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Green Chemistry Promoting Environmental Sustainability: A Scientometric Analysis

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Abstract: ***The faster growth in this modern society eventually affect the nature for fulfilling their need. The more development in Science and Technology also have the more impact on nature. And to overcome this problem we have the solutions like Green Environment, Green Chemistry Green Synthesis, Green Energy etc. This scientometric study explores the research trend growth and fluctuation by measuring different metrics and plots the every potential contribution towards green chemistry. It also criticizes the lacuna where it should have the attention. During the study 1240 publications from 2013 to 2022 were analysed to draw the trend, potential and the depression point. A reader can know about the most active contribution, organisation, collaborative pattern, usage pattern etc. which have played the important role towards Green Chemistry Publication.***

Keyword: Green Chemistry, Scientometric, Environmental Sustainability

1. Introduction

Human progress, driven by the quest for advancement, has led to environmental challenges that threaten both individual and societal well - being. Activities like deforestation, pollution, and the disruption of ecosystems have destabilized the Earth's natural balance. While nature maintains stability through its own processes, human actions have severely impacted this equilibrium.

Green chemistry has emerged as a response to these issues, promoting environmentally friendly chemical processes that reduce waste, minimize ecological damage, and conserve resources. Traditional chemical practices, often harmful to both the environment and human health, are increasingly being replaced by more sustainable alternatives. Despite the growing importance of green chemistry, there is a lack of significant application, awareness & research quantifying the body of work in this field.

This study, “Green Chemistry Promoting Environmental Sustainability: A Scientometric Analysis, ” aims to assess scientific output on green chemistry from 2013 to 2022, addressing gaps in the literature regarding growth trends, productivity, and global research activities.

The primary objective of the study is to conduct a quantitative analysis of the research output for green chemistry promoting environment sustainability as listed in the Web of Science database (2013 - 2022).

Some specific objectives are framed with the unique idea of the current study:

- To assess the growth of research productivity for sustainable environment in the field of green chemistry during 2013 - 2022.
- To assess author productivity, authorship pattern & collaborative pattern in Green Chemistry research output.
- To determine the keyword frequency & different research area of Green Chemistry research output.
- To assess the Institution wise, journal wise, language wise research concentration on Green Chemistry research output.

2. Literature Review

Green chemistry, a field dedicated to reducing the environmental impact of chemical processes, has garnered growing attention. Scientometric studies on green chemistry, such as Khalajet et al. (2020) and Kamali et al. (2021), have applied quantitative methods to assess the advancements in green synthesis and nanomaterial fabrication. These studies highlight trends in green chemical innovations, particularly in environmentally friendly and sustainable technologies. Research by Kreuder et al. (2017) introduced a green chemistry metrics (GCM) framework to evaluate chemical processes based on sustainability criteria, while Van Schoubroeck (2018) examined sustainability indicators for biobased chemicals. Both studies emphasize the need for comprehensive metrics to assess the environmental, economic, and social dimensions of green chemistry.

Several studies have explored themes similar to the present research, particularly those focused on the scientometric analysis of green chemistry. For example, Armenda & de la Guardia (2019) conducted a scientometric review of green spectroscopy, highlighting gaps in the adoption of sustainable analytical methods. Similarly, Kreuder et al. (2017) used scientometric tools to assess chemicals and processes through the lens of the 12 principles of green chemistry. Chen et al. (2022) utilized bibliometric analysis to track research trends in grain storage technology,

identifying key contributors and emerging research areas. These studies parallel the current research's goal of mapping the scientometric landscape of green chemistry, providing a foundation for future scientific advancements in sustainability.

3. Methodology

To perform the scientometric analysis, the data was retrieved from Web of Science. The literature search was conducted on April 03, 2023 with the advanced search facility available in Web of Science search interface. The data was searched through using different Field tags, Boolean operators along with asterisk (*) and Keywords. Field tags and Boolean operators were the key function in search string along with asterisk was used to include all variant of the search term.

