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A bibliometric study of carbon neutrality: 2001-2022

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ABSTRACT

Carbon neutrality refers to a state of net-zero carbon emissions that can be achieved by balancing the discharge and removal of carbon compounds into and from the atmosphere. It is a crucial step to avoid the catastrophic consequences of climate change. This study aims to reveal the development of carbon neutrality research using a bibliometric approach. Using a keyword search of carbon neutrality (or carbon neutral), 8,071 publications including journal articles, review articles, conference papers, book chapters, and books were identified from 2001 to 2022 (up to 8 October) from Scopus. Data were analysed using Scopus bibliometric tools and VOSviewer. The results show that the number of carbon neutrality publications has increased exponentially in the past two years and Chinese researchers have produced most of the publications, followed by U.S. researchers. Co-occurrence of keywords analysis showed that four clusters of carbon neutrality research have emerged, namely carbon neutrals using biofuels and hydrogen; carbon neutralities focusing on energy efficiency, energy utilisation and renewable energies; carbon neutrality aiming to achieve sustainable development, and greenhouse gas emissions from coal. The findings of the study suggest that future research should focus on biomass and biofuels as they are key reservoirs of carbon.

KEYWORDS Carbon neutrality; bibliometric; Scopus; carbon offsetting; China
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1. Introduction

In nature, carbon is exchanged between the atmosphere, hydrosphere, pedosphere, geosphere and biosphere of the Earth. Carbon is a key component of biological compounds that sustain all life including human life. According to the Earth Observatory of NASA (2022), the slow carbon cycle, i.e., carbon exchanging through geochemical reactions between soil, rocks, ocean, and atmosphere takes about 100 to 200 million years while the fast carbon cycle, i.e., the movement of carbon through living organisms into the atmosphere and back to living organisms takes several tens to hundreds of years. On average, the slow carbon cycle moves 10 to 100 million tonnes (Mt) of carbon each year whereas the fast carbon cycle moves 1 to 100 gigatonnes (Gt) of carbon every year. As a whole, the fast and slow carbon cycles keep relatively steady amounts of carbon in different Earth systems. However, with the increase in population and affluence over the past hundred years, the mining and consumption of fossil fuels and the emissions of carbon in the form of carbon dioxide (CO_2) into the atmosphere have increased continuously. Global anthropogenic carbon emission was around 0.53 Gt in 1900 (Boden et al., 2017). It increased to 1.63 Gt in 1950, 4.05 Gt in 1970, and 6.56 Gt of carbon, i.e., 24.1 Gt of CO_2 in 1990 (Boden et al., 2017). The Intergovernmental Panel on Climate Change (IPCC, 2022) reported that global anthropogenic emissions further increased to 38 Gt of CO_2 in 2019 from the burning of fossil fuels. Additionally, 6.6 Gt of CO_2 was added to the atmosphere due to changes in land use and 14.4 Gt of CO_2-eq was emitted into the atmosphere due to emissions of other greenhouse gases including methane, nitrous oxide, and fluorinated gases, making the total anthropogenic greenhouse gases (GHG) emission 59 Gt of CO_2-eq in 2021 (IPCC, 2022). The IPCC Report (2022) indicated that the cumulative net CO_2 emissions from 1850 to 2019 were 2400 Gt of CO_2. About 1000 Gt of CO_2 (i.e., 42% of the cumulative total) occurred between 1990 and 2019. In order to limit global warming to 1.5ºC, the remaining carbon budget is estimated as 500 Gt of CO_2 (IPCC, 2022). If the limit is set to 2ºC, the remaining carbon budget should be around 1150 Gt of CO_2 (IPCC, 2022). Thus, no matter which limit humans decide to opt for, prompt actions must be taken to lower global anthropogenic GHG emissions to achieve carbon neutrality, i.e., net-zero carbon emissions.

