Elucidating Carbon Dot Research Coupled with Bibliometric Analysis

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Abstract

Two decades have gone by since the discovery of carbon dots (CDs) and a lot of research on CDs has been published. However, still, there is no comprehensive overview of how this research has evolved and to which direction it is going. Herein, with the power of big data analytics, an attempt was made to illuminate the journey of CD research. A total of 24599 publications from the Web of Science Core Collection for the period of 2004 – 2024 were studied with Biblioshiny and VOSviewer coupled with manual studies. The included publications originate from 115 countries, ~8K institutions, and ~66K authors. China produced ~50% of the publications. The Chinese Academy of Science appeared as the most productive institution. Authors with nine or more publications emerged as the core authors. Publications were categorized as per the United Nations Sustainable Development Goals. Synthesis (green synthesis, facile synthesis, hydrothermal synthesis), sensing, photoluminescence, photocatalysis, composites, drug delivery, bioimaging, etc. appeared as the hot research topics on CD.

Keywords: graphene quantum dot, carbon quantum dot, performance analysis, science mapping, review

1. Introduction

Carbon dots (CDs) are quasi-spherical zero-dimensional fluorescent carbon nanoparticles with a usual size of <10 nm. Abundant raw materials, inexpensive and facile synthesis, tuneable photoluminescence, negligible photobleaching, decent water dispersibility, good biocompatibility, etc. are considered as the advantages of CD.[1] It was discovered in the year 2004 at the University of South Carolina, USA.[2] Since then two decades have gone and a lot of research articles have been published on CD. Nearly a dozen synonyms of CD have come out.[3] Enormous varieties of raw materials, and a dozen of synthesis methods, have been exercised in numerous potential applications.[1, 4, 5] Bioimaging, sensing, drug or gene delivery, photodynamic therapy, catalysis, light-emitting diodes, batteries, food packaging, anti-counterfeiting, lubricants, etc. are only a few examples.[3] Measuring the impact of such an emerging research domain is imperative to comprehend its direction of research.

Bibliometric analysis is an analytical technique that quantitatively measures scholarly publications through performance analysis and science mapping.[6, 7] Performance analysis evaluates productivity (publications) and impact (citations) of research (articles) and contributors (countries, institutions, authors, funders); while science mapping unveils key themes, patterns, trending topics, and research gaps in the field.[6, 8, 9] As a form of big data analytics, bibliometrics employs algorithms (e.g., clustering, network metrics) to analyse and report complex data in an objective manner.[6] Usually, the scientific scholarly research data was collected from databases such as Web of Science, and Scopus.[10] The collected data is often massive and almost impractical and inefficient to analyse manually. The advent of bibliometric software such as Bibliometrix in R, Bibexcel, Gephi, VOSviewer, etc. has made this feasible.[8] The cumulative scientific knowledge and evolutionary nuances of a particular research field can be structured to gain a one-stop overview.[11] In other words, bibliometric analysis can elucidate the foundations of advancing a field in a novel and meaningful way.[8] Recently, a few publications have demonstrated a few areas of CD research through bibliometric analysis.[12, 13] However, there are still no systemic studies, and in-depth analysis of CD research through bibliometrics. For systemic bibliometric analysis, the collected bibliometric data need to be polished, and the results should be interpreted, rather than a mere description of results.[6]

Herein, for the first time, CD research was elucidated with the power of advanced analytics of bibliometric software. Biblioshiny, the shiny app for bibliometrix,[14] and VOSviewer[15] was used for the bibliometric analysis. The data was collected from the Web of Science Core Collection. As bibliometric data sometimes may be ambiguous, manual interpretation was coupled to the bibliometric analysis to explore the true potential of this advanced technology. The data was analysed in terms of annual growth of publications, productivities of countries, institutions, authors, and journals, publications and references, domain of publications, and keywords (word cloud, trend topics, thematic map, keywords co-occurrence clustered network) that generated a holistic view of CD research. The

development of CD research was illustrated with a few three-field Sankey plots. Finally, A brief note was written on the factual state of CD research. Overall, a systemic overview of the evolution of CD research was illustrated.

2. Methods

2.1 Data collection

The research procedures for bibliometric analysis comprise four-step methods that include the determination of search keywords, refinement of the search results, compilation of the preliminary data, and data analysis. The data was collected on 24th December 2023 from the Web of Science Core Collection using the phrases TS = ("carbon dot*" OR "graphene quantum dot*" OR "carbon quantum dot*"). The search results were then refined as depicted through the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram (**Figure 1)**.[16] The retrieved publications were downloaded in plain text format that included full records and cited references for analysis with the bibliometric software.

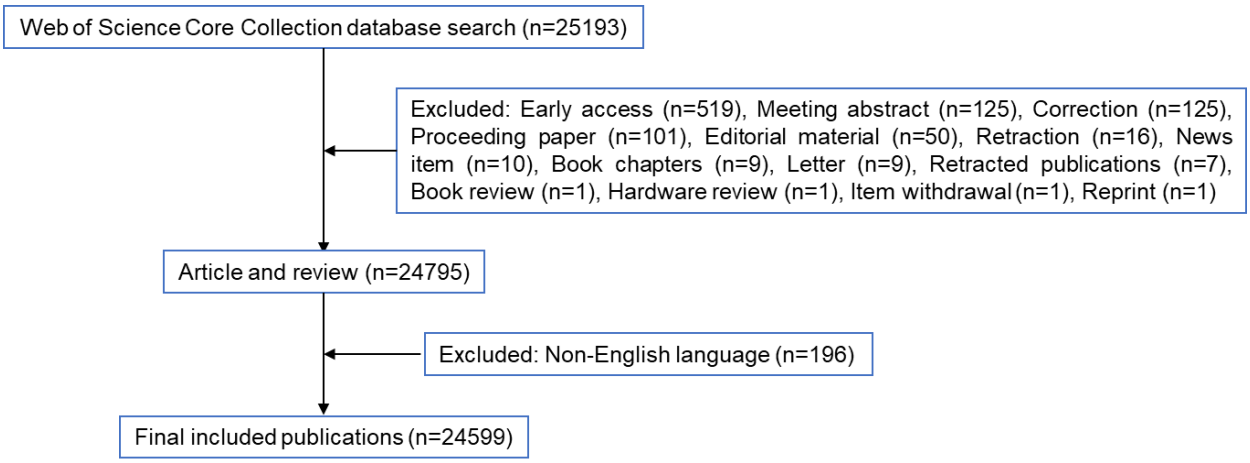

Figure 1. PRISMA diagram depicting the collection and refining of data.

2.2 Data analysis

The bibliometric data was analysed with two bibliometric software. Biblioshiny in an interface of RStudio version 4.3.3 with installed bibliometrix package version 4.2.0 was used to extract and analyze the data in various possible ways.[14] The results were exported as Excel files. VOSviewer 1.6.20 was another bibliometric software used in this study.[15, 17] MS Excel (Microsoft 365) was often used to plot the analysed results.

3. Results and Discussions

A total of 24599 publications from the Web of Science Core Collection with a time span of 2004 – 2024 were studied.

