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Global Trends and Influences in Green Chemistry Education: A Comprehensive Review of Contributions (2014-2024)

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Abstract

Since the 1990s, chemists' interest in green chemistry has been increasing annually, accompanied by a growing number of research reports on green or clean chemistry in both academia and industry. There is an increasing realization that science and technology alone are insufficient to manage chemical waste and hazardous substances effectively, thereby protecting human health and the environment. Consequently, the development and promotion of green chemistry are imperative. Education plays a unique and crucial role in disseminating the principles of green chemistry. This study focuses on publications related to green chemistry education from 2014 to 2024. It employs a combination of systematic literature review (SLR) and bibliometric analysis (BR) methodologies, following the 2020 PRISMA statement template. By screening 512 relevant publications from the Web of Science database, this paper identifies the most influential journals and authors in the field of green chemistry education and analyzes the countries that have made the most significant contributions to this research area. Furthermore, the paper provides a detailed review and analysis of key research keywords and significant subject areas. These findings offer valuable insights into understanding research trends in green chemistry education. By examining critical areas such as journals, authors, countries, and keywords, this study aims to provide an overview of current research trends and valuable insights for future research and practical applications. Ultimately, the goal is to improve the existing chemistry education system and enhance public awareness of sustainable development and environmental protection concepts.

Keywords: Green Chemistry, Chemistry Education, Sustainable Development

Introduction

Green chemistry emerged in the 1990s, and over the subsequent decades, its principles gradually became an essential part of industrial, educational, and societal practices(Armstrong et al., 2018; Marteel-Parrish & Newcity, 2017). Green chemistry is seen as a natural progression of pollution prevention efforts. It introduces a fresh perspective on the development, design, and use of chemical processes. From this standpoint, chemists and engineers are expected to design chemicals, chemical processes, and commercial products in ways that, at a minimum, prevent the creation of toxic substances and waste(Gawlik-Kobylińska et al., 2020).

The American Chemical Society regards green chemistry as a field open to innovation, new ideas, and transformative advancements(Brun, 2021; Ferk Savec & Mlinarec, 2021). The international community's commitment to green chemistry education is very strong, as evidenced by the United Nations' Agenda 21(Armstrong et al., 2018). The increasing emphasis on green chemistry by various sectors of society has significantly impacted chemistry education(Andraos & Dicks, 2012; Ferk Savec & Mlinarec, 2021).

Integrating sustainability and green chemistry into the education of future chemists and chemical engineers is considered crucial for students' success in an evolving job market and societal roles(Avsec & Jagiełło-Kowalczyk, 2021; Ferk Savec & Mlinarec, 2021). Educating future chemists and engineers in green chemistry is crucial for developing a new generation of environmentally conscious scientists. Sustainability education provides future graduates with effective tools to address complex problems(Lokteva, 2018).

The growing interest and concern for environmental sustainability necessitate a closer examination of the activities of chemists and chemical engineers that significantly impact the environment, both in laboratories and industrial settings. The concept of green chemistry is closely linked to the spread of sustainable development principles and the increasing implementation of these principles in various chemical practices. Over time, the principles of green chemistry have been embraced across different chemistry fields, leading to the establishment of additional frameworks such as the Principles of Green Chemical Technology, the 12 Principles of Green Engineering, and the 12 Principles of Green Analytical Chemistry(Kurowska-Susdorf et al., 2019).

Hence, Green chemistry education plays a pivotal role in promoting sustainable development and environmental protection. This paper aims to provide a comprehensive review of the publications from the green chemistry perspective over the past decade, covering all fields of chemistry, all levels of education, and the 12 principles of green chemistry. To explore the possibilities in green chemistry education, the following research questions have been established. Data is taken from the web of science database to answer the following research questions:

1. How is the distribution of publications in green chemistry education from 2014-2024?
2. Who are the most influential journals and authors in green chemistry education?
3. Which countries contribute most significantly to research in green chemistry education?
4. What are the main keywords in research related to green chemistry education over the past decade?
5. What are the current core research hotspots in the field of green chemistry education?