Carbon neutrality can be achieved by reducing carbon emissions and utilising carbon offsetting. The reduction of carbon emissions relies on technological advancements by shifting towards the use of green and/or renewable energy as well as social change including the adoption of a green lifestyle at the individual level to produce a low-carbon and circular economy at the national level. Carbon offsetting refers to an organisation or a country paying another party that invests in sequestration projects such as reforestation and geological carbon sequestration to offset its carbon emissions. Carbon neutrality has been mentioned in media since the late 1990s (Ball, 2008; Myers, 2020; Simister, 1998). Yet, it has not attracted too much attention from research communities until the last few years. A bibliometric search using Scopus on 8 October 2022 was carried out using "carbon neutrality" and "bibliometric" in "Article title, Abstract, Keywords". The search results indicated that there were 15 bibliometric studies on carbon neutrality-related topics and all of them were published in 2022. However, most of these bibliometric studies were focused on a particular topic such as carbon utilisation technology (Wang et al., 2022c), carbon sequestration in blue, i.e., ocean ecosystems (Lai et al., 2022), green consumption (Huang et al., 2022; Hui et al., 2022), carbon neutrality for global health (Mao et al., 2022), carbon neutrality in social science and business research (Dobrowolski et al., 2022; Zheng et al., 2022; Zhong et al., 2022), carbon neutrality in the building sector (Sun et al., 2022), the impact due to Covid-19 (Wang et al. 2022b), and carbon neutrality policies in China (Zhou et al., 2022). Many of these and the other four bibliometric studies (Fan et al., 2022; Wang, 2022a; Yang et al., 2022; Zhang et al., 2022b) used the Web of Science Core collection and reported the development trend of carbon neutrality research up to 2020 or 2021. Additionally, another Scopus search using "carbon neutral" or "carbon neutrality" in "Article title, Abstract, Keywords" revealed that there were more carbon neutrality-related studies published in 2022 (up to 8 October 2022) than the cumulative sum of carbon neutrality-related studies published over the past five years before 2022. The search results also showed that the first carbon neutrality article was written by Ahamer (1994) in which the use of biomass for energy was proposed as a substitute for fossil fuels due to its "carbon neutral" nature. The second and third carbon neutrality articles appeared in 1995 (Quakernatt, 1995; Schlamadinger et al., 1995). Quakernatt (1995) discussed the use of hydrogen as one of carbon-neutral sources of energy from a long-term perspective while Schlamadinger et al. (1995) showed that the use of bioenergy from logging residues in temperate and boreal forests can achieve close to carbon neutrality in the long run. There were no more than two carbon neutrality papers per year before 2001.

The rate of research on carbon neutrality is accelerating. Additionally, many applied science and engineering journals such as HKIE Transactions and the Chinese Journal of Environmental Engineering and conference proceedings are not covered in the Web of Science Core collection (see Kwok, 2021; Qi et al., 2022; Zhang et al., 2021a). Additionally, carbon neutrality studies involving carbon trading and green consumption (or people's pro-environmental behaviour) have been published in the fields of business, economics, management, and social sciences (Berger and Wyss, 2021; Whiting et al., 2014; Yu et al., 2022; Zhang et al., 2021b). Therefore, the decision was made to perform a timely bibliometric study of carbon neutrality in all fields using Scopus as the source of data during the period 2001-2022 (up to 8 October). Specifically, this study aims at addressing the following research questions. Who are the most prolific authors in relation to carbon neutrality? Which countries are producing the most carbon neutrality publications? Which higher education/research institutions are producing the most carbon neutrality publications? Which funding bodies are supporting the most carbon neutrality publications? Which are the most highly cited publications on carbon neutrality? Are there active research collaborations between authors and countries in regard to carbon neutrality publications? What sources of publications do carbon neutrality publications frequently cite? What are the emerging themes of carbon neutrality research? Answering these questions can shed important light on the understanding of carbon neutrality including its past and emerging hot topics. Specifically, the study's findings can reveal the most productive authors, institutions and countries, the most supporting funding bodies, and the most highly cited publications on carbon neutrality research. The study should also identify the emerging themes of carbon neutrality research so that future research efforts can be properly oriented.

The rest of the paper is structured as follows. Section 2 presents the methodology including data source and data analysis approach. It is followed by results and discussion in Sections 3 and 4. Section 5 concludes the paper with the study's limitations and future research.

