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INCLUSION AND IMPACT OF GREEN CHEMISTRY TO CHEMISTRY EDUCATION LANDSCAPE: A BIBLIOMETRIC ANALYSIS FROM 2000-2024

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ABSTRACT

This paper analyzes the changes in chemistry education landscape as green chemistry is integrated into the science curriculum from 2000-2024. With the aid of VOS viewer, this bibliometric analysis uses 619 articles extracted from Scopus. The findings suggest that green chemistry studies were scanty in the first decade due to limited international collaboration among authors, organizations, and countries. There is a steady but fluctuating increase in article counts starting 2010. Authors from the US, UK, Germany, and Canada are found to be the most prolific in green chemistry studies and their research were also the most cited. The Journal of Chemical Education in the US dominates the publication of green chemistry studies, with China and India being the leaders in Asia. The most active and prolific institutions and organizations that promote green chemistry are also found in the US, UK, Canada, and Germany. Further, the trend in green chemistry core topics indicates a shift to laboratory instruction, hands-on learning, education, and sustainability. Moreover, the results show that initiatives in green chemistry instruction are mostly driven by institutional objectives based on their government goals. In developing countries, more professional development programs and advanced training in green chemistry are required due to lack of experts and theoretical foundations. Overall, the chemistry education landscape has accommodated green chemistry in response to government regulations on greener chemicals and technologies.

Keywords: Collaborative research, green chemistry studies, bibliometric analysis

INTRODUCTION

Recent developments in science education research (SER) indicate important shifts in science core concepts. From 2006-2015, scientific literacy and socio-scientific issues became hot topics in science education. Sadler and Zeidler (2009) argued that students must be taught how scientific literacy is applied to socio-related issues and real-world problems. The density of SER was then diverted to scientific argumentation and STEM education. Such trend was due to scientific inquiry where students explore established scientific phenomena through practical investigations and contextualization (Wang *et al.,* 2023).

However, the emergence of environmental problems led to the transformation of science education. Both sustainability and environmental education converge with chemistry education to address these issues. Moreover, environmental sustainability had recently raised concerns on energy conservation and technological innovation (Lei *et al.,* 2023). Consequently, chemistry education needs to accommodate these significant reforms to educate the next generation about environmental preservation and sustainability.

The inclusion of green chemistry to chemistry education may address this issue. For example, Haack and Hutchison (2016) commended the infusion of green chemistry in their laboratory experiments which led to less waste disposal and less use of hazardous materials. Since green chemistry is changing the landscape of chemistry education, this bibliometric analysis aims to reveal the influence of various studies from 2000 to 2024 as a result of author collaborations and networks. Further, it evaluates the impact of active participation of various countries and organizations in advancing green chemistry studies. This analysis examines the trends in the number of published studies and evaluates their effect on the formation of emerging themes in chemistry education. Such evaluation is anchored in the relationship between the development of green chemistry themes and the changing landscape of chemistry education.

Specifically, this paper addresses these research questions:

1. Who are the most prolific and most cited authors of green chemistry?
2. Which countries and organizations are actively publishing studies on green chemistry?
3. What are the top sources that promote the advancement of green chemistry research?
4. What are the trends in the development of green chemistry concepts?
5. What are the emerging reforms in chemistry education as an implication of green chemistry inclusion?

GREEN CHEMISTRY

What is Green Chemistry?

Manahan (2005) explained that green chemistry promotes environmental preservation while reducing the harmful effects of chemicals. Further, the processes and products must be carefully designed to minimize energy use and waste disposal. Thus, green chemistry provides pathways to synthesize new chemicals that are more eco-friendly without compromising the quality of the products that people need.

Origins of Green Chemistry

The roots of Green Chemistry can be attributed to the Federal Pollution Prevention Act of 1990. The main aim of this policy is to reduce pollution at its source. Source reduction is more beneficial because it leads to a more proactive solution to pollution problems

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(Freeman *et al.,* 1998). Consequently, the proponents of Green Chemistry such as Anastas and Warner (1998 and 2000) published the 12 principles of Green Chemistry which served as a fundamental guide in implementing green chemistry practices.

Advocacy for Green Chemistry Inclusion to Academe

Various organizations emerged to promote green chemistry inclusion to chemistry education. These organizations include the American Chemical Society Green Chemistry Institute (ACS-GCI), the University of Oregon, and Center for Green Chemistry and Engineering at Yale (Etzkorn & Ferguson, 2023). The ACS-GCI generated guidelines in teaching green chemistry and initiated the Green & Sustainable Chemistry Education Module. Meanwhile, the University of Oregon focused on the implementation of green organic chemistry workshops. Furthermore, the Center for Green Chemistry and Engineering at Yale produced open-access teaching resources for green chemistry, most notably on dealing with toxic materials.