The search strings (including Field tag, Boolean operator, asterisk and Keyword) were: 1. (TS= ("green chemistry*")) AND ALL= (environment) 2. (TS= ("green chemistry*")) AND ALL= (sustainability) 3. ((TS= ("green chemistry*")) AND ALL= (sustainability)) AND ALL= (environment) 4. (TS= ("green chemistry*")) AND ALL= (environmental sustainability) 5. ((TS= ("green chemistry*")) AND ALL= (sustainability)) AND ALL= (environment) AND ALL= (Scientometric). Then the list of documents or data was exported from WOS in plain text file and Excel format.

For reference management zetero is used with APA 7th style.

While writing for this paper the help of AI is used for make this paper more effective regarding grammar, vocabulary & understandable language

4. Data Analysis

The output of Green Chemistry from the Web of Science database between 2013 and 2022 is used as a tool to evaluate performance at various levels. Total 2628 no. of publications are collected and analysed.

Growth Studies

AGR= (Ending value – Beginning value) / Beginning value*100

Where,

AGR= Annual Growth Rate
Ending Value= No .of Document at the Year End
Beginning value= No .of Document at the Starting of the Year

RGR=W2-W1/T2-T1

Where,

RGR= Relative Growth Rate
W1=lnw1: (Natural log of the initial number of Publications/pages)
W2=lnw2: (Natural log of the final number of Publications/pages)

DT = 0.693/R

Where,

DT= Doubling Time
R= RGR

Table 1: Yearwise Growth, RGR & Dt

S No.	Year	No. of Paper	Cumulative Paper	lnw1	lnw2	RGR	Dt
1	2013	123	123	_	4.81	_	_
2	2014	121	244	4.81	5.49	0.68	1.01
3	2015	147	391	5.49	5.96	0.47	1.46
4	2016	183	574	5.96	6.35	0.38	1.80
5	2017	182	756	6.35	6.62	0.27	2.51
6	2018	233	989	6.62	6.89	0.26	2.57
7	2019	297	1286	6.89	7.15	0.26	2.63
8	2020	350	1636	7.159	7.40	0.24	2.87
9	2021	443	2079	7.40	7.63	0.23	2.89
10	2022	549	2628	7.63	7.87	0.23	2.95
Total	2013 - 2022	2628				7.87	20.89
AVG						0.78	2.08

Source: *WoS*

Table 1 provides an overview of the annual growth in research papers on "Green Chemistry" from 2013 to 2022. The data shows a steady increase in the number of publications each year, starting with 123 papers in 2013 and rising to 549 papers by 2022.

The cumulative number of papers rose consistently from 123 in 2013 to 2, 628 by 2022, indicating a strong and growing interest in green chemistry research over the decade.

RGR measures the growth rate of scientific output over time. The RGR steadily declined from 0.68 in 2014 to 0.23 by 2022.
This declining trend indicates that the rate of new publications is slowing down, which is common as research fields mature. While the number of publications is still increasing, the growth is happening at a decreasing rate year over year.

The Dt increased from 1.01 in 2014 to 2.95 in 2022. This suggests that as green chemistry research became more established, it took longer to double the output of publications, further confirming the field's stabilization.

Table 2: Document Type wise Distribution of Publications

Sl No.	Document Type	Document No.	Percentage
1	Article	1873	71.27
2	Review	583	22.18
3	Editorial Material	57	2.17
4	Meeting Abstract	39	1.5
5	Article; Proceedings Paper	36	1.36
6	Article; Early Access	26	0.99
7	Review; Early Access	7	0.27
8	Article; Book Chapter	3	0.11
9	Review; Book Chapter	2	0.07
10	Editorial Material; Book Chapter	1	0.03
11	Letter	1	0.03
12	Total	2628	100

Source: *WoS*

Table 2 presents the distribution of document types in the dataset. The majority (71.27%) consists of "Articles, " indicating a strong focus on original research contributions. "Reviews" follow with 22.18%, reflecting the importance of synthesizing existing knowledge. Other categories, such as "Editorial Material" (2.17%) and "Meeting Abstracts" (1.5%), are less prevalent but still contribute to academic discourse. Minor categories, including "Proceedings Papers" (1.36%) and "Early Access" articles (0.99%), highlight emerging research. Niche types like book chapters and letters are rare, comprising less than 1% of the total. This distribution aligns with typical scholarly publication trends, emphasizing original research and critical review.

