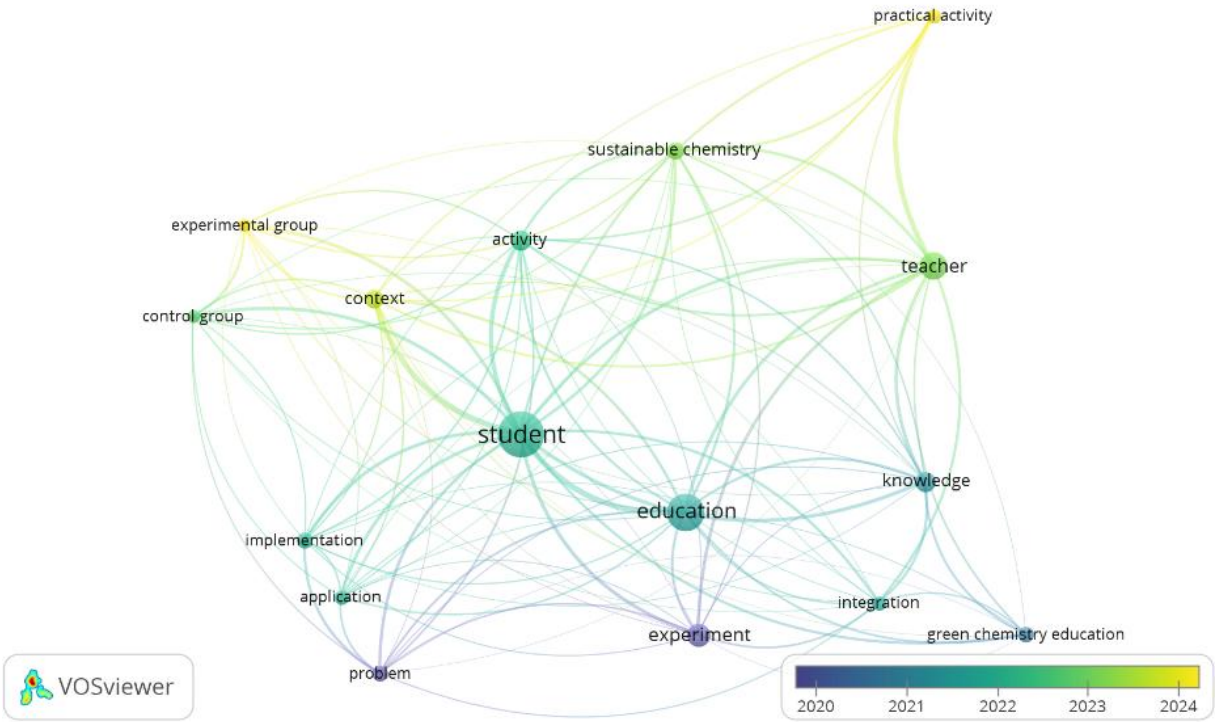


Figure 2. Keyword Co-Occurrence Network of Green Chemistry Education Research At The Secondary School Level.

The keywords "education" and "teacher" also appear as important nodes with strong connections to other concepts. This pattern indicates that GCE research is not only concerned with students' learning outcomes but also with broader educational processes, including teacher roles, curriculum integration, instructional design, and classroom implementation. The relationship between "teacher" and "practical activity" further suggests that teachers play an important role in translating green chemistry principles into laboratory activities and contextual learning experiences. This finding is consistent with previous studies showing that teacher readiness, pedagogical knowledge, and practical resources are central to the successful integration of GCE in secondary chemistry education (Carangue et al., 2021; Karpudewan & Kulandaisamy, 2018).

The network also shows strong connections between "student," "activity," "experiment," "application," and "education." These relationships indicate that secondary-level GCE research frequently emphasizes active and practice-based learning. This pattern reflects the pedagogical character of green chemistry education, which commonly uses experiments, hands-on activities, and inquiry-based learning to connect chemical concepts with environmental and sustainability issues. Previous studies have similarly shown that green chemistry can be introduced through safer laboratory practices, experimental redesign, and sustainability-oriented learning activities (Hoffman & Dicks, 2020; Koulougliotis et al., 2024).