METHODOLOGY

Data Collection

Bibliometric analysis was used to analyze the data from Scopus. The keywords used include green chemistry, science education, chemistry education, environment education, sustainability, recycling, reuse, hazardous substances, waste management, safe chemicals, auxiliary substances, energy efficient, renewable materials, pollution prevention, degradation, catalytic reagents, and enzymes in organic synthesis. The document type was limited to articles, conference papers, and book chapter; the publication stage was limited to final; and the language was restricted to English.

There were 623 articles generated from Scopus search from 2000 to 2024. All articles were exported to CSV format together with the citation information, bibliographical information, abstract, and keywords. After duplicate removal, only 619 articles were retained for analysis.

Data Analysis and Procedure

The data extracted were analyzed using VOS viewer for mapping and visualization (Van Eck & Waltman, 2010; Ye, 2018). The co-authorship analysis was used to identify the leading authors, organizations, countries and their networks. The nodes represent the author, organization, and country; their color denotes their cluster, and their size indicates the article counts. The network lines represent collaboration and their thickness indicates collaboration frequency. Cluster analysis was also conducted to gain insights on the trends. The co-occurrence analysis was utilized in identifying the frequency of all keywords and author keywords. Cluster analysis, frequency, and timeline overview were used to analyze the trends.

RESULTS

Number of Articles by Year

Figure 1 shows that green chemistry articles published from 2000-2007 were only 46. Article count increased rapidly from 2008, with a total of 164 articles until 2013. Studies declined in 2014 until 2017, publishing only 90 articles. From 2018 until 2020, a total of 132 articles were published but suddenly declined in 2022. Article count increased again in 2023, with 57 articles.
The top sources with the greatest number of articles are Journal of Chemical Education (JCE), and ACS Symposium Series (Figure 2). Rapid increase in publication is shown from 2008 to 2013, but there is a sharp decline from 2014 to 2017. The greatest number of documents were published by JCE in 2013 (32) and ACS in 2020 (14). In contrast, only one article on average is shown to be published by other sources annually. Overall, the number of green chemistry publications from prolific sources are scanty in two decades.

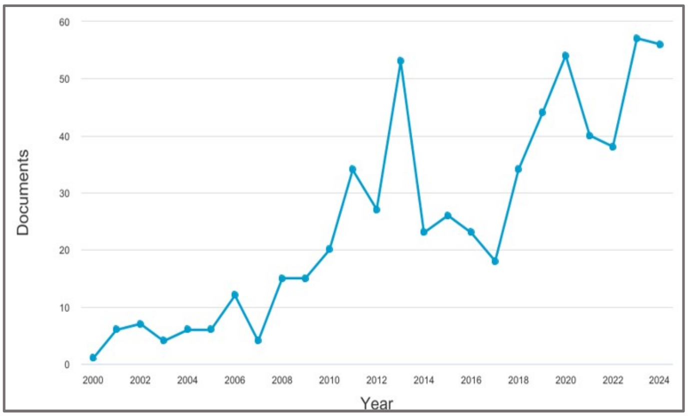

Figure 1 Number of Articles by Year

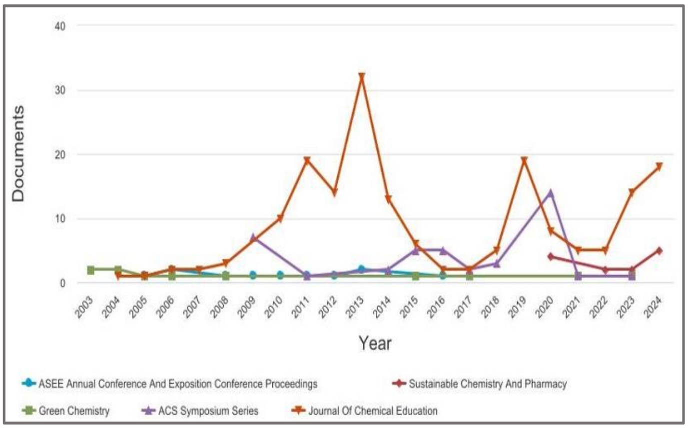

Figure 2 Number of Articles by source

Leading Authors

There are 2056 authors in the analysis. Setting the minimum documents at 3 and minimum citations at 50 results to 32 that meet the thresholds.