3.1 Publications and Annual Growth

The yearly growth in CD research was analysed through Biblioshiny based on the publication year of the articles. In the initial years after its discovery in the year 2004, the growth in the number of publications was found very slow. The number of publications has grown exponentially in the last 10 years (**Figure 2**). Notably, the CD has a much lower number of total publications as compared to its nano-carbon coeval graphene (**Figure S1**).[18] However, with an annual growth rate of 29.93% in the number of publications, CD has attracted decent attention from the researchers.

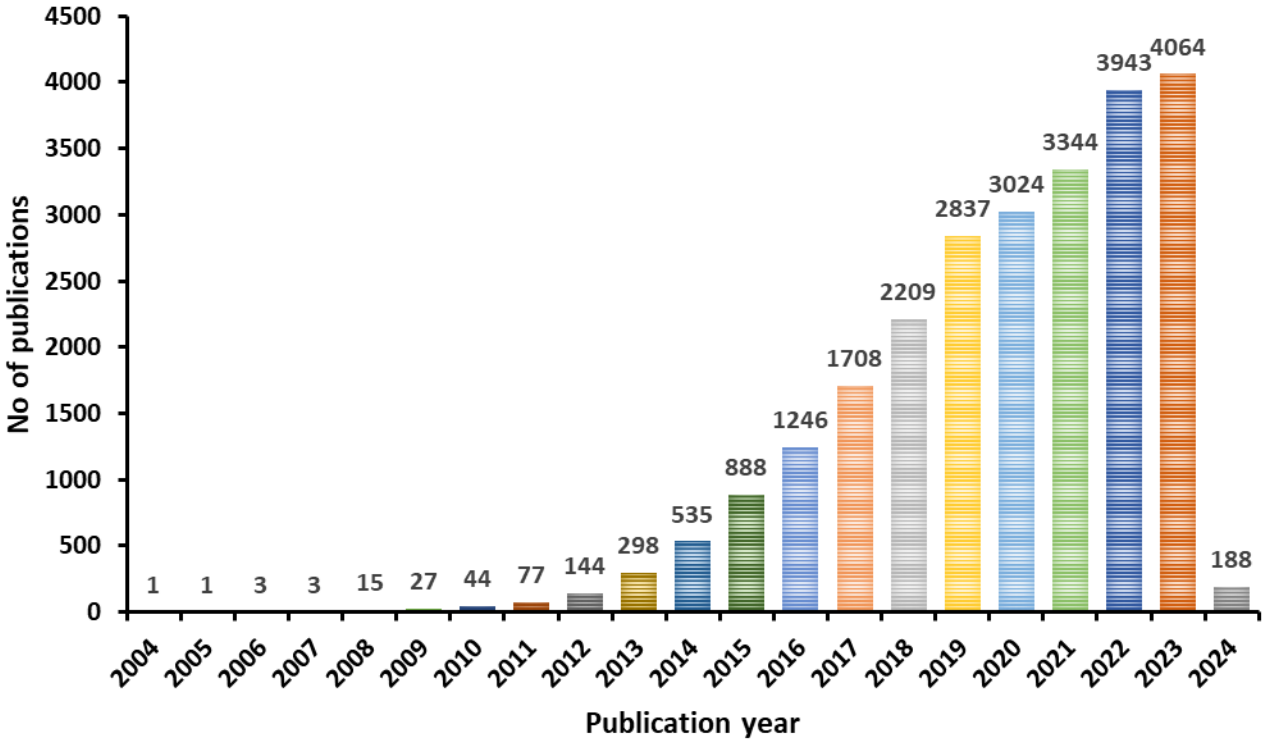

Figure 2. The number of publications on CD research over the years.

3.2 Countries

The included publications comprise of 66651 authors from 8191 organizations in 115 countries as analysed through VOSviewer. China published the highest number of publications (n=14982, 48.00%), followed by India (n=2915, 9.34%), and the USA (n=1796, 5.75%) (**Figure 3, Table 1, Table S1**). The countries' production over time that

Biblioshiny analyzed, showed that the publications from China are the major contributing factors behind the exponential growth in publications in the last 10 years (**Figure S2**). In terms of the total no of citations, China (51.42%) tops the list, followed by the USA (9.52%), and India (6.58%) (**Figure S3, Table 1, Table S1**). Interestingly, average citations analysis revealed Singapore (91.37) at the top followed by Wales (81.04), and the Czech Republic (67.29) (**Figure S4, Table 1, Table S1**). In this list, the USA (62.77), China (40.64), and India (26.74) are in the 4th, 23rd, and 41st positions, respectively.

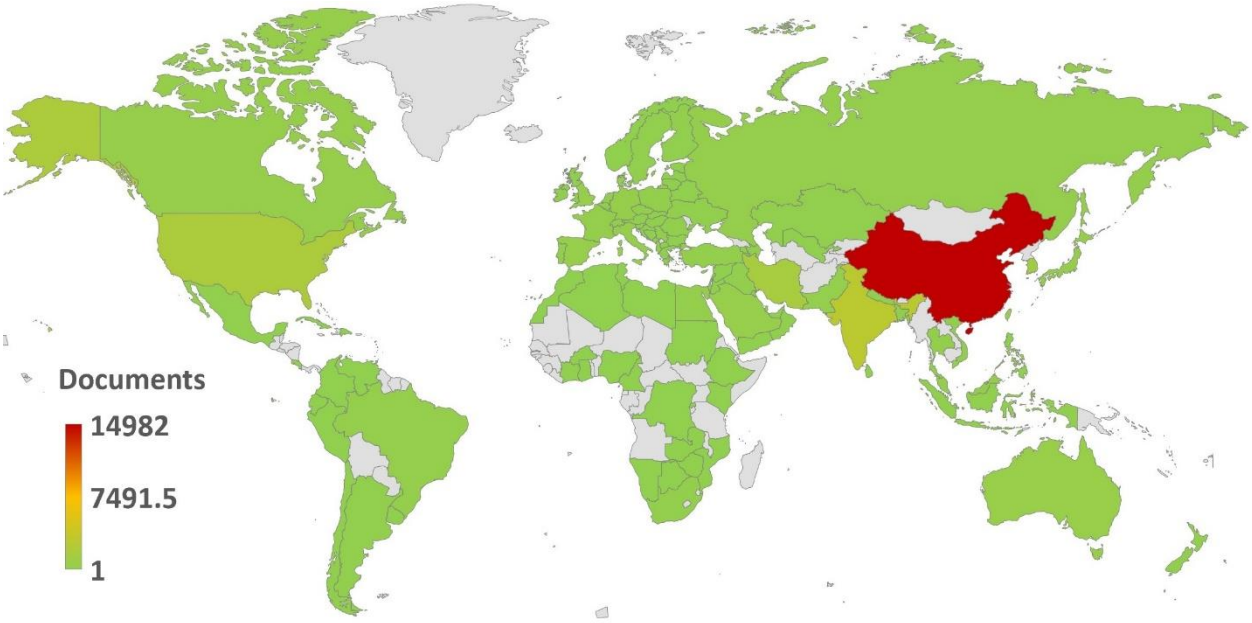

Figure 3. World map based on the number of publications.

Table 1. Top ten countries and publications.