Language wise Distribution of Publications

Table 3: Language wise Distribution of Publications

Sl No.	Language	No. of publication	Percentage
1	English	2578	98.09
2	Chinese	33	1.25
3	Portuguese	6	0.22
4	German	4	0.15
5	Czech	2	0.07
6	Spanish	2	0.07
7	Japanese	2	0.07
8	Polish	1	0.03
Total	Language	2628	100

Source: *WoS*

Table 3 shows that 98.09% of publications are in English, reflecting its dominance as the global language of academic communication. Non - English publications, led by Chinese (1.25%), are minimal but still notable, with smaller contributions from languages like Portuguese (0.22%), German (0.15%), and others. This distribution highlights the overwhelming preference for English while recognizing some linguistic diversity in scholarly output.

Top 20 Countries in Green Chemistry Publication

Table 4: Top Countries

Sl. No.	Country	No. of Publication
1	China	570
2	Usa	469
3	India	313
4	Italy	188
5	Spain	146
6	France	138
7	England	137
8	Germany	129
9	Iran	123
10	Poland	114
11	Brazil	106
12	SaudiArabia	99
13	SouthKorea	97
14	Japan	76
15	Canada	71
16	Malaysia	69
17	Egypt	61
18	Australia	60
19	Sweden	56
20	Pakistan	55

Source: *WoS*

Table 4 reveals the top 20 proudctive countries in Green Chemistry during 2013 - 2022. China is the most productive country in Green Chemistry research Publication. India ranked at no.3 in Green Chemistry research publication.

Journal wise Distribution of Publications

Table 5: Top Journal

Sl. No.	Journal - wise Name	No. of Publication
1	Acs sustainable chemistry & engineering	139
2	Green chemistry	135
3	Journal of chemical education	98
4	Chemsuschem	58
5	Molecules	53
6	Journal of cleaner production	48
7	Current opinion in green and sustainable chemistry	41
8	Abstracts of papers of the american chemical society	37
9	Rsc advances	34
10	Sustainability	33
11	Sustainable chemistry and pharmacy	26
12	Chemistryselect	24
13	Journal of molecular liquids	24
14	Science of the total environment	23
15	Current organic chemistry	22
16	Chinese journal of organic chemistry	21
17	Angewandtechemie - international edition	21
18	Green chemistry letters and reviews	20
19	Environmental chemistry letters	18
20	Chemosphere	18

Source: *WoS*

Table 5 shows the top journals based on the number of publications in the field of sustainable chemistry.

Acs sustainable chemistry & engineering has the highest number of publications, with 139 papers. Green chemistry is the second - highest journal with 135 publications, closely following Acs sustainable chemistry & Engineering, journal of chemical education ranks third with 98 publications. Chemsuschem and Molecules hold the fourth and fifth positions with 58 and 53 publications, respectively.

The top five journals (Acs sustainable chemistry & engineering, Green chemistry, Journal of chemical education, Chemsuschem, and Molecules) have the highest number of publications, indicating their significance in the field of sustainable chemistry.