Table 1 Top 10 Authors ranked by number of citations

Authors	Articles	Citations	Total link strength
Eilks, Ingo	11	290	4
Zuin, Vania G.	3	229	4
Dicks, Andrew P.	11	212	1
Sharma, R.K.	3	197	0
Mahaffy, Peter G.	5	191	7
Sjostrom, Jesper	3	161	2
Andraos, John	5	157	0
Kummerer, Klaus	3	156	5
Machado, Adelio	3	143	0

The most cited authors are James Clark, Ingo Eilks, and Vania Zuin (Table 1). Clark's most cited articles are "Green Chemistry: Challenges and Opportunities" (Clark, 1999) and "Handbook of Green Chemistry and Technology" (Clark & Macquarrie, 2008). Meanwhile, Eilks and Zuin's highly cited articles are "Education for Sustainable Development (ESD) and chemistry education" (Burmeister *et al.,* 2012) and "Education in green chemistry and in sustainable chemistry: perspectives towards sustainability (Zuin *et al.,* 2021).

On the other hand, the most prolific authors in this field are Eilks Ingo (11), Andrew Dicks (11), and James Clark (7) (Figure 3). Professor Clark works extensively on green chemical technologies (University of York, n.d.). Meanwhile, Professor Dicks contributed mainly to designing microscale organic laboratory investigations (University of Toronto, 2024). Furthermore, Professor Ingo contributes mainly to chemistry education and teaching.

Figure 4 shows five clusters of authors. Cluster 1 (red) shows the strongest links between Anastas and co-authors. Meanwhile, cluster 2 (green) and cluster 4 (yellow) were linked mainly by Peter Mahaffy, who consistently worked with Jane Wissinger. Wissinger works with Michael Wentzel in cluster 3, who consistently collaborates with James Clark. Eilks Ingo of cluster 5 (purple) is linked with Klause Kummerer in cluster 4, who contributed many articles in 2020 (Figure 5). Interestingly, these figures show that the most prolific authors tend to work independently. Generally, these clusters seem to have loose collaboration.

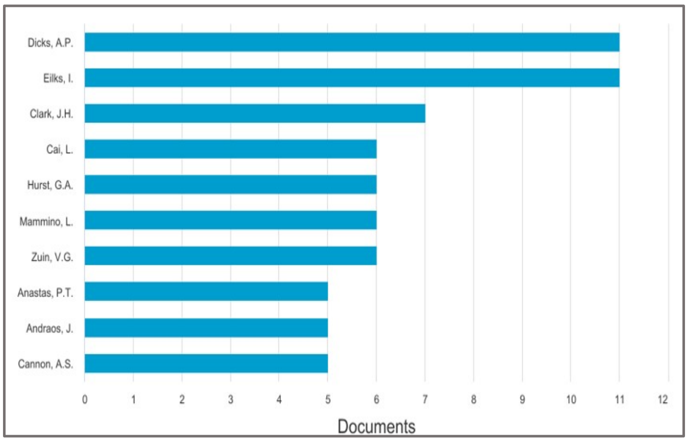

Figure 3 Leading authors by number of articles

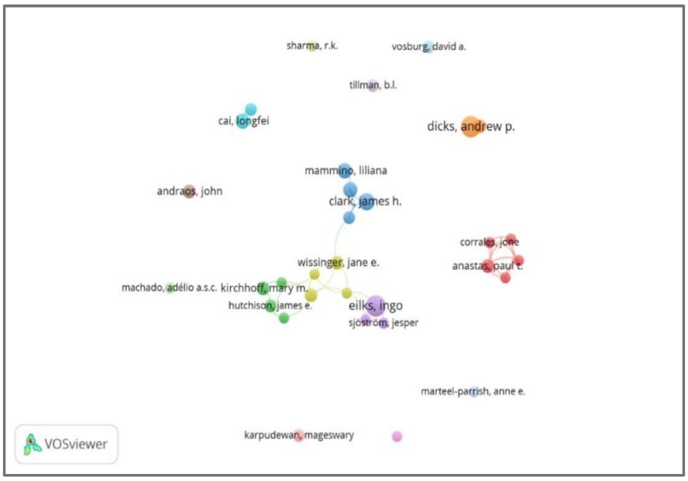

Figure 4 Collaborative research networks between authors by cluster

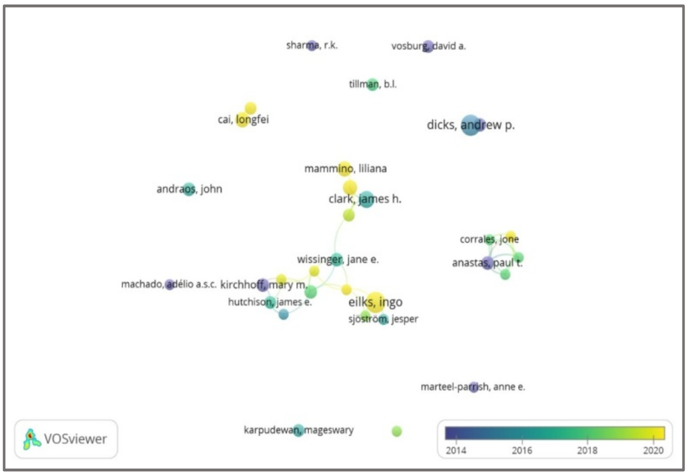

Figure 5 Link strengths between authors by cluster

Leading Countries

The database indicated 82 countries. When the minimum number of citations is 100 and a minimum of 5 documents per country were set, 23 countries meet this threshold.