Another important pattern is the connection among "education," "knowledge," "integration," and "green chemistry education." This relationship indicates that curriculum integration has become an important concern in recent GCE research. Rather than treating green chemistry as an isolated topic, recent studies increasingly frame it as part of broader curriculum reform and Education for Sustainable Development. This finding aligns with studies emphasizing that GCE should be integrated into chemistry learning to develop systems thinking, scientific literacy, environmental responsibility, and socio-scientific decision-making (Aubrecht et al., 2019; Linkwitz & Eilks, 2020; Zuin et al., 2021).

Table 1. Trends in Green Chemistry Education Research at The Secondary School Level from 2016 to 2025.

Year	Authors	Country	Main Theme	Research Focus
2016–2017	(Borreda & Peña, 2016; Haack & Hutchison, 2016; Kolopajlo, 2017; Nuswowati et al., 2017)	USA, Spain Indonesia	Curriculum, pedagogy	Early development and learning models
2018	(Armstrong et al., 2018; Karpudewan & Kulandaisamy, 2018; Mellor et al., 2018; Płotka-Wasylka et al., 2018; Summerton et al., 2018)	USA, United Kigdom, Malaysia, Polandia	Assessment, games, laboratory, green chemistry challenges	Learning media and evaluation
2019	(Armstrong et al., 2019; Aubrecht et al., 2019; Linkwitz & Eilks, 2019; Listyarini et al., 2019)	Indonesia, USA, Germany	Curriculum and practicum	Curriculum and experimentation
2020	(Chen et al., 2020; Gawlik-Kobylińska et al., 2020; Hoffman & Dicks, 2020; Hurst, 2020; Wissinger et al., 2020)	UK, China, USA dan Canada	Greening laboratory, SDGs, methods	Sustainability and technology integration
2021	(Ballard & Mooring, 2021; Koulougliotis et al., 2021; Li & Eilks, 2021; Zuin et al., 2021)	China, Brazil, USA, Greece	Case-Based Learning	Learning approaches
2022	(Ahmad et al., 2022; Dewi & Listyarini, 2022; Nahlik et al., 2022; Zidny & Eilks, 2022)	Indonesia, USA	Ethnoscience and teachers	Environmental literacy and teacher competence
2023	(Hoffman & Dicks, 2023; Putri et al., 2023; Wardani et al., 2023)	Indonesia, Canada, USA	Culturally Responsive Teaching and SDGs	Contextual learning
2024	(da Silva Júnior et al., 2024; Delaney et al., 2024; Lathwesen & Eilks, 2024; Pertiwi & Wahyuningrum, 2024)	Indonesia, Brazil, Germany, Australia,	Curriculum, gamification, and practicum	Learning innovation
2025	(Anisah et al., 2025; Manarisip et al., 2025; Mashami et al., 2025; Retnani et al., 2025; Ribau, 2025; Salsabila & Ayugea, 2025; Sunday et al., 2025; Teplá et al., 2025; Wahyudi et al., 2025; Widyantoro et al., 2025)	Indonesia, Austria, Nigeria, Portugal, Singapore	PjBL, PBL, STEM, literacy, integration of practicum instruments (KIT), and ethnochemistry	Recent trends and sustainability

Table 1 summarizes the development of GCE research at the secondary school level from 2016 to 2025. During the early period of 2016–2018, research was mainly focused on the introduction of green chemistry principles, pedagogical foundations, curriculum awareness, and safer laboratory practices. Studies in this period were important in establishing green chemistry as a relevant educational approach for chemistry learning, although much of the broader development of GCE was still strongly influenced by higher education and laboratory-based curriculum reform (Haack & Hutchison, 2016; Kolopajlo, 2017; Karpudewan & Kulandaisamy, 2018).

From 2019 to 2022, the focus of research began to shift toward curriculum integration, systems thinking, teacher involvement, contextual learning, and socio-scientific issues. This period indicates that GCE was no longer viewed only as a strategy for making laboratory work safer, but also as a framework for connecting chemistry with real-world sustainability problems. The emergence of studies on systems thinking, curriculum reform, and ethnoscience suggests that researchers increasingly recognized the need to connect green chemistry principles with students' lived experiences, local contexts, and broader sustainability challenges (Aubrecht et al., 2019; Chen et al., 2020; Linkwitz & Eilks, 2020, 2022a; Zidny & Eilks, 2022).

In the most recent period, from 2023 to 2025, GCE research became more diverse and implementation-oriented. Recent studies have addressed digital learning, project-based

learning, problem-based learning, STEM integration, ethnochemistry, local wisdom, scientific literacy, environmental literacy, and alignment with the Sustainable Development Goals (SDGs). This development reflects the growing influence of global sustainability agendas and curriculum reforms that require chemistry education to contribute not only to conceptual understanding but also to students' capacity for responsible environmental action (Hoffman & Dicks, 2023; Koulougliotis et al., 2024; Mashami et al., 2025; Teplá et al., 2025; Wahyudi et al., 2025).