Rank	Country	Total no of publications	Publications %	Country	Total no of citations	Citations %	Country	Average citations
1	China	14982	48.00	China	608821	51.42	Singapore	91.37
2	India	2915	9.34	United States	112737	9.52	Wales	81.04
3	United States	1796	5.75	India	77948	6.58	Czech Republic	67.29
4	Iran	1499	4.80	South Korea	40813	3.45	United States	62.77
5	South Korea	1155	3.70	Iran	37924	3.20	Switzerland	61.23
6	Taiwan	575	1.84	Singapore	27045	2.28	Austria	54.68
7	Australia	473	1.52	Australia	24912	2.10	Germany	53.83
8	Saudi Arabia	413	1.32	Germany	19701	1.66	Netherlands	53.83

9	Spain	403	1.29	United Kingdom	19063	1.61	Nepal	53.00
10	Italy	386	1.24	Taiwan	17803	1.50	Australia	52.67

3.3 Institutions

The bibliographic coupling analysis of institutions was performed through VOSviewer and represented through a density visualization map of the top 100 institutions based on the total link strength (**Figure 4**). The map was generated in rainbow colouring and front size variation format, where the red colour and larger front size denotes most productive institutions. Chinese Academy of Sciences was found as the most productive institution followed by Jilin University (**Table S2**), both of which are from China.

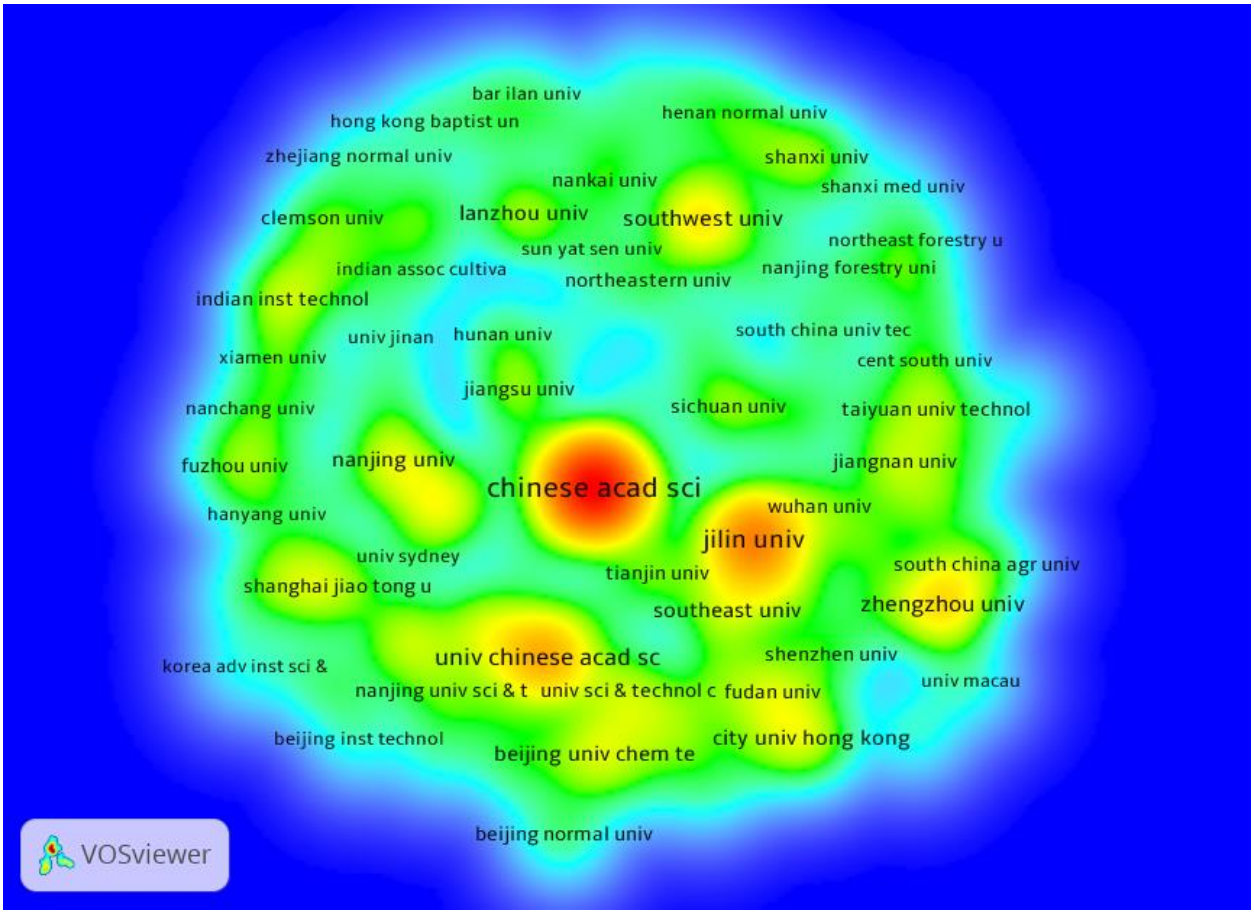

Figure 4. Density visualization map of the top 100 institutions based on the total link strength.

3.4 Authors

Productivity of author's were analysed by Biblioshiny based on Lotka's law, that describes the frequency of publications by authors in any given field (**Figure 5A**). Regarding CD research, authors who have written nine or more number of publications comes in the

core authors list (i.e., within 1% proportion of authors). MCP (multiple countries publication) is a measure of the international collaboration strength of a country. Herein, countries with at least 100 numbers of publications were considered for the MCP:SCP (SCP is single country publication) analysis (**Figure 5B**). United Kingdom tops the list with an MCP:SCP ratio of 0.637, followed by France (0.620) and Australia (0.563). Two topmost productive countries on CD research, China and India have comparatively low international collaboration with MCP:SCP scores of 0.130 and 0.169, respectively.

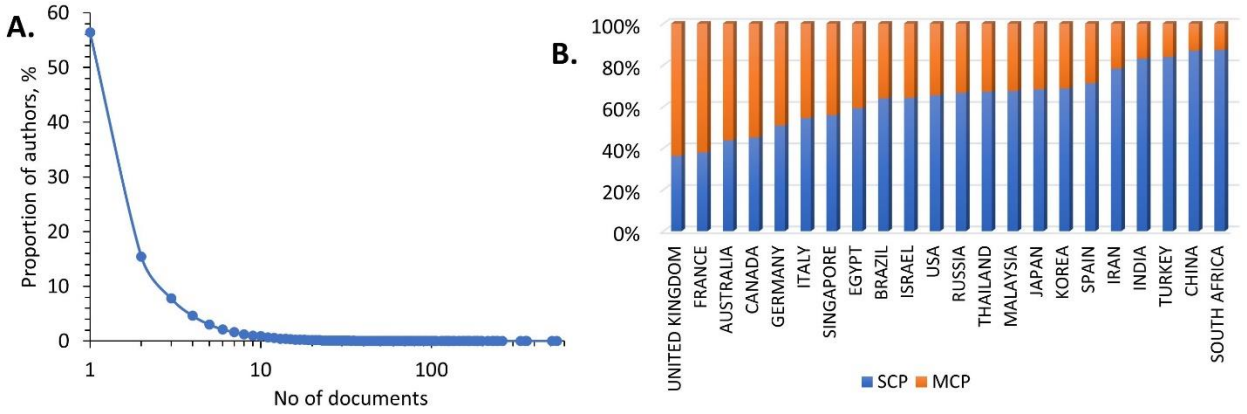

Figure 5. A. Author productivity based on Lotka's law. **B.** Countries with the highest MCP:SCP ratio.