Materials and Methods

The bibliometric analysis and meta-analyses method was used in conducting this study's systematic literature review (SLR)(Samsul et al., 2023). The research process and procedure used in this study are based on Preferred Reporting Items for Systematic Reviews (PRISMA) 2020 guidelines (Page et al., 2021), which focus on several aspects to ensure transparent, replicable, and scientifically adequate systematic reviews. The details of this processes are explained further in Fig. 1.

Information Sources and Search Strategy

This study conducted an advanced search of articles published between 2014 and 2024 in the Web of Science (WoS) database, chosen for its comprehensive coverage of scholarly journals and conference papers across the natural sciences, social sciences, arts, and humanities. This extensive coverage ensures access to influential and current research. Additionally, WoS provides detailed citation analysis tools, allowing researchers to trace citation relationships and identify highly cited articles and key publications(Falagas et al., 2008; Meho & Yang, 2007).

The search strategy was developed using core concepts related to the study, including "green chemistry," education, teach*, student, and curriculum. Search strings were constructed with Boolean operators (AND, OR) and simple operators to ensure comprehensive literature coverage.

To enhance the study's credibility and integrity, only peer-reviewed articles were included. Additional parameters were applied to refine the search results based on the inclusion and exclusion criteria described in Table 2.1. The final search was conducted on July 28, 2024. For data analysis and visualization, VOSviewer software was used, which is highly effective for analyzing and visualizing bibliometric data

Table 2.1
Search Parameters and Criteria

The searching string	Articles	Date
"green chemistry " (Topic) AND education OR teach* OR student OR curriculum (Topic)	1010	2024/7/28
Inclusion criteria	**Exclusion criteria**	
IC1: The paper published in a scientific peer-reviewed journal. **IC2:**The paper is written in English. **IC3:**The paper type is journal articles or review articles. **IC4:**Papers that aren't duplicate within the search documents . **IC5:**The study was conducted in an educational environment. **IC6:**The study is related to green chemistry.	**EX1:**The paper published isn't in peer-reviewed journal. **EX2:**The paper isn't written in English. **EX3:**Proceedings of congresses, conference papers, books, book chapters **EX4:**Papers that are duplicated within the search documents. **EX5:**The study was not conducted in an educational environment. **EX6:**The study is not related to green chemistry.	

Data Collection and Analysis

The systematic literature review was carried out in four phases following the PRISMA 2020 guidelines. The first phase was an initial search of the literature in the WoS (n = 1010). Based on the inclusion (IC1, IC2, IC3, IC4) and exclusion (EX1, EX2, EX3, EX4) criteria, a total of 459 papers were excluded as ineligible regarding the type of paper, language, peer-review criteria and the time of the publication. In the thirdly phase, a total of 514 papers were carefully screened for eligibility by applying inclusion (IC6, IC7) and exclusion (EX6, EX7) criteria. In the last phase, 2 duplicate papers were excluded using Microsoft Excel software.

In the end, this study analyzed a total of 512 selected articles. The described process is summarized in a PRISMA flow diagram (Figure2.1).

Results

Research question 1: This paper aims to comprehensively review green chemistry publications. Figure 3.1 shows the distribution of publications in the field of green chemistry education from 2014 to 2024. Over the past decade, the number of