Table 2 Countries ranked by number of citations

Country	Articles	Citations	Link strength
United Kingdom	40	2179	52
Canada	43	831	29
China	45	672	25
Germany	39	550	36
India	38	528	20
Brazil	32	454	32
Spain	28	438	22
France	11	437	15
Taiwan	7	427	2

The top three most cited countries are United States, United Kingdom, and Canada. This is not surprising since the most prolific authors such as Dicks, Clark, and Hurst also come from these countries. In terms of publication, United States (241) leads with a huge difference (Figure 6), followed by China (45) and Canada (43). Interestingly, China, India, and Indonesia are becoming involved in green chemistry studies. Moreover, Taiwan publishes few articles but tend to gain more citations than Indonesia. However, the number of publications seems to be low in most countries, with the highest average of 1.845 articles per year (e.g., Canada and China).

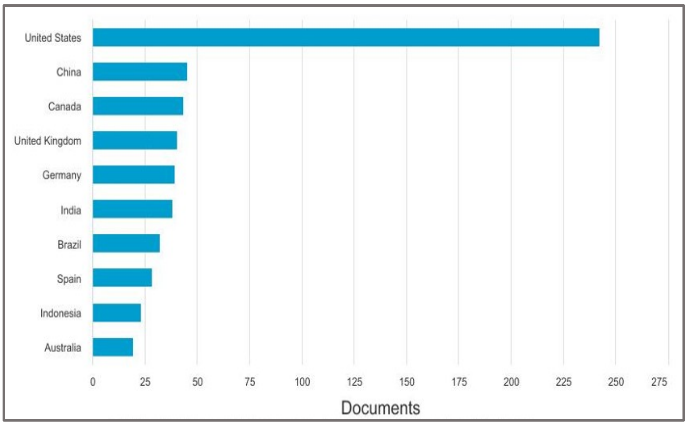

Figure 6 Leading countries by number of articles

Figure 7 shows five clusters of collaboration among countries. The US (20) and UK (18) show the greatest number of collaborative networks. China (13) in cluster 1 (red) tends to collaborate with prolific researchers from all clusters. Germany, a leading country in this field, forms fewer links in all clusters. Moreover, India and Brazil have few networks and no network in cluster 1 except for China. Spain only collaborates with the most prolific countries per cluster. It can be observed that the English speaking countries such as US, UK, Australia, and Canada are mostly linked with all clusters.

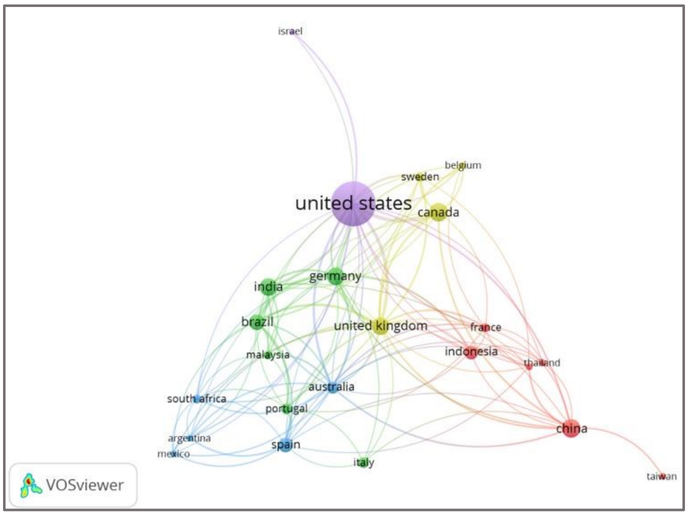

Figure 7 Collaborative research networks by countries

Leading Organizations and Institutions

There are 1233 organizations analyzed. The threshold was set to 2 minimum numbers of documents and 50 minimum numbers of citations per organization. This setting resulted in 20 organizations.

Figure 8 shows that many organizations are involved in green chemistry studies but rarely collaborate with each other. This implies that many green chemistry studies tend to be initiated by individual institutions through private funding.

Highly cited organizations are Green Chemistry Network Centre (152) in India, University of Wisconsin-Madison (128) in the US, and the University of Toronto (124) in Canada. Meanwhile, Figure 9 shows that the prolific institutions by publication are University of Toronto (25), University of York (15), Universitat Bremen (11), and American Chemical Society (11). The prolific authors are also affiliated with these institutions. On average, only 1.04 articles per year are produced by the most prolific organization.