Subject Area wise Distribution in Green Chemistry Publications

Table 6: Top Subject Area

Sl. No.	Different Subject Area	No of Publication
1	Chemistry	1684
2	Science & Technology - OtherTopics	709
3	Engineering	523
4	Environmental Sciences & Ecology	349
5	Materials Science	255
6	Biochemistry & Molecular Biology	141
7	Physics	123
8	Education & Educational Research	114
9	Polymer Science	104
10	Biotechnology & Applied Microbiology	98
11	Energy & Fuels	80
12	Food Science & Technology	53
13	Pharmacology & Pharmacy	53
14	Agriculture	30
15	Electrochemistry	23
16	Toxicology	22
17	Metallurgy & Metallurgical Engineering	21
18	Water Resources	20
19	Public, Environmental & Occupational Health	18
20	Microbiology	17
21	History & Philosophy of Science	12
22	Biophysics	12
23	Plant Sciences	10
24	Spectroscopy	10
25	Crystallography	10
26	Marine & Freshwater Biology	8
27	Life Sciences & Biomedicine –Other Topics	7
28	Nuclear Science & Technology	5
29	Thermodynamics	5
30	Acoustics	5

Source: *WoS*

Table 6 reveals the top 30 subject of Green Chemistry research output. Out of 2628 documents, 1684 documents of green chemistry research belong to Chemistry followed by Science & Technology with 709 in green chemistry research. While 523 documents were published in the area of Engineering, 349and 255 documents were published in the area of Environmental Science & Materials Science respectively. The minimum number of productivity in subject areas is Thermodynamics and Acoustics with 5 publications each.

Most Prolific Author in Green Chemistry Publication

Table 7: Most Prolific Author

Ranking	Author Name	Affiliation	No. of Publication
1	Anastas PT	Yale Univ, Dept Chem, New Haven	25
2	ZimmermanJB	Yale Univ, SchForestry & Environm Studies, New Haven	24
3	Brooks BW	Baylor Univ, Dept Environm Sci, Waco	18
4	Arico F	CaFoscari Univ, Dept Environm SciInformat & Stat	16
5	AnilkumarG	Mahatma Gandhi Univ, Adv Mol Mat ResCtrAMMRC, Priyadarsini Hills	14
6	Clark JH	UnivYork, DeptChem, Green Chem Ctr Excellence	14
7	Wang Y	Shanghai Univ, SchEnvironm & ChemEngn,	13
8	KummererK	Univ Luneburg, InstSustainable & EnvironmChem	12
9	Varma RS	Palacky Univ Olomouc, Reg Ctr Adv Technol & Mat	11
10	Namiesnik J	Gdansk Univ Technol, Fac Chem, Dept Analyt Chem	10
11	Sneddon HF	Glaxo Smith Kline, Green Chem Performance Unit	10
12	Sheldon RA	Delft Univ Technol, Julianalaan	10
13	Kumar A	Lovely Profess Univ, Dept Chem	10
14	Gallou F	Novartis Pharma AG, Chem & Analyt Dev	10
15	Tsang DCW	Hong Kong Polytech Univ, Dept Civil & Environm Engn	9
16	Hessel V	Univ Warwick, SchEngn	9
17	Allen DT	KTH Royal Inst Technol, Wallenberg Wood SciCtr	9
18	Kumar S	Guru Jambheshwar Univ Sci & Technol, Dept Bio & Nano Technol,	9
19	Zhang J	Hebei UnivSci & Technol, Coll Chem & Pharmaceut Engn	9
20	Kumar P	Kurukshetra Univ, Dept Chem	9

Source: *WoS*

Table 7 reveals that Anastas PT is the most productive authors with 25 publication in Green Chemistry research output followed by Zimmerman JB with 24 publication, Brooks BW with 18 publication and Arico F has 16. Only these four authors have contributed more than 15publication in Green Chemistry research. Anilkumar G have produced 14 documents which is tracked by Clark JH and Yang Y have supplied 13 documents respectively. In top 20 authors, the least number of contributions was given by six authors as Tsang DCW, Hessel V, Allen DT, Kumar S, Zhang and Kumar P with 9 publication respectively.