3.5 Journals

More than 1200 journals have published research on CD and analyzed through VOSviewer. The bibliographic coupling analysis of journals was represented through a density visualization map of the top 100 journals based on the total link strength, where the red colour and larger font size of the journal name indicate the most apposite journals (**Figure 6**). **Table 2** lists the top 10 journals, and **Table S3-S5** lists the top 100 journals in terms of the number of publications, number of citations, and h-index. RSC Advances, Nanoscale, Sensors, and Actuators B: Chemical, and ACS Applied Materials & Interfaces appeared as the most relevant journals.

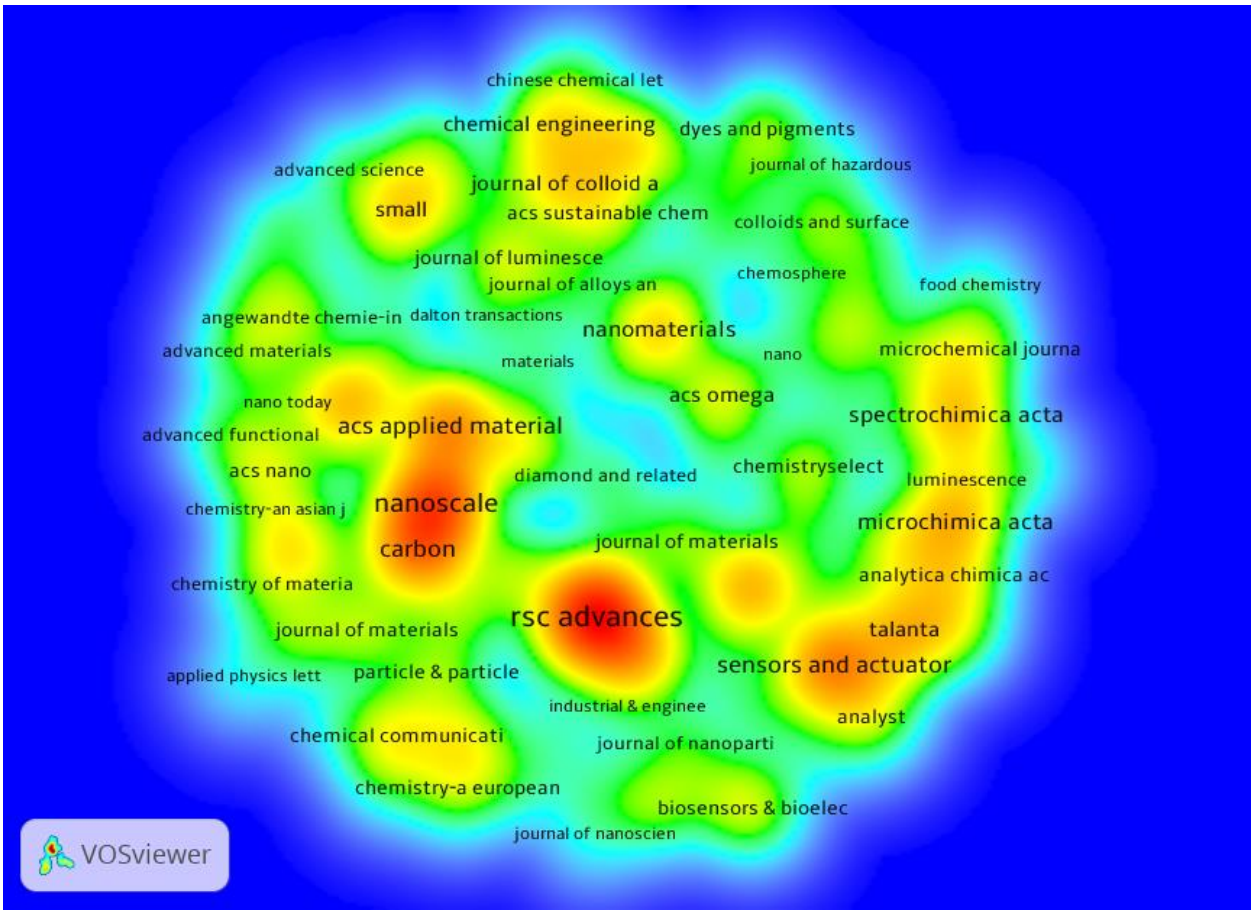

Figure 6. Density visualization map of the top 100 journals based on the total link strength.

Table 2. Top 10 journals and publications.

Rank	Journals	No of publications	Journals	No of citations	Journals	h-index
1	RSC advances	841	ACS applied materials & interfaces	41147	Nanoscale	101
2	Sensors and actuators B chemcial	702	Journal of the american chemical society	41055	ACS applied materials & interfaces	99
3	ACS applied materials & interfaces	560	Angewandte chemie-international edition	39304	Biosensors & bioelectronics	88
4	Michrochimica acta	508	Sensors and actuators B chemical	36492	Sensors and actuators B chemical	87
5	Spectrochimica acta part a-molecular and	490	Advanced materials	36285	Carbon	84

	biomolecular spectroscopy						
6	Nanoscale	486	Nanoscale	35897	Analytical chemistry	79
7	New journal of chemistry	421	Chemical communications	34647	ACS nano	75
8	Chemical engineering journal	399	Analytical chemistry	32162	Chemical communications	72
9	Carbon	384	ACS nano	30324	RSC advances	72
10	Talanta	361	Biosensors & Bioelectronics	29205	Applied catalysis B environmental	71

3.6 Publications and References

A total of 24599 publications and 573308 references were studied with Biblioshiny. The top 10 cited documents as per total global citations (**Table 3**) and total local citations (**Table S6**) were listed. The global citations are a measure of the number of citations of a document as per the entire Web of Science database. Whereas the local citations are a measure of the number of citations received by a document from the documents included in the analyzed collection. Notably, the pioneering publication by Sun *et al.* in the year 2006 tops the list of most cited documents.[19]

Table 3. Top 10 global cited publications.

Rank	Paper	Title	DOI	Total global Citations
1	SUN YP, 2006, J AM CHEM SOC	Quantum-sized carbon dots for bright and colorful photoluminescence	10.1021/ja062677d	3688
2	LIM SY, 2015, CHEM SOC REV	Carbon quantum dots and their applications	10.1039/c4cs00269e	3370
3	ZHU SJ, 2013, ANGEW CHEM INT EDIT	Highly photoluminescent carbon dots for multicolor patterning, sensors, and bioimaging	10.1002/anie.201300519	3265
4	PAN DY, 2010, ADV MATER	Hydrothermal route for cutting graphene sheets into blue-luminescent graphene quantum dots	10.1002/adma.200902825	2327
5	LI HT, 2012, J MATER CHEM	Carbon nanodots: synthesis, properties and applications	10.1039/c2jm34690g	2179
6	LI HT, 2010, ANGEW CHEM INT EDIT	Water-soluble fluorescent carbon quantum dots and photocatalyst design	10.1002/anie.200906154	2160

7	ZHU SJ, 2015, NANO RES	The photoluminescence mechanism in carbon dots (graphene quantum dots, carbon nanodots, and polymer dots): current state and future perspective	10.1007/s12274-014-0644-3	1958
8	LI Y, 2012, J AM CHEM SOC	Nitrogen-doped graphene quantum dots with oxygen-rich functional groups	10.1021/ja206030c	1948
9	PENG J, 2012, NANO LETT	Graphene quantum dots derived from carbon fibers	10.1021/nl2038979	1912
10	CAO L, 2007, J AM CHEM SOC	Carbon dots for multiphoton bioimaging	10.1021/ja073527l	1846

Reference publication year spectroscopy is a scientometrics method that emphasizes years when relatively significant findings on the concerned research field have been published.[20] **Figure S5** indicates that within the year 2012 – 2020, the research on CD has grown most significantly peaking in the year 2018.