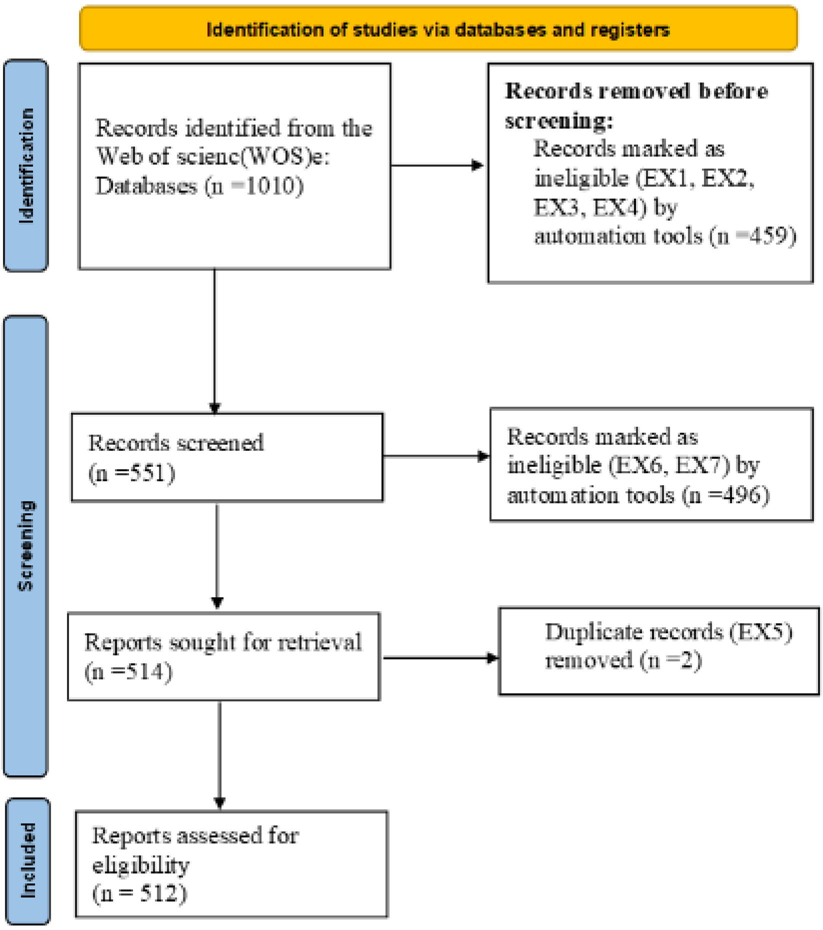

Figure 2.1 PRISMA 2020 flow diagram

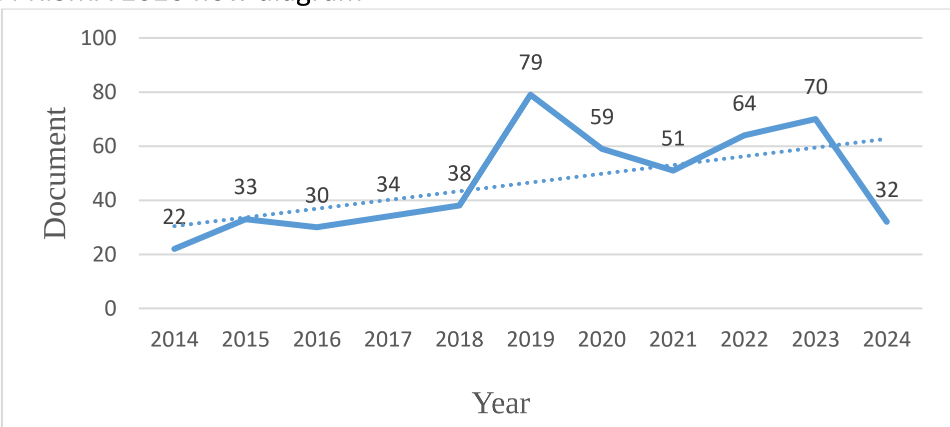

Figure 3.1 The number of publications produced over 10 years.

publications has shown an overall increasing trend. Notably, the highest number of publications was in 2019. Due to the impact of the COVID-19 pandemic, there was a slight decline in the number of publications from 2019 to 2021. As the pandemic subsided, the number of publications increased annually, reaching levels comparable to 2019 by 2023.

Research question 2: Figure 3.2 illustrates the distribution of the most relevant journals in the field of green chemistry education, based on total publications. The chart highlights that the Journal of Chemical Education accounts for the majority, with 73% of the total publications. Other notable journals include Green Chemistry Letters and Reviews, Chemistry Education Research and Practice, and Sustainability.