Top 20 Keywords of Green Chemistry Publication (2013 - 2022)

Table 8: Top Keyword

S. No.	Keyword	No. of Record
1	Green Chemistry	1111
2	Sustainability	213
3	Catalysis	67
4	Green synthesis	61
5	Sustainable chemistry	57
6	Heterogeneous catalysis	48
7	Nano particles	46
8	Ionic liquids	46
9	Life cycle assessment	44
10	Bio catalysis	37
11	Biomass	35
12	Environmental Chemistry	33
13	Photo catalysis	33

14	Circular economy	32
15	Systems Thinking	32
16	Synthesis	31
17	Laboratory Instruction	31
18	Curriculum	30
19	Adsorption	30
20	High School/Introductory Chemistry	28

Source: *WoS*

The table highlights "Green Chemistry" as the dominant keyword with 1, 111 records, followed by "Sustainability" (213), reflecting the central focus on environmentally friendly practices. Other key themes include "Catalysis" (67), "Nanoparticles" (46), and "Life Cycle Assessment" (44), indicating a strong interest in efficient catalysts and sustainability assessments. Emerging topics like "Circular Economy" (32) and educational keywords such as "Laboratory Instruction" (31) suggest a growing emphasis on holistic sustainability approaches and integrating green chemistry into education.

Most Productive Affiliation in Green Chemistry Publication

Table 9: Most Productive Affiliation

Sl. No.	University Name	No. of Publication
1	Taif University	78
2	Isfahan University of Technology	72
3	NationalTaipei University of Technology	58
4	Texas A & M University College Station	52
5	Institute of Fuel Research & Development (IFRD)	51
6	Wichita State University	41
7	Annamalai University	40
8	Ural Federal University	40
9	Universidadeda Coruna	33
10	Indian Institute of Technology (IIT) – Kharagpur	32
11	University of Nizwa	31
12	Universitatd' Alacant	28
13	Saha Institute of Nuclear Physics	28
14	Hamburg University of Technology	27
15	Institute for Molecular Science (IMS)	27
16	Istituto per lo Studiodei Materiali Nanostrutturati (ISMN - CNR)	26
17	Ibn Tofail University of Kenitra	23
18	Medical University of Bialystok	23
19	Alagappa University	22
20	Kaunas University of Technology	22

Source: *WoS*

Table 9 reveals that Taif University leads in publications (78), followed by Isfahan University of Technology (72) and National Taipei University of Technology (58), indicating strong research contributions. The representation of universities from diverse regions, including Asia, the US, and Europe, highlights a global interest in the field. Institutions such as Texas A&M University (52) and the Institute of Fuel Research & Development (51) show similar outputs, suggesting potential research clusters. Specialized contributors like the Saha Institute of Nuclear Physics (28) and emerging universities like Alagappa University (22) indicate a broadening landscape of research activity.

Year wise distribution of Authorship pattern

Table 10: Growth of Authorship Pattern

Year	Single Author	Double Author	3 Author	4 Author	5 Author	More Than 5Author	Total No. of Publication
2013	11	20	17	16	18	41	123
2014	8	12	17	26	21	37	121
2015	7	18	24	23	20	55	147
2016	19	29	32	24	31	48	183
2017	17	18	28	25	25	69	182
2018	12	40	31	38	28	84	233
2019	19	30	46	37	50	115	297
2020	14	46	48	60	51	131	350
2021	20	64	67	80	53	159	443
2022	23	55	95	103	67	206	549
Total	150	332	405	432	364	945	2628

Source: *WoS*

Table - 10 shows the year - wise authorship pattern of world green chemistry research output during 2013 - 22022. The number of single author publications shows a fluctuating trend with ups and downs. The number of single authored publications was 11 in 2013, 08 in 2014, 7 in 2015, 19in 2016, 17 in 2017, 12 in 2018, 19 in 2019, 14 in 2020, 20 in 2021 and 23 in 2022.