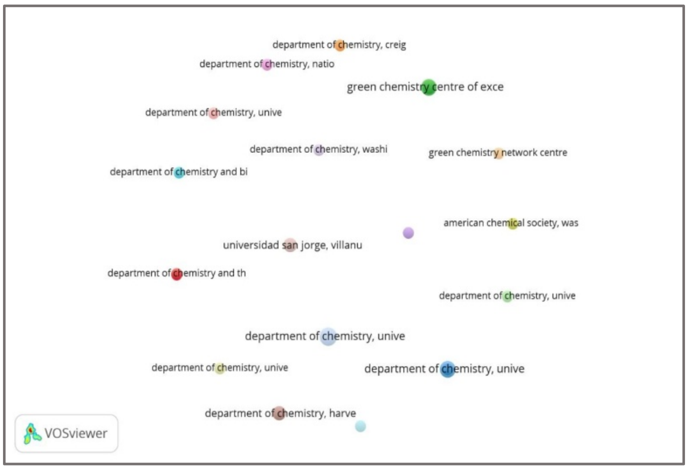

Figure 8 Leading organizations and institutions by citation

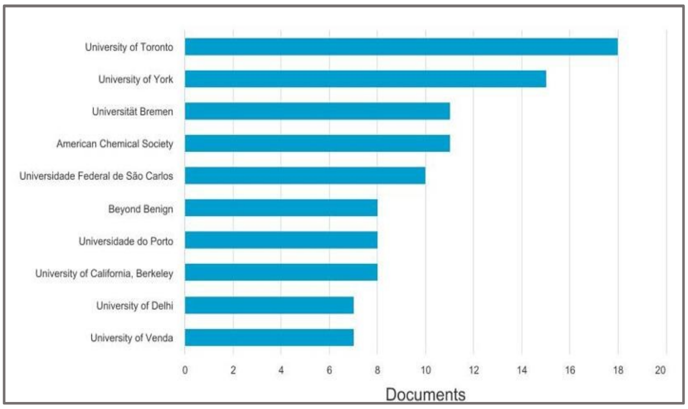

Figure 9 Leading organizations by number of documents

Table 3 Leading organizations or institutions by number of citations

Organization/Institution	Articles	Citations
Green Chemistry Network Centre	2	152
Department of Chemistry, University of Wisconsin-Madison	2	128
Department of Chemistry, University of Toronto (University College)	5	124
Department of Environmental Science, Baylor University	2	119
Department of Chemistry and the King's Centre for Visualization in Science	2	117
Institute of Global Health Innovation, Imperial College London	2	117
American Chemical Society	2	96
Department of Chemistry, Harvey Mudd College	3	93
Department of Chemistry, University of Toronto (Saint George)	4	88
Green Chemistry Centre of Excellence, Department of Chemistry, University of York	4	83
Department of Chemistry, Creighton University	2	80

The Most Frequently Used Keywords

Abstract Keywords

A total of 4456 keywords were extracted. The minimum number of keyword occurrences was set at 25. Thirty keywords met this threshold. The most frequently occurring keywords are green chemistry, education, article, human, laboratory instruction, chemistry, and hands-on learning. The keywords that are strongly linked are green chemistry, laboratory instruction, human, chemistry, hands-on learning, and education.

Three clusters of core keywords frequently occur (Figure 10). In cluster 1 (red), green chemistry occurs 331 times. In cluster 2 (green), human/s (137 occurrences) and chemistry (82 occurrences) are strongly linked to green chemistry. In cluster 3 (blue), education (97), sustainable development (70), and students (63) occur frequently, and they are strongly linked to green chemistry.

Table 4 Top 10 Most frequently occurring keywords

Keyword	Occurrences	Total Link Strength
Education	96	297
Article	93	342
Human	84	335
Laboratory instruction	83	335
Chemistry	82	268

Hands-on learning/manipulatives	77	303
Organic chemistry	69	296
Upper-division undergraduate	65	270
Second-year undergraduate	64	292