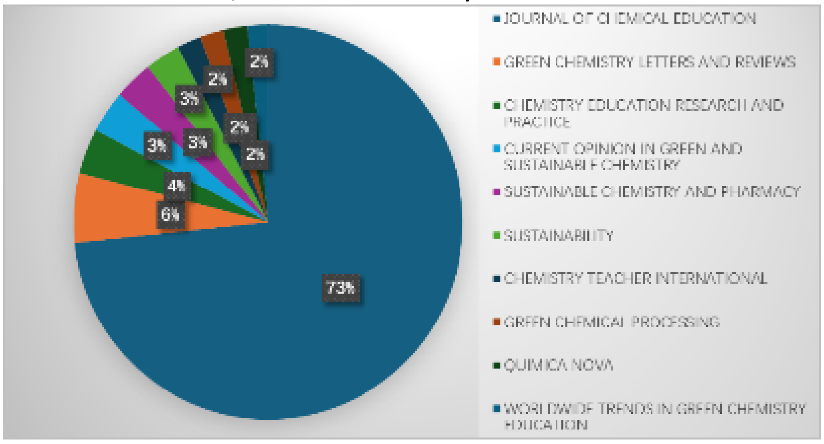

Figure 3.2 The pie chart showing most relevant journals in green chemistry education

Table 3.1
Summary of the most relevant journals in green chemistry education

No.	Journal	TP	TC	Citation Score (2023& 2024.7.28)	Most cited article (Reference)	Times Cited	Publisher
1	JOURNAL OF CHEMICAL EDUCATION	297	3378	970	Humanizing Chemistry Education: From Simple Contextualization to Multifaceted Problematization	62	AMER CHEMICAL
2	GREEN CHEMISTRY LETTERS AND REVIEWS	23	147	49	The safer chemical design game. Gamification of green chemistry and safer chemical design concepts for high school and undergraduate students	30	TAYLOR & FRANCIS LTD
3	CHEMISTRY EDUCATION RESEARCH AND PRACTICE	15	165	57	Education for sustainable development in chemistry - challenges, possibilities and pedagogical models in Finland and elsewhere	28	ROYAL SOC CHEMISTRY
4	CURRENT OPINION IN GREEN AND SUSTAINABLE CHEMISTRY	14	267	76	Green analytical chemistry as an integral part of sustainable education development	47	ELSEVIER
5	SUSTAINABLE CHEMISTRY AND PHARMACY	13	81	47	Green Chemistry: Some important forerunners and current issues	23	ELSEVIER
6	SUSTAINABILITY	12	74	44	Design of an Extended Experiment with Electrical Double Layer Capacitors: Electrochemical Energy Storage Devices in Green Chemistry	13	MDPI
7	CHEMISTRY TEACHER INTERNATIONAL	8	10	4	Student explorations of calcium alginate bead formation by varying pH and concentration of acidic beverage	5	WALTER DE GRUYTER
8	GREEN CHEMICAL PROCESSING	8	7	0	Green chemistry and the grand challenges of sustainability	4	WALTER DE GRUYTER
9	QUIMICA NOVA	8	7	0	Green chemistry and the grand challenges of sustainability	4	SOC BRASILEIRA
10	WORLDWIDE TRENDS IN GREEN CHEMISTRY EDUCATION	7	47	12	On the Development of Non-formal Learning Environments for Secondary School Students Focusing on Sustainability and Green Chemistry	10	ROYAL SOC CHEMISTRY

Table 3.1 focused on the total number of publications, total citations, citation scores, and the most cited articles. The Journal of Chemical Education leads the field with 297 publications and 3,378 citations, demonstrating its dominant position in green chemistry education.

Other journals, such as Green Chemistry Letters and Reviews and Chemistry Education Research and Practice, although having fewer publications, hold significant influence in specific research areas. For instance, Current Opinion in Green and Sustainable Chemistry, with only 14 articles, boasts high total citations and citation scores, indicating the high quality and impact of its articles.

Research Question 2 also identified the most productive authors in the field of green chemistry education and learning analytics. Figure 3.3 lists the most productive authors in green chemistry education based on Total Citations (TC ≥ 20). Table 3.2 summarizes these prolific authors, including Author Name, Year of First Publication, Total Publications (TP), h-Index, Total Citations (TC), Current Affiliation, and Country.