This fluctuation was visible throughout the study period. In the case of joint authored, three authored, four authored, five authored, more than five authored publications too, we could observe an incessant increase in the whole period of publications on world green chemistry research output. This increasing trend shows the growing interest of the green chemistry researchers to work in medium - large teams.

Year Wise Citation Count on Green Chemistry Publication

Table 11: Year wise Citation

Sl. No.	Year	Total Cited Reference of published item	Total No. of Record	Avg. citation Count per Publication
1	2013	6515	123	52.96
2	2014	7221	121	59.67
3	2015	9429	147	64.14
4	2016	11214	183	61.27
5	2017	12234	182	67.21
6	2018	16657	233	71.48
7	2019	19863	297	66.87
8	2020	26528	350	75.79
9	2021	38588	443	87.10
10	2022	46402	549	84.52
Total	2013-2022	194651	2628	74.06

Source: *WoS*

Table 11 shows a consistent increase in total citations from 6, 515 in 2013 to 46, 402 in 2022, indicating growing recognition of research in this field. Publication records peaked at 549 in 2022, while the average citation count per publication reached its highest in 2021 at 87.10, although it declined slightly to 84.52 in 2022. This fluctuation suggests that while the volume of research has increased significantly, it may have diluted the average impact of individual publications. Overall, the data reflects an evolving research landscape with heightened engagement and visibility over the years.

Co - authorship Visualisation

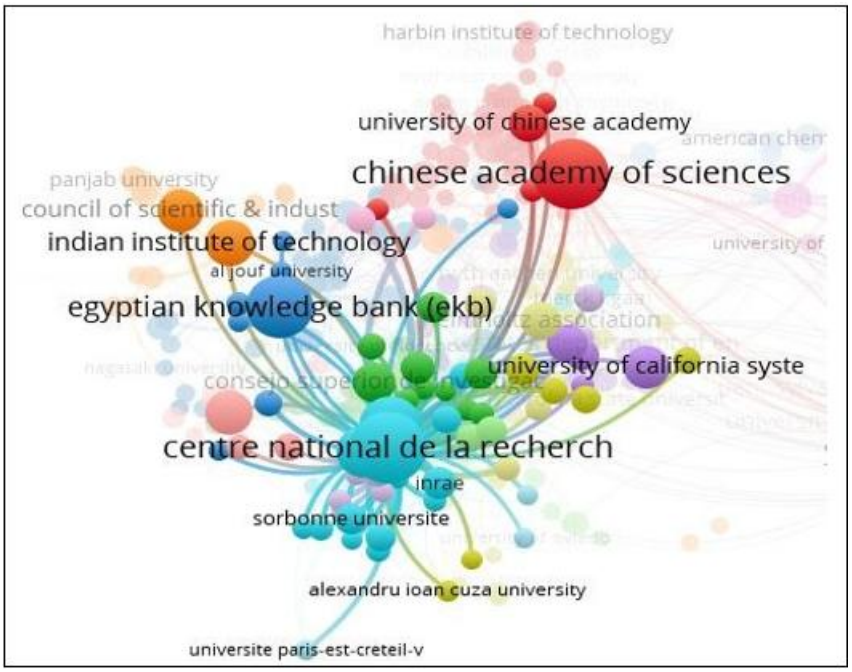

Figure 1: Co - Authorship Visualization

The network visualization shows the Co - Authorship among the Organization in Green Chemistry Output. Many of the University in China, Iran, Saudi Arabia have impressive no. of co - authorship among their national universities. Also the Authors from different Organization and different countries including India have great no. of Co - Authorship in Green Chemistry Research Output. In case of Indian Universities the Co - Authorship between Indian Universities is very less as compared to other listed countries.