3.7 Domain of the Publications

The publications were analyzed in terms of different Web of Science subject categories, and appeared mostly in the material science, chemistry, nanotechnology, and applied physics domain (**Figure 7, Table S7**).

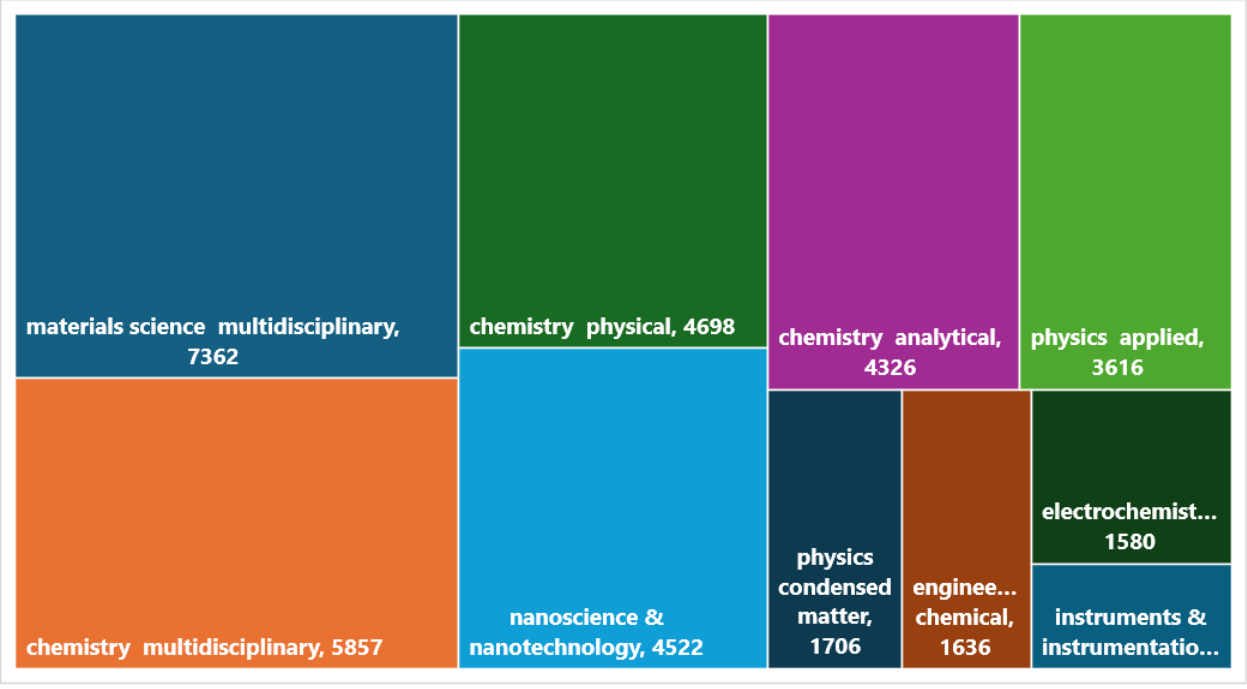

Figure 7. Publications in different Web of Science categories.

In the year 2015, the United Nations (UN) has adopted 17 Sustainable Development Goals (SDGs) addressing global economic, environmental, and social issues, and this has also influenced the core of academic research.[21, 22] Herein, the publications were categorized following the UN SDGs (**Figure 8**). 3,078 publications (12.513%) do not contain data in the field being analyzed, and hence, cannot be added to any category of the SDGs. Notably, the majority of the publications (17,270, 70.21%) are in the Good Health and Well Being category, followed by Clean Water and Sanitation (1991, 8.09%), Affordable And Clean Energy (1322, 5.37%), and Sustainable Cities And Communities (906, 3.68%).

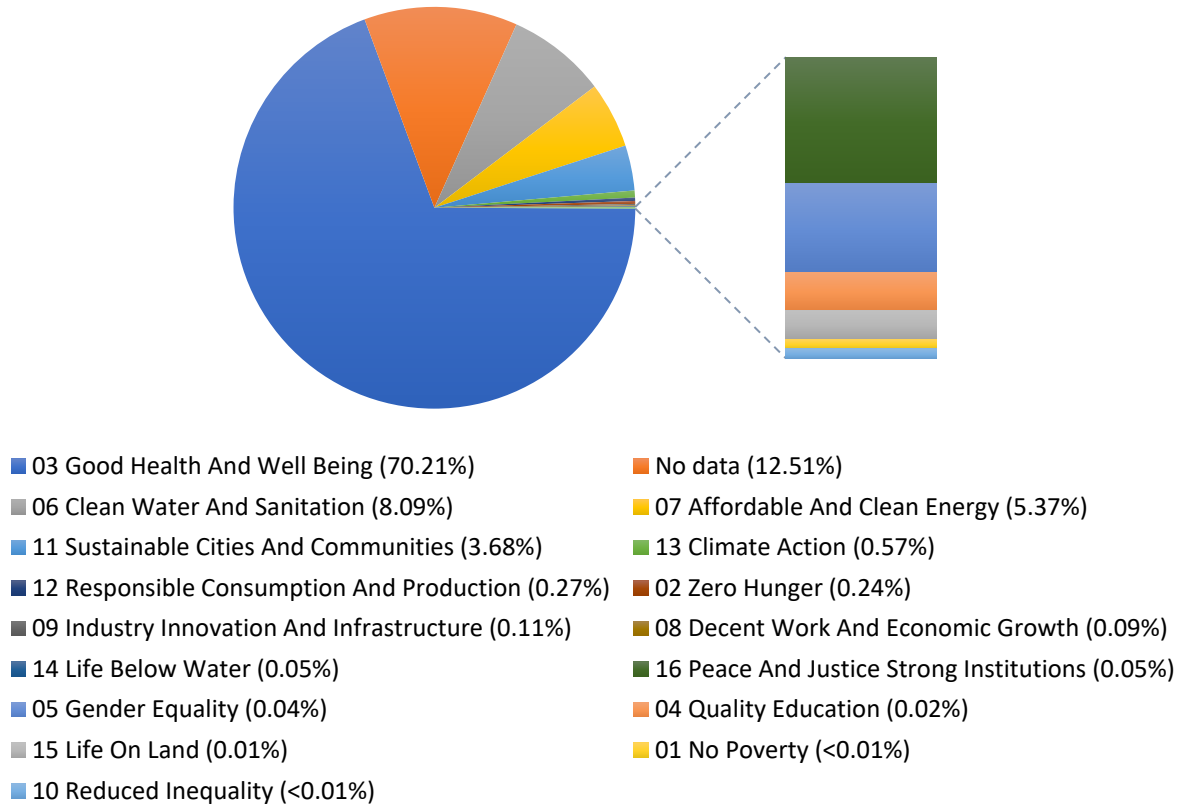

Figure 8. Publications on the category of United Nations SDGs.