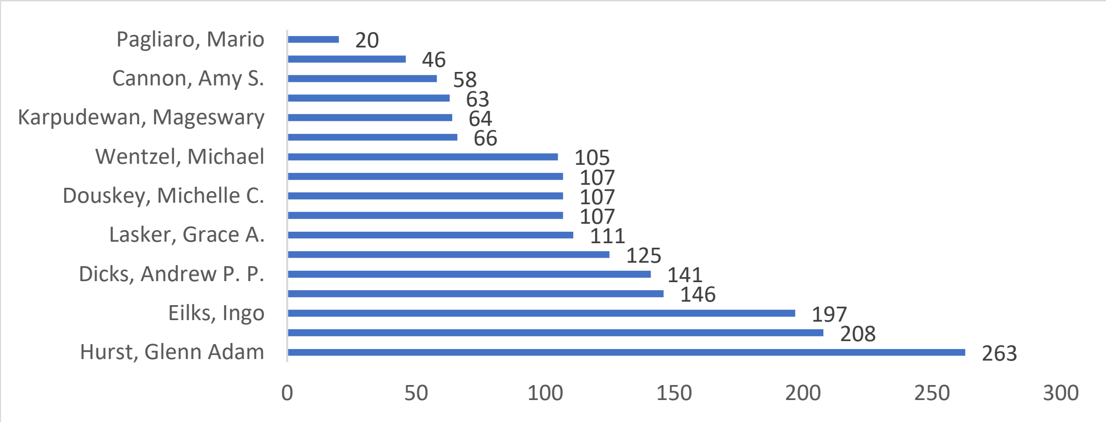

Figure 3.3 The most productive authors in green chemistry education according to total citation.

Table3.2
Summary of the most productive authors in green chemistry education

Author	Year of 1st publication	TP	h-index	TC	Current affiliation	Country
Hurst, Glenn Adam	2017	15	11	263	University of York	UK
Zuin, Vania	2015	8	6	208	Leuphana University	Germany
Eilks, Ingo	2015	12	5	197	University of Bremen	Germany
Wissinger, Jane E.	2014	10	6	146	University of Minnesota Twin Cities	USA
Dicks, Andrew P. P.	2014	11	7	141	University of Toronto	Canada
Clark, James	2016	7	6	125	University of York	UK
Lasker, Grace A.	2017	6	6	111	University of Washington	USA
Baranger, Anne M.	2016	6	4	107	University of California Berkeley	USA
Douskey, Michelle C.	2016	6	4	107	University of California Berkeley	USA
Armstrong, Laura B.	2016	6	4	107	University of California Berkeley	USA
Wentzel, Michael	2014	7	5	105	Augsburg University	USA
Leontyev, Alexey	2020	7	5	66	North Dakota State University Fargo	USA
Karpudewan, Mageswary	2015	6	4	64	Universiti Sains Malaysia	Malaysia
Mammino, Liliana	2015	8	4	63	University of Venda	South Africa
Cannon, Amy S.	2014	6	4	58	Beyond Benign Inc	USA
Grieger, Krystal	2020	6	4	46	North Dakota State University Fargo	USA
Pagliaro, Mario	2020	6	3	20	Consiglio Nazionale delle Ricerche (CNR)	Italy

According to the data, the most productive author is Glenn Adam Hurst from the University of York, UK. His first publication was in 2017, and he has published a total of 15 articles with an h-index of 11 and a total citation count of 263.

Research Question 3: The third research question aims to identify the countries that have made the greatest contributions to research in green chemistry education. Figure 3.4 shows the countries with the highest contributions based on Total Publications (TP) according to the Web of Science (WoS) database. Table 3.3 provides a summary of the most significant countries in the field of green chemistry education research. This table lists the ranking, country, TP, major academic institutions, and the TP of these institutions.