Overall, the results show that GCE research at the secondary school level has moved through three broad phases. The first phase emphasized conceptual introduction and laboratory safety. The second phase focused on curriculum integration and contextual learning. The third phase shows a stronger orientation toward interdisciplinary, culturally relevant, and sustainability-driven implementation. This progression suggests that GCE is increasingly positioned as a pedagogical framework for linking chemistry learning with environmental literacy, socio-scientific reasoning, and sustainable development.

Despite this development, the analysis also indicates several research gaps. First, existing studies are still dominated by short-term classroom interventions and learning material development, while long-term evaluation of students' behavioral change and sustained environmental responsibility remains limited. Second, teacher-related research is visible but still less dominant than student-centered research, indicating the need for further studies on teacher professional development, pedagogical competence, and institutional support. Third, interdisciplinary integration remains an emerging area, particularly in relation to STEM, digital learning, local wisdom, and SDG-oriented curriculum design. These gaps indicate that future research should move beyond the development of isolated learning activities toward more comprehensive models of sustainable Green Chemistry Education at the secondary school level.

Discussion

The findings show that research on Green Chemistry Education (GCE) at the secondary school level has developed from an initial emphasis on green chemistry principles and safer laboratory practices toward broader concerns with curriculum integration, contextual learning, and sustainability-oriented pedagogy. This development indicates that GCE is no longer treated merely as an additional topic in chemistry education, but increasingly as a pedagogical framework for linking chemical concepts with environmental responsibility, scientific literacy, and sustainable development.

One important factor driving this shift is the growing influence of Education for Sustainable Development (ESD) and the Sustainable Development Goals (SDGs). As sustainability has become a global educational priority, chemistry education has been expected to contribute more directly to students' understanding of environmental issues, responsible consumption, waste reduction, and safer chemical practices. This explains why recent studies increasingly connect GCE with SDG-oriented curriculum reform, environmental literacy, and socio-scientific issues (Hoffman & Dicks, 2023; Koulougliotis et al., 2024; Lathwesen & Eilks, 2024; Zuin et al., 2021). In this sense, the increasing attention to GCE reflects a broader transformation in chemistry education from content transmission toward sustainability-oriented scientific citizenship.

The dominance of keywords related to students, education, teachers, activities, and experiments also suggests that GCE research remains strongly pedagogical and classroom-oriented. This pattern is understandable because secondary school education requires instructional approaches that can translate abstract green chemistry principles into concrete learning experiences. Laboratory activities, project-based learning, problem-based learning, and context-based learning provide opportunities for students to understand chemistry through real environmental problems rather than through decontextualized concepts. Previous studies have shown that green chemistry experiments and socio-scientific contexts can support students' awareness of green chemistry principles, environmental issues, and responsible decision-making (Hoffman & Dicks, 2020; Karpudewan & Kulandaisamy, 2018; Koulougliotis et al., 2021).

Another important finding is the increasing attention to curriculum integration. This trend may be explained by the growing recognition that

GCE cannot be implemented effectively if it remains limited to isolated activities or optional enrichment materials. Instead, green chemistry needs to be embedded into learning objectives, teaching materials, laboratory practices, and assessment systems. Studies on systems thinking and curriculum integration emphasize that students need to understand the relationship between chemical processes, environmental impacts, safety, and broader social consequences (Aubrecht et al., 2019; Linkwitz & Eilks, 2020, 2022a). Therefore, curriculum integration represents a crucial step in moving GCE from fragmented classroom innovation toward more systematic educational reform.

The emergence of ethnochemistry, local wisdom, and culturally relevant contexts also reflects an important direction in recent GCE research. These approaches indicate that sustainability-oriented chemistry learning does not have to rely only on global environmental issues, but can also be connected to students' local environments, cultural practices, and everyday experiences. For example, studies integrating ethnoscience and local wisdom show that green chemistry can be made more meaningful when students examine familiar materials, local practices, or community-based environmental problems through scientific concepts (Mashami et al., 2025; Wardani et al., 2023; Zidny & Eilks, 2022). This development is particularly relevant for secondary education because contextual and culturally grounded learning can improve students' engagement and scientific literacy.