3.8 Keywords

Investigating the keywords of publications can unveil the research directions of the concerned field. For analysing the keywords, herein, the Author Keywords, and Keywords Plus have been considered. Author Keywords are terms created by the authors to represent the core concept of their paper.[23] Keywords Plus are words or phrases that appear frequently in the title of the article's references and not necessarily in the article's title or as Author Keywords. Although Keywords Plus are less specific descriptors of the

article's content in comparison to the Authors Keyword, they have the advantage of being a larger quantity of terms and their broader meanings.[24] In this study, the Author Keywords data quality is poor with 27.04% missing data. Hence, Keywords Plus were used unless specified. The synonyms are merged into the term with most occurrences.

The word cloud is a visual representation of text metadata, where greater prominence is given to the words that appear more frequently in the concerned text. Herein, word cloud was created using Biblioshiny and synonyms were merged. Notably, topics (top ten) like sensor, graphene quantum dots, photoluminescence, nanoparticles, quantum dots, nanodots, facile synthesis, nitrogen, green synthesis, and oxide appeared prominent in the word cloud (**Figure 9**).

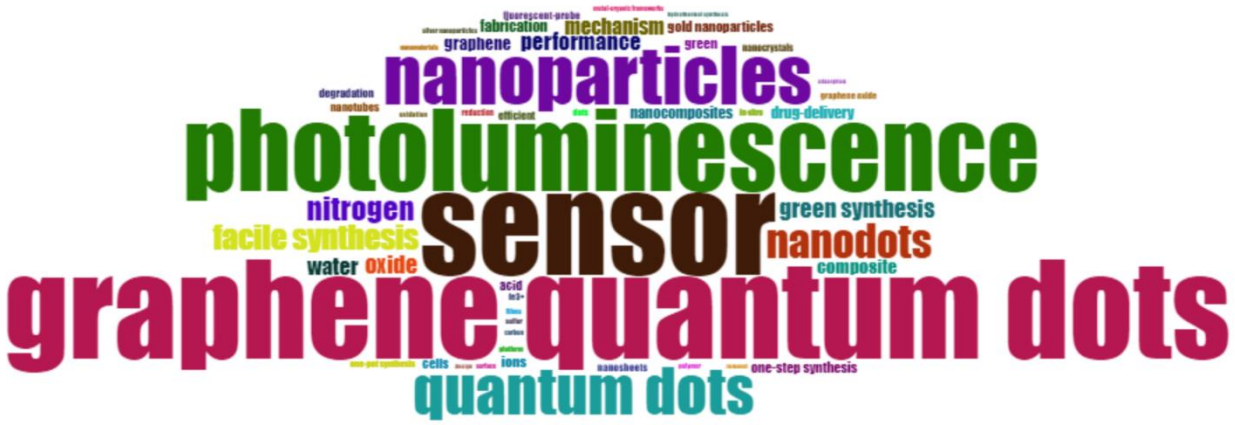

Figure 9. Word cloud based on Keywords Plus.

The trend topics were analysed through Biblioshiny based on Author Keywords, and Keywords Plus (**Figure 10, Figure S6**). It portrays topics like graphene quantum dots, photocatalysis, fluorescent probes, green synthesis, adsorption, antibacterial, electrochemical sensing, active packaging, etc. are the latest trends.

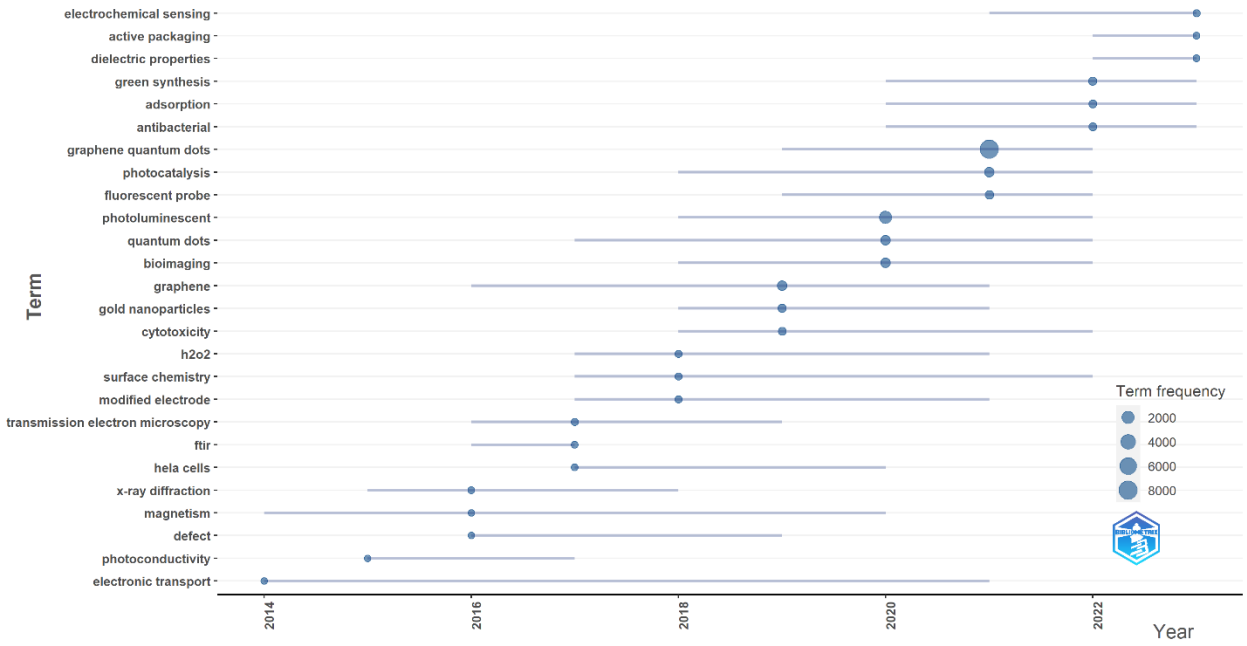

Figure 10. Trend topics analysis based on Author Keywords.

By applying clustering algorithms, the keywords network can be mapped in a two-dimensional strategic diagram that highlights different themes of the concerned study. In the thematic map, the centrality indicates the importance of the theme in the concerned whole research field, whereas the density signifies the theme's development.[25] The four quadrants of the thematic map consist of niche themes (well-developed, but less important for the concerned research field), emerging or declining themes (weakly developed and marginal importance for the field), basic themes (important, but not developed), and motor themes (well developed and most relevant to the concerned research field).[26] In the map, each bubble represents a cluster in which keywords with higher occurrence values appear. The bubble size is proportional to the cluster keywords occurrence, while the bubble position is determined according to the centrality and density. The thematic map revealed topics like sensors, photoluminescence, quantum dots, nanodots, and facile synthesis are well-developed and moderately relevant to the CD research (**Figure 11**). Areas like performance, composite, nanocomposites, fabrication, and degradation appeared somewhat developed but less important to CD research. Whereas topics like graphene quantum dots, nanoparticles, oxide, water, and mechanism formed the basis of the CD research that is yet to develop well.