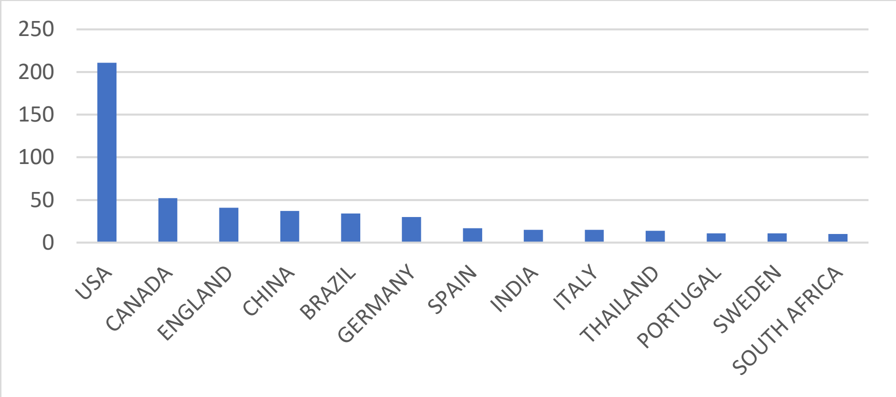

Figure 3.4 The most productive authors in green chemistry education according to total publication.

Table3.3

Summary of the most significant countries in green chemistry education

Rank	Country	tp	Most significant academic institution
1	USA	211	UNIVERSITY OF CALIFORNIA SYSTEM16 UNIVERSITY OF MINNESOTA SYSTEM13
2	CANADA	52	UNIVERSITY OF TORONTO21
3	UNITED KINGDOM	41	UNIVERSITY OF YORK UK23
4	CHINA	37	HANSHAN NORMAL UNIVERSITY5
5	BRAZIL	34	UNIVERSIDADE FEDERAL DE SAO CARLOS8
6	GERMANY	30	UNIVERSITY OF BREMEN12
7	SPAIN	17	UNIVERSIDAD DE CORDOBA3 UNIVERSIDAD SAN JORGE3
8	INDIA	15	UNIVERSITY OF DELHI4
9	ITALY	15	UNIVERSITY OF DELHI4
10	THAILAND	14	MAHIDOL UNIVERSITY4
11	PORTUGAL	11	FAHRENHEIT UNIVERSITIES3 GDANSK UNIVERSITY OF TECHNOLOGY3
12	SWEDEN	11	MALMO UNIVERSITY5 ROYAL INSTITUTE OF TECHNOLOGY3
13	SOUTH AFRICA	10	Chemistry Multidisciplinary8 Green Sustainable Science Technology7

As shown in Table 3.3, the most significant country in the field of green chemistry education is the United States, with a total of 211 publications. The University of California System is the leading research institution in the US. The following country is Canada, with a total of 52 publications, where the University of Toronto stands out as the most important research institution. China ranks fourth with 37 publications. Other Asian countries listed in Table 3.3 include India and Thailand, with 15 and 14 publications respectively.

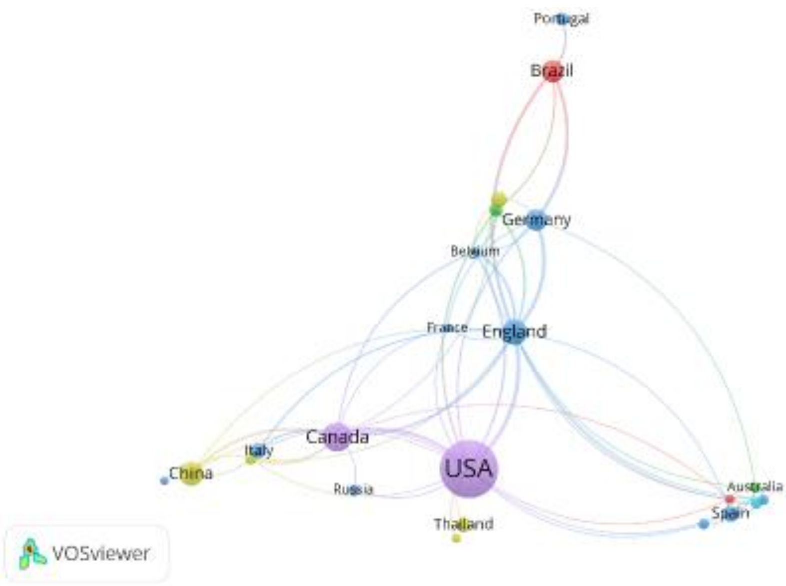

Figure3.5 A map based on the relationship of co-authorship with countries.