However, the findings also reveal that several areas remain underdeveloped. First, many studies still focus on short-term instructional interventions, such as modules, experiments, textbooks, or classroom activities. Although these studies are valuable, they do not sufficiently explain whether GCE produces long-term changes in students' environmental behavior, sustainability attitudes, or decision-making practices. This indicates the need for longitudinal studies that examine the durability of GCE outcomes beyond immediate post-test achievement.

Second, teacher-related research needs stronger attention. The presence of "teacher" as an important keyword shows that teachers are recognized as key actors in GCE implementation. However, the literature still appears more student-centered than teacher-development-centered. This is problematic because the successful integration of GCE depends heavily on teachers' conceptual understanding, pedagogical competence, laboratory readiness, and access to teaching resources. Previous research has shown that teachers may perceive GCE as important, but their knowledge and level of integration can remain limited without sufficient professional development and institutional support (Carangue et al., 2021; Karpudewan & Kulandaisamy, 2018).

Third, interdisciplinary integration is still emerging. Although recent studies have begun to connect GCE with STEM, digital learning, ethnochemistry, and SDGs, these approaches are not yet fully consolidated into coherent models of secondary chemistry education. Future studies should therefore develop more integrated frameworks that combine chemistry content, sustainability issues, local contexts, technology, and cross-disciplinary competencies. Such integration is important because environmental problems cannot be understood through chemistry alone, but require connections with ecological, technological, social, ethical, and policy dimensions.

Overall, this study shows that GCE research at the secondary school level is moving toward a more contextual, interdisciplinary, and sustainability-oriented direction. The main contribution of this bibliometric analysis is to clarify how the field has evolved, what themes dominate the literature, and which gaps require further attention. These findings suggest that future GCE research should move beyond isolated classroom innovations and develop more comprehensive, evidence-based, and scalable models for sustainable chemistry education in secondary schools.

CONCLUSION

This study mapped the development of Green Chemistry Education (GCE) research at the seconddary school level through a bibliometric analysis of 43 articles published between 2016 and 2025. The findings show that research in this field has developed progressively, moving from the introduction of green chemistry principles and safer laboratory practices toward broader concerns with curriculum integration, contextual learning, teacher involvement, ethnochemistry, digital innovation, STEM-oriented learning, and alignment with the SDGs.

Keyword co-occurrence analysis indicates that the research landscape is mainly centered on students, education, teachers, activities, experiments, and curriculum integration. This pattern suggests that GCE at the secondary school level is strongly oriented toward pedagogical implementation and classroom-based learning. The trend analysis further shows that GCE has gradually shifted from a laboratory-centered approach toward a more contextual, interdisciplinary, and sustainability-driven pedagogical framework.

The main contribution of this study lies in providing a structured bibliometric overview of secondary-level GCE research. Unlike studies that discuss green chemistry education in general or focus on individual learning interventions, this study clarifies the thematic structure, research trends, and underexplored areas within the field. The findings indicate that future research should give greater attention to long-term impact evaluation, students' behavioral change, teacher professional development, interdisciplinary implementation, and scalable curriculum models for sustainable chemistry education.

IMPLICATIONS

For educators, the findings suggest that GCE should be implemented through active, contextual, and practice-based learning. Teachers can integrate green chemistry principles into laboratory activities, project-based learning, problem-based learning, socio-scientific issues, and local environmental contexts. Rather than presenting green chemistry as a separate topic, teachers should connect it with existing chemistry concepts such as chemical reactions, acids and bases, organic compounds, environmental chemistry, waste, energy, and material use.

For policymakers and curriculum developers, this study highlights the need to position GCE as part of sustainable chemistry education at the seconddary school level. Curriculum support should include clear learning outcomes, contextual teaching materials, safer laboratory guidelines, and assessment tools that measure not only conceptual understanding but also environmental literacy, systems thinking, and responsible decision-making. Policy support is also needed to provide teacher training, laboratory resources, and institutional conditions that enable schools to implement GCE consistently.

For researchers, the findings indicate several future research directions. Further studies should examine the long-term effects of GCE on students' environmental attitudes, behavioral change, and sustainability-oriented decision-making. More research is also needed on teacher readiness, professional development models, interdisciplinary curriculum design, and the integration of local wisdom, digital technology, and STEM approaches. These directions are important for moving GCE research beyond isolated classroom interventions toward more comprehensive and evidence-based models of sustainable chemistry education.

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