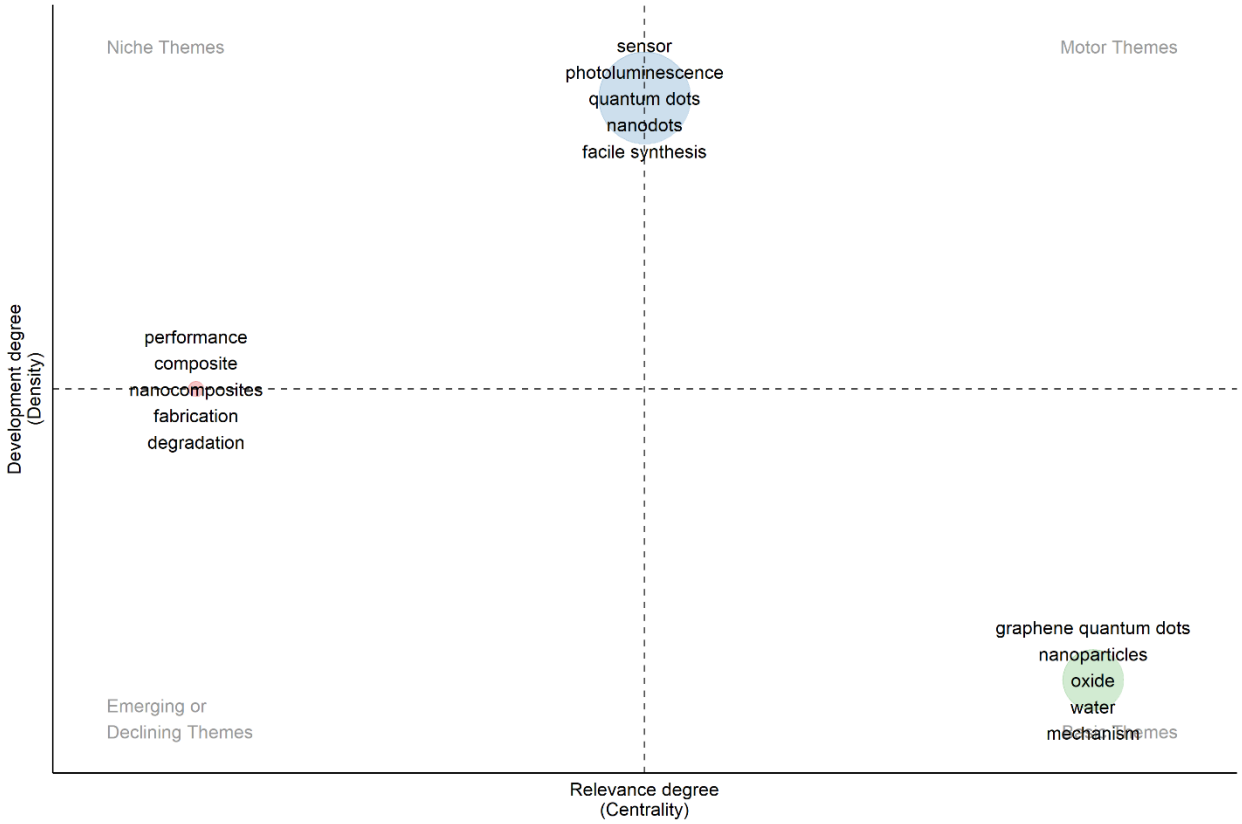

Figure 11. Thematic map based on Keywords Plus.

The keywords co-occurrence analysis with VOSviewer clustered CD research into synthesis and sensing, photoluminescence, performance-photocatalysis, and drug delivery domain, where font size corresponds to the total link strength (**Figure 12**). Green synthesis, facile synthesis, hydrothermal synthesis, sensing, photoluminescence, photocatalysis, drug delivery, bioimaging, etc. have emerged as hot research topics.

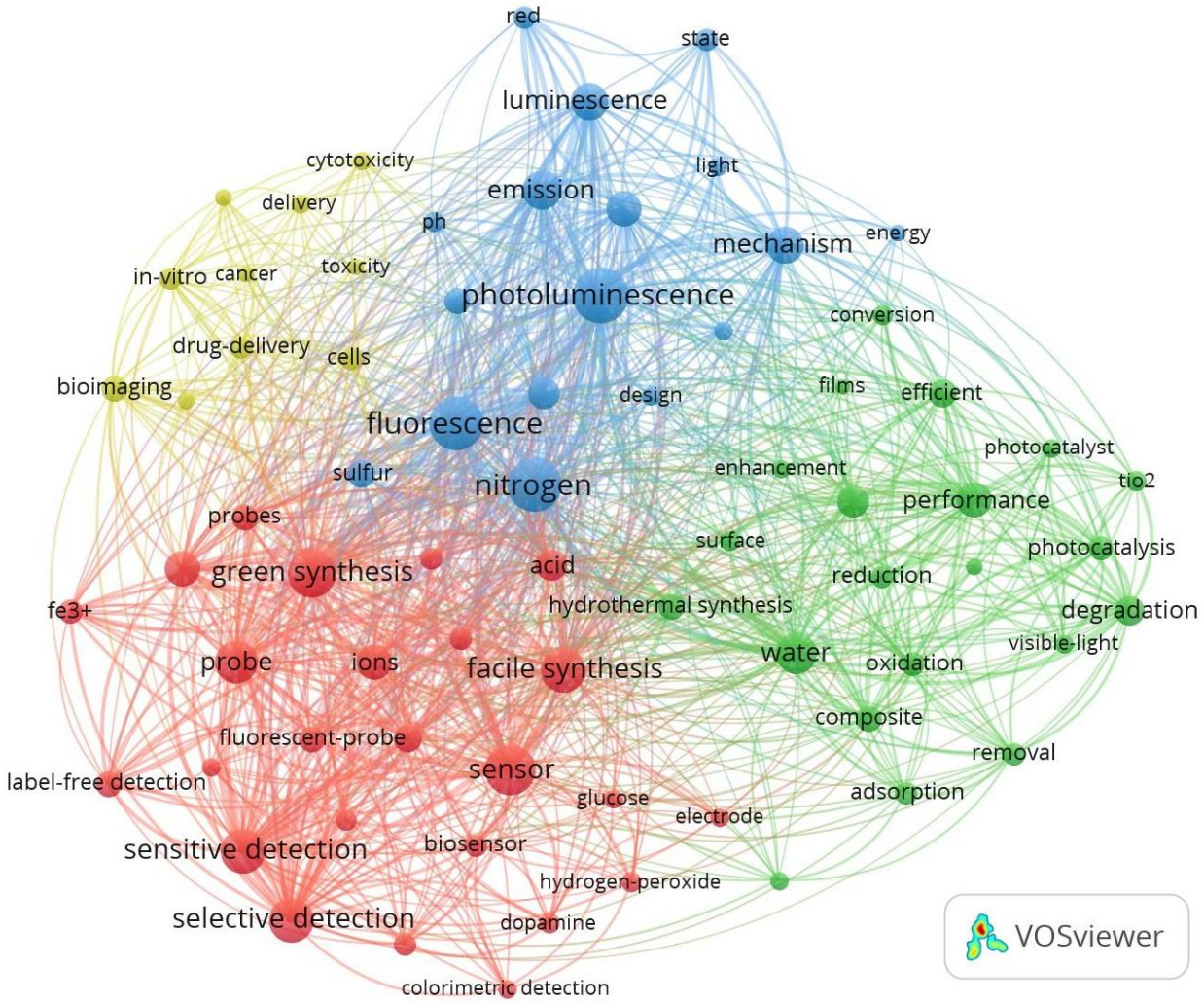

Figure 12. Network visualization of keywords co-occurrence.