Subsequently, VOSviewer software was utilized to generate a co-authorship map of countries engaged in research on green chemistry education, as depicted in Figure 3.5. The United States exhibits the highest number of links, with 15 connections encompassing 209 documents and 2728 total citations (TC). The United Kingdom ranks second in terms of link strength, with 16 connections involving 40 documents and 774 TC. The figure3.5 also illustrates the collaborative relationships of other countries in this domain.

Research question 4: In the analysis of Figure3.6 the network and density maps generated by VOS viewer based on the co-occurrence of author keywords in green chemistry education, a clear pattern of research focus emerges.The network map highlights the interconnections between key terms, revealing “green chemistry” as the most dominant keyword, appearing 358 times and with a total link strength of 1552. This indicates its centrality and strong association with other terms, affirming its pivotal role in the field. The keywords “undergraduate” (194 occurrences), “organic chemistry” (142 occurrences), “laboratory” (138 occurrences), and “hands-on learning” (126 occurrences) also feature prominently, suggesting an emphasis on practical, student-centered approaches within educational research.

The density map complements this, visually indicating areas of research concentration. The terms “green chemistry”, “undergraduate”, “organic chemistry”, “laboratory”, and “hands-on learning” are bright spots, confirming their significance. These bright areas represent the high frequency and strong connections of these terms, suggesting that the research over the past decade has been largely focused on integrating green chemistry into undergraduate curricula, especially in laboratory settings, where hands-on, experiential learning is emphasized.

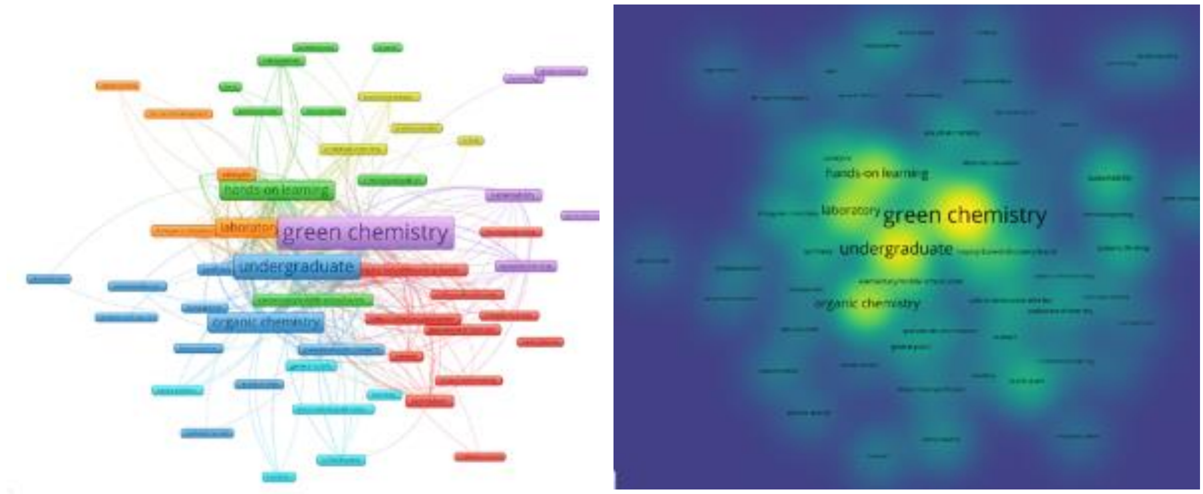

Figure3.6 The network and density map based on the co-occurrence with author keywords.