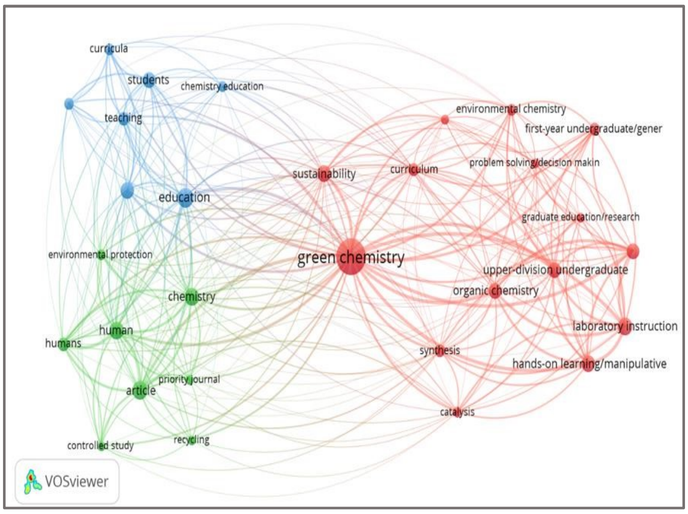

Figure 10 Core keywords in green chemistry studies

Author Keywords

There are 1293 keywords most frequently used by authors. Of these, 26 keywords met the threshold when the minimum number of keyword occurrences was set at 15. Figure 11 shows the core topics in this field. These include green chemistry (242), laboratory instruction (83), hands-on learning/manipulatives (77), upper division undergraduate (65), secondary-year undergraduate (64), organic chemistry (60), and sustainability (59).

Figure 12 shows four clusters of core topics in green chemistry. The dominant topics in each cluster by link strength are green chemistry (blue), first-year undergraduate/general (red), laboratory instruction (green), and graduate education/research (yellow). The word green chemistry is strongly related to the words laboratory instruction, hands-on learning, organic chemistry, sustainability, curriculum, environmental chemistry, first-year undergraduate, second-year undergraduate, upper-division undergraduate, and problem-solving.

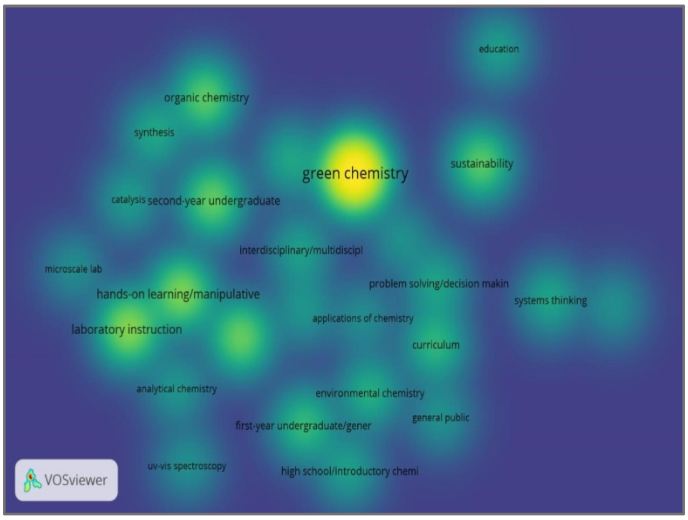

Figure 11 Core research topics in green chemistry

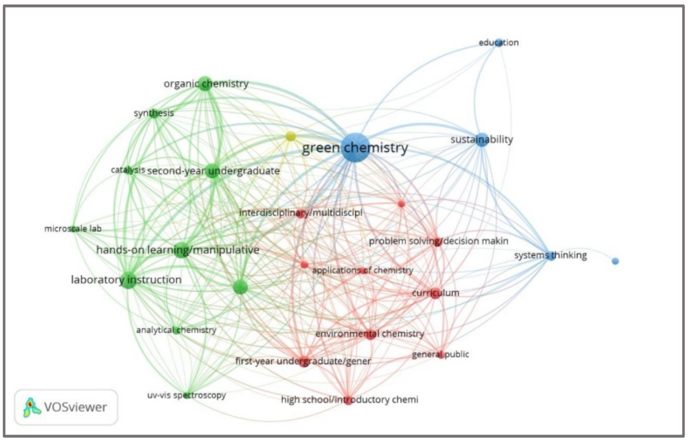

Figure 12 Link strength of the core topics in green chemistry studies

DISCUSSIONS, IMPLICATIONS, AND LIMITATIONS

Green chemistry studies respond to government initiatives for environmental protection. However, this bibliometric analysis shows that green chemistry research for the first decade was scanty. Most of the earliest studies were conducted by researchers from the US, Canada, and UK; thus, the initiatives on green chemistry propaganda primarily concentrated on these countries in its earliest conception. The Journal of Chemical Education (JCE) started to publish green chemistry research only in 2004 with a relatively slow growth and fluctuating number of studies until 2008. Moreover, other journals published on average one article annually (Figure 2). Thus, the dissemination of green chemistry and its general impact on science education are still limited.

This trend can be attributed to green chemistry practice in various sectors. Nameroff *et al.,* (2004) reported that green chemistry patents were exclusively granted to chemical manufacturers and universities in the USA and Europe from 1996-2001. Research initiatives to evaluate the environmental strategies implemented by these sectors may have circulated mainly in these countries. Consequently, the steady but slow growth in research from 2000-2008 is likely to correspond to the legislative and regulatory pressures to adopt, design, and innovate green technologies in various sectors. Additionally, Matus, Clark, and Anastas (2012) reported major barriers to green chemistry implementation in the US alone which includes costs, incentives, uncertainty, training, education, awareness, and attitudes. After this concerted study, green chemistry research increased rapidly until 2013 (Figure 1).