3.9 Three-Field Plot

A three-field Sankey plot could unveil relationships among intellectual roots and research contents. **Figure 13** depicts the relationship among top authors, the references they cite, and the Author Keywords they use. Sankey plots were also made focusing on top authors, their relationships with the journals they publish, the Author keywords they use (**Figure S7**), and the journals they cite, Author Keywords they use (**Figure S8**). In another instance, keeping the author countries and Keywords Plus fixed, the focus was shifted to journals and cited journals (**Figure S9-S10**). In all these plots, the change in ranking, which is based on linkage strength, is apparent and indicates how the CD research has developed so far.

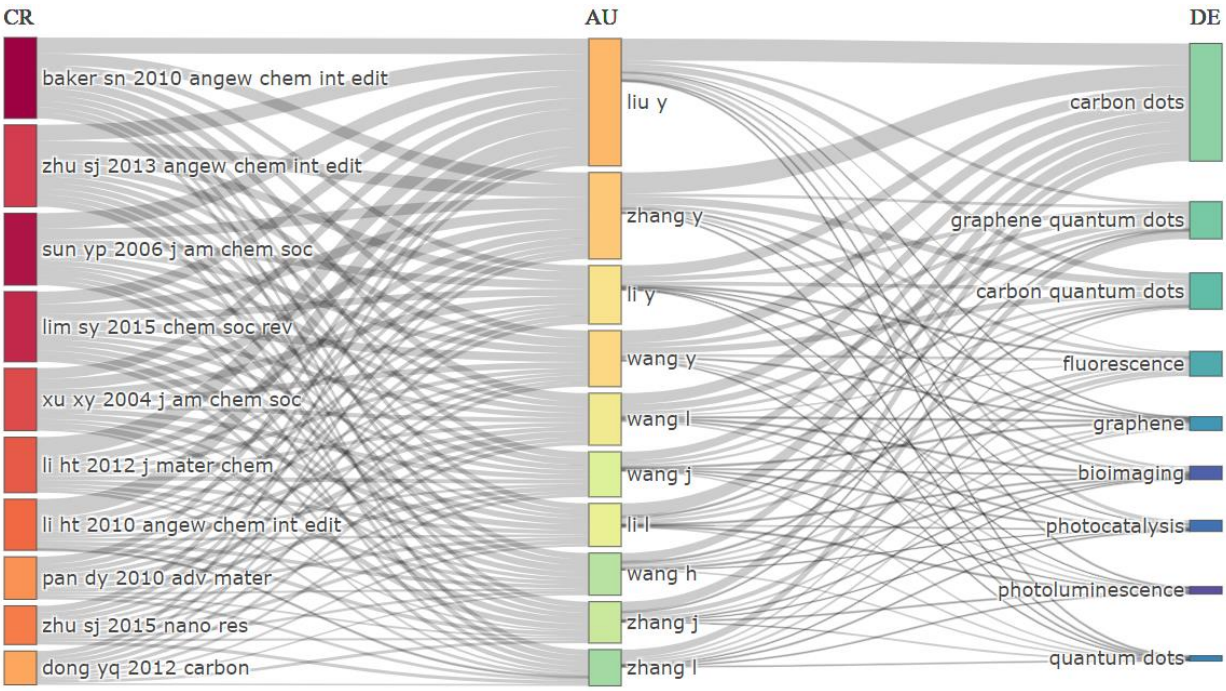

Figure 13. The Sankey plot focuses on authors and their relationship with references and Author Keywords.

3.10 Factual state of CD research

After 20 years of research, there is plenty of puzzlement on the fundamentals of CD, which has been discussed elsewhere in detail.[3, 27] On CD research things could hardly be generalized. Lack of standardization, inconsistency in results and representation, lack of robustness in research, etc. have a substantial negative impact on the factual growth of this field.[3, 27, 28] Even after a decent amount of research, one of the most basic questions on CD research is what method and conditions to choose first for the synthesis of CD, and whether to purify it or not after synthesis.[28] The perplexity arises at least partly due to the availability of numerous options to start with. Briefly, each synthesis methods have its advantages and limitations, and the concerned researcher should choose this based on their focal points of research. It should be remembered that CD is a partially carbonized nanomaterial in which a few tiny graphite layers (usual size <10 nm) are stacked together. Hence, heating should be controlled accordingly to prevent complete pyrolysis, while the application of pressure could be favourable in stacking the graphitic fragments. For the top-down synthesis of CD, the choice of raw materials is limited and is more standardized. Purification is an integral part of any material. However, a researcher may consider both the purified and the unpurified CD for the studies and critically discuss the results. The origin of the fluorescence of CD is yet to be decoded clearly. A decent number of papers have shown the presence of molecular fluorophores as the origin of the fluorescence of CD. However, other possible reasons for the fluorescence of CD could not be invalidated. Additionally, as there are numerous types of raw materials for the synthesis of CD, the

origin of fluorescence may vary from one type to another. Nevertheless, a few general areas that could be crucial for the factual growth of CD research are:

i) batch-to-batch reproducibility for the synthesis of CD,
ii) scale-up synthesis of CD,
iii) toxicity evaluation of CD on different cell lines and animal models.

4. Conclusions

After two decades of research on CD, a systematic bibliometric study was performed for the first time with the bibliometric tools (Biblioshiny, and VOSviewer) coupled with the manual review. In the last 10 years, the number of publications has grown exponentially to which publications from China are the major progressing factor. China alone contributes about 50% of the total number of publications, and the total number of citations. Authors with nine or more publications was considered as the core authors of CD research as per Lotka's law. The most relevant journal was found as RSC Advances. Interestingly, the most impactful publications have been published on or before 2015. Most of the publications are in chemistry and material science multidisciplinary domains. The keywords analysis revealed sensing as the most studied topic on the potential application of CD, while photoluminescence, photocatalysis, and drug delivery are other hot topics. Special attention should be given to batch-to-batch reproducibility of CD synthesis, scale-up of CD synthesis, and toxicity evaluation of CD. The limitation of this study is that only published articles in the English language and included in the Web of Science Core Collection were considered for the bibliometric analysis. Additionally, the bibliometric tools are in the growing phase, and the bibliometric data are sometimes ambiguous. However, this work illustrates a comprehensive overview of CD research towards advancing this field of research.

Data availability statement

The original contributions presented in the study are included in the main article or in the Supplementary information. Further inquiries can be directed to the corresponding author.

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Conflict of interest

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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