Visualization of International Collaboration

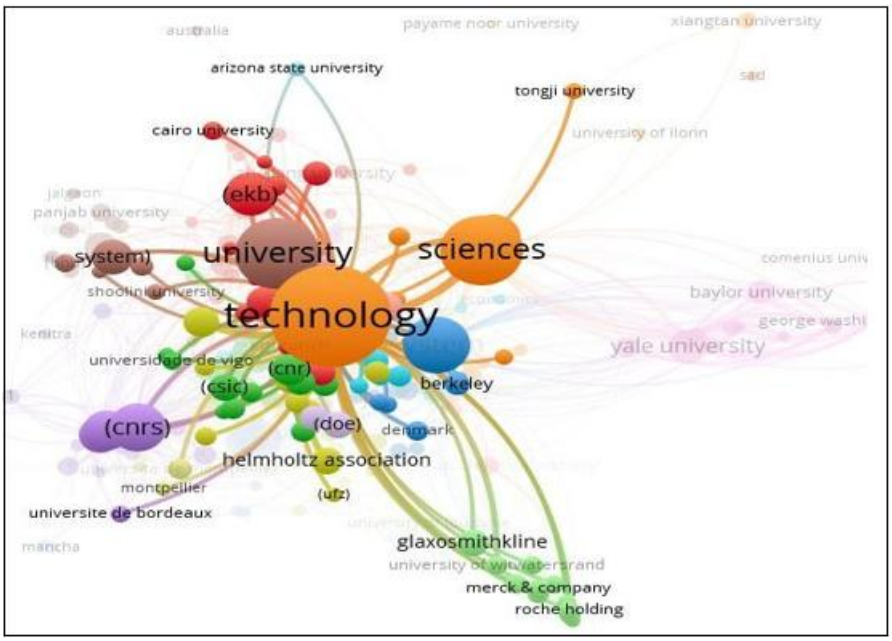

Figure 2: Visualization of International Collaboration

The network visualization from figure 2 shows the international collaboration between the institutions in which all the technology related institutions have most no. of collaboration in the field of Green Chemistry then

Universities & Science institutions are next to technology - based institutions.

5. Findings

During the study it is found that when the RGR is decreasing, the Doubling Time is increasing, it indicates that the Green chemistry research output experienced a decreasing relative growth rate over the years, accompanied by an increasing doubling time, which signifies a slower pace of growth in the field.

The study provided articles being the most prevalent type, followed by reviews. China is the most productive country in Green Chemistry research publication during the period of 2013 - 2022. India is ranked at number 3 among the top 20 productive countries in Green Chemistry research publication. Acs sustainable chemistry & engineering is the top journal in the field of sustainable chemistry, with the highest number of publications (139 papers). The distribution of Green Chemistry research output across various subject areas, with Chemistry and Science & Technology leading the way, while Thermodynamics and Acoustics have the lowest number of research publications. The research productivity of highly prolific authors in Green Chemistry, with Anastas PT and Zimmerman JB leading the way. Researchers commonly employ the keywords like 'Green Chemistry', 'Sustainability', 'Catalysis', 'Green Synthesis' to describe and categorize their work, indicating their importance and relevance within the field. The research productivity of various affiliations in Green Chemistry, with Taif University and Isfahan University of Technology leading the way. The authorship patterns in Green Chemistry research, showcasing a mix of single - author contributions, as well as collaborations involving two, three, four, and five authors. Additionally, the significant proportion of contributions involving more than five authors highlights the collaborative nature of research in the field.

A general increase in the average citation count per record over the years, with notable growth in 2021. This suggests a growing recognition and impact of Green Chemistry research, as reflected in the increasing number of citations received by the publications in this field (Aksnes et al., 2019).

The collaborative nature of Green Chemistry research, with a majority of publications involving multiple authors. It also indicates the increasing trend of collaboration over time, reflecting the importance of teamwork and interdisciplinary research in advancing the field (Iles & Mulvihill, 2012b).

The international nature of collaborations in Green Chemistry research, with universities and organizations from various countries actively participating in co - authorship. It also emphasizes the importance of technology - related organizations in driving collaborative research in the field (Iles & Mulvihill, 2012b).

During the preparation of this work the authors used Chatgpt in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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