Meanwhile, green chemistry infusion in academic practice may be attributed to an incident in the US when many students complained about the presence of various hazardous chemicals in their laboratory in 1996 (Haack & Hutchison, 2016). Since then, universities started to use alternative and safer chemicals. Haack & Hutchison argued that green chemistry integration in the curriculum was still a huge struggle due to overcrowded curriculum and limited number of teaching materials. In developing countries, curriculum developers need to consider the revision of the traditional chemistry content, compensate investment costs, and prioritize teacher training.

Furthermore, the slow transition to green chemistry integration might be due to the lack of funding sponsors and professionals in a country. Figure 13 shows that most documents by funding sponsors come from the Americas and Europe. In 2022, the National Science Foundation appealed to scientists and professionals to intensively engage students in research and promote greener technologies (National Science Foundation, 2022). This indicates that most professionals focus and prioritize their studies based on the educational goals of their country which are intended to upgrade their curricular scheme. This trend agrees with the analysis that the most prolific authors and various highly cited authors rarely collaborate (Figure 5). This implies that global initiatives for green chemistry inclusion might be stunted.

The focus of green chemistry for the last 24 years is increasingly inclined to chemistry, social sciences, and environmental science (Figure 14). In the late 1990s, the American Chemical Society Division of Education partnered with International Activities and the Environmental Protection Agency to produce green chemistry instructional materials. This eventually led to the production of Greener Educational Materials for Chemists, the first open access database in green chemistry and the establishment of the Green Chemistry Education Network in 2006 (Haack & Hutchison, 2016). These efforts were intended to design teaching materials, create collaborative networks among schools, initiate workshops, and coordinate with textbook publishers to promote green chemistry to a broader audience.

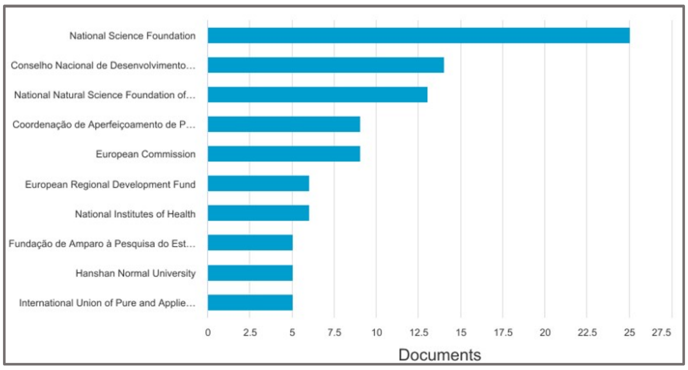

Figure 13 Number of articles by funding sponsors

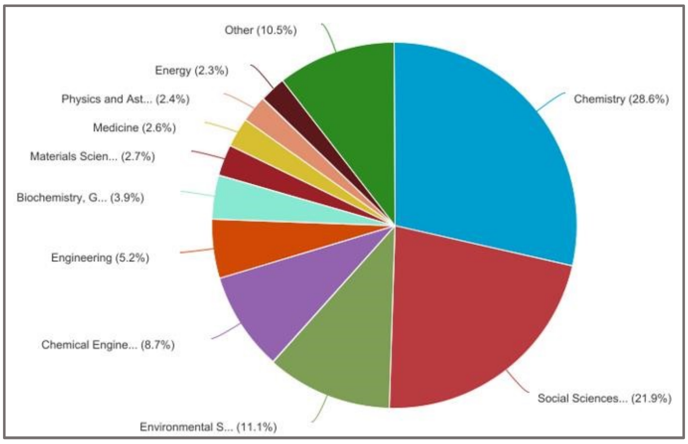

Figure 14 Percentage of articles per subject area

These recent developments in green chemistry infusion into the science education landscape agree with the rapid increase in green chemistry research from 2018 to 2023 (Figure 1). For instance, the instructional materials developed and distributed by UNESCO World Decade of Education for Sustainable Development (ESD) (20052014) provided excellent support to advance green chemistry inclusion in secondary schools and universities worldwide (Zuin *et al.,* 2021). This indicates a paradigm shift in academic curriculum that radically changes traditional chemistry content for future generations. As seen in Figure 11, the current core topics in green chemistry are laboratory instruction, hands-on learning, upper-division graduates, and first-year and second-year undergraduate students conducting organic chemistry investigations, sustainability, and education. These concepts are strongly linked to green chemistry (Figure 12), indicating an increased emphasis on green chemistry inclusion to chemistry education.