Research question 5: The fifth research question focuses on the current core research hotspots in the field of green chemistry education. Trends and comparative data, as shown in Figure 3.7 and Figure 3.8, indicate that the core research hotspots currently include a strong focus on “undergraduate” , “laboratory”, “organic chemistry”, and “hands-on learning”. The significant increase in publication counts in these areas suggests that educators and researchers are prioritizing the integration of green chemistry principles at the undergraduate level and employing practical, hands-on methods for teaching. This shift reflects a broader movement to make green chemistry an essential part of the educational experience, aiming to equip students with the necessary knowledge and skills to address environmental challenges.

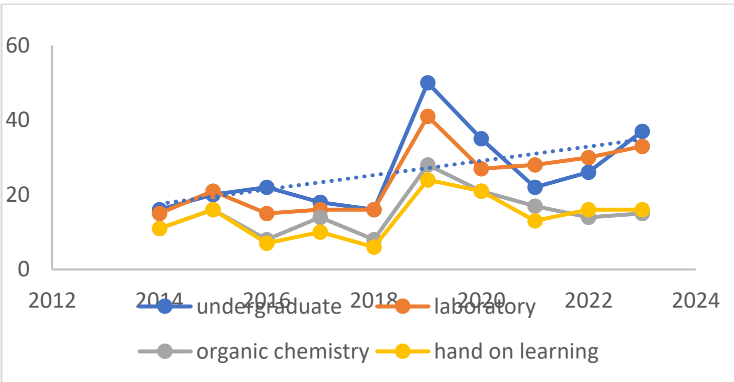

Figure3.7 Trends in Core Keywords in Green Chemistry Education (2014-2024)

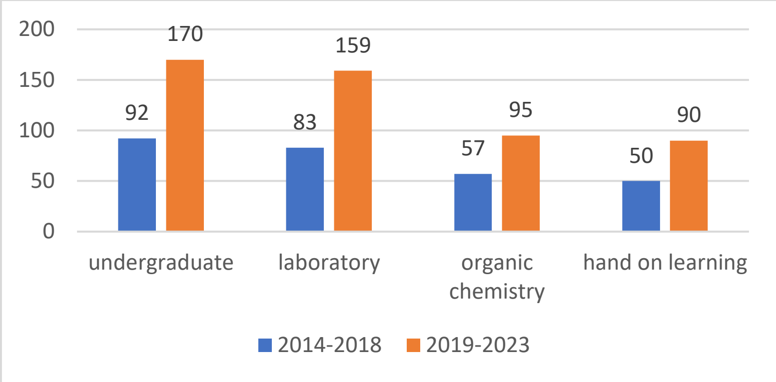

Figure3.8 Occurrences comparison for Core Keywords in Green Chemistry Education (2014-2018 vs. 2019-2023)

Discussion and Conclusions

Key Findings and Implications

This study conducted a bibliometric analysis of 512 publications on green chemistry education, covering the past decade from 2014 to 2024. During this period, the number of publications on green chemistry education has significantly increased, indicating the growing recognition of its importance. The relevant articles were primarily published in the *Journal of Chemical Education*, making significant contributions to the field of green chemistry education.

Among all authors, Glenn Adam Hurst from the UK is the most prolific, with his works being cited 263 times since his first publication in 2007. Additionally, this study found that the United States is the most important country in the field of green chemistry education research, with a total of 211 publications, greatly contributing to the development of this field.

"Undergraduate," "laboratory," "organic chemistry," and "hands-on learning" are the most frequently occurring keywords in the publications analyzed in this study. This finding reflects a broader movement to integrate green chemistry as an essential part of the educational experience, aiming to equip students with the necessary knowledge and skills to address environmental challenges.

In summary, the current research hotspots in the field of green chemistry education emphasize practical and experiential learning methods at the undergraduate level, particularly in laboratory practices and organic chemistry. These trends highlight the ongoing efforts to embed sustainability and green chemistry principles in the education of future chemists.

Limitations

One limitation of this study is the restricted information access, as only the Web of Science database was used for bibliometric analysis. Utilizing other databases such as Scopus, Springer Link, or IEEE Xplore Digital Library could have offered different insights and results. Additionally, this review is subject to language bias, as only English-language papers were included.

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