Among Asian countries, China and India lead green chemistry studies and education (Table 2; Figure 6). However, Figure 7 shows that China does not collaborate with India but rather forms active links with Taiwan, Thailand, and Indonesia. In 1998, the Green Chemistry Center of The University of Science and Technology in China intensified its research on biomass conversion. In addition, Nankai University and the Ministry of Education in China offered "Green Chemistry and Sustainable Development" course. Meanwhile, Hebei University opened the "Green Chemical Technology" class (Wang, Li, & He, 2018). The Chinese Academy of Sciences at Beijing and the Green Chemistry Center at Peking University are specializing in nanoparticles catalysis (Cui, Beach, & Anastas, 2011). These efforts indicate China's intensive promotion of green chemistry practices in chemistry education (Zuin *et al.,* 2021).

Meanwhile, India's Green Chemistry Network Center (GCNC) leads the most citations in green chemistry studies (Table 3). Established in 2009, GCNC published 157 documents and conducted 179 lectures that highlight the training of academics, design of teaching materials, and promotion of intensive research on green chemistry (see https://www.gcnc.in/aboutus). Catalysis was first established as core focus implemented by India's Department of Science and Technology in 2003. Additionally, the University of Delhi established the Green Chemistry Institute which promoted green chemistry workshops for teachers. The University of Mumbai's Institute of Chemical Technologies collaborated with other Indian universities in advancing research and education in green chemistry. Such efforts influenced the University Grants Commission to create the Center for Green Technology in 2005 which focuses on innovative catalyst technology and develops educational programs and workshops in green chemistry (Yadav *et al.,* 2006). These efforts emphasize India's commitment to promote green chemistry in educational sectors.

The Philippines implemented the Green Curriculum Model in response to Republic Act 9512 and Education for Sustainable Development (Valenzuela *et al.,* 2018; Balanay & Halog, 2016). However, recent studies suggest that green chemistry inclusion to chemistry education is rather challenging. For instance, Idul and Walag (2024) found that SHS science teachers possess low awareness of green chemistry principles. Moreover, Valenzuela et al. (2018) found that most students lack awareness of chemical waste management and proper waste disposal. Moreover, Balanay and Halog's critical review of green education contended that Philippine universities still need to strengthen their international collaboration and research. In contrast, Estalilla (2022) found that most teachers feel pedagogically effective but still need further enhancement in their content knowledge of green chemistry. These findings suggest that Filipino teachers still need more professional development and international exchange programs, trainings and workshops, and advanced studies in emerging concepts in green chemistry.

On the other hand, this paper acknowledges that studies in other languages were not included in the analysis. The top journals in green chemistry are published in English, mostly dominated by the US (Figure 6). Wang *et al.,* (2023) asserted that authors publishing in non-English medium might be deprived from establishing global networks, making less contribution to the green chemistry literature and practice. Consequently, Zuin *et al.,* (2021) contended that language barrier to international literature on green chemistry tends to prevent awareness and access to green chemistry instructional

materials. Thus, academic institutions in these countries may have difficulties in designing their curriculum that infuses green chemistry.
Furthermore, this analysis was limited to articles published from 2000 to 2024. The concepts and themes prior to these years were not included in the core topics discussed. Moreover, the articles were extracted mainly from Scopus. Other databases such as Web of Science might provide robust documents in green chemistry that are relevant for bibliometric analysis.

CONCLUSION

Green chemistry was adopted by various industries to innovate greener technologies and was integrated into the curriculum to integrate greener practices in academic institutions. However, this analysis found that green chemistry studies were scanty over the first decade. Since the most prolific authors come from US and European countries, research initiatives mainly come from the funding sponsors, affiliations, and organizations in these countries. Further, these authors rarely form collaborations, leading to limited international collaboration.

The same trend emerges among countries, indicating loose international collaboration where English-speaking countries appear to dominate research initiatives. Moreover, non-English authors may have been limited from international exposure. Thus, instructional materials, pedagogies, and training were primarily focused on the Western countries, limiting the developing countries from international exchange of theoretical knowledge and applications of green chemistry.

However, it was observed that Asian countries such as China, India, Taiwan, and Indonesia are increasingly involved in green chemistry studies. Many universities and organizations in China and India have implemented various courses, training, and instructional materials in green chemistry. Still, however, these initiatives are focused on their institutional and government goals.

Even though green chemistry principles were primarily applied to chemical industries, this analysis indicates that recent green chemistry studies increasingly shifted to core topics such as laboratory instruction, hands-on learning, curriculum, education, and sustainability. Hence, current efforts seem to have shifted to the modification of the existing science curriculum to accommodate green chemistry in chemistry education.

Interestingly, the Philippine education adopted green chemistry, but it was found that educators have inadequate knowledge and lack the necessary skills to implement green chemistry practices in schools. Therefore, academic institutions need a rigid educational policy that requires serious implementation of green chemistry practices, especially in the teaching laboratories.

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