2. Methodology

Bibliometric analysis refers to the use of quantitative techniques that reveal the statistical properties, trend, and underlying structures of bibliometric data (Donthu et al., 2021a; Okubo, 1997). Due to the availability and advancement of academic indexing databases such as Web of Science, Scopus, PubMed, etc. and bibliometric visualisation tools including VOSviewer and CiteSpace, the number of bibliometric studies has grown rapidly across a wide range of research fields in the past two decades. Specifically, Donthu et al. (2021a) reported that the number of bibliometric studies increased from 170 in 2005 to over 1,900 in 2020 in social sciences, and general business and management areas. Additionally, a search using "bibliometric" in "Article Title, Abstract, Keywords" and in the field of "Environmental Science" based on Scopus on 8 October 2022 identified that 2,277 documents were published from 2005 to 2021. The number of bibliometric studies in the field of environmental science was found to increase from seven in 2005 to 817 in 2021.

2.1. Data source

Web of Science and Scopus have been widely used in bibliometric studies (Archambault et al., 2009; Cui and Zhang, 2018; Van Nunen et al., 2018). Both of them have stringent criteria for journal inclusion. The Web of Science Core Collection covers over 21,000 journals with about 85 million records. Scopus covers over 40,000 journals, 0.34 million books including book series, and papers from over 14,000 conferences with over 87 million records. Additionally, Scopus covers the emerging journals such as HKIE Transactions and the Chinese Journal of Environmental Engineering. It has 1.7 billion cited references so that extensive bibliometric and historic trend analysis can be performed. Besides, Scopus offers easy-to-use bibliometric tools. Thus, this study used Scopus as the source of data.

A literature search was performed in Scopus using "carbon neutrality" or "carbon neutral" in "Article title, Abstract, Keywords" and "the date range" from "2001" to "2022" on 8 October 2022. In Scopus terms, this search was [(TITLE-ABS-KEY("carbon neutral") OR TITLE-ABS-KEY("carbon neutrality")) AND PUBYEAR>2000 AND PUBYEAR<2023] and 8,302 publications were identified. After removing 94 notes, 41 editorials, 36 short surveys, 22 letters, 21 conference reviews, nine errata, seven data papers, and one retracted article, 8,071 publications including 5,561 journal articles, 906 review articles, 1,219 conference papers, 38 books, and 906 book chapters were retained. The identified publications were screened manually for relevance and missing important information. No obvious error was found and all the identified publications were exported as five CSV files from Scopus (because Scopus sets 2,000 records as the limit for each data extraction).

2.2. Data analysis approach

Bibliometric analysis includes performance analysis and science mapping (Okubo, 1997; Donthu et al., 2021b). Performance analysis is used to identify the most prolific authors, the most productive affiliations and countries, and the most active funding bodies. It can also cover top source titles and the most highly cited publications on the selected topic. In this study, performance analysis was conducted using the built-in bibliometric functions of Scopus.

Science mapping is used to study the relational aspects of the identified publications. It can characterise interactions and scientific relationships between authors (or research teams), countries, and research themes. The CSV files downloaded from Scopus were merged and checked for unidentified information. The merged CSV file was imported to VOSviewer (version 1.6.11) for visualisation analysis. The analysis can map co-authorship networks and perform co-citation analysis and co-occurrence of keywords analysis (Van Eck and Waltman, 2010). Figure 1 presents the process of this study.

3. Results

3.1. Bibliometric analysis using Scopus tools

Figure 2 shows the number of publications on carbon neutrality from 2001 to 2022 (up to 8 October 2022). It shows that there were five to 16 carbon neutrality publications each year from 2001 to 2005. The number of carbon neutrality publications increased to 164 in 2010 and then to 468 in 2020. The number of carbon neutrality publications increased sharply to 1,659 in 2021 and 3,376 in 2022 (up to 8 October 2022). Overall, there were 8,071 carbon neutrality publications including 5,561 journal articles, 906 reviews, 1,219 conference papers, 38 books and 347 book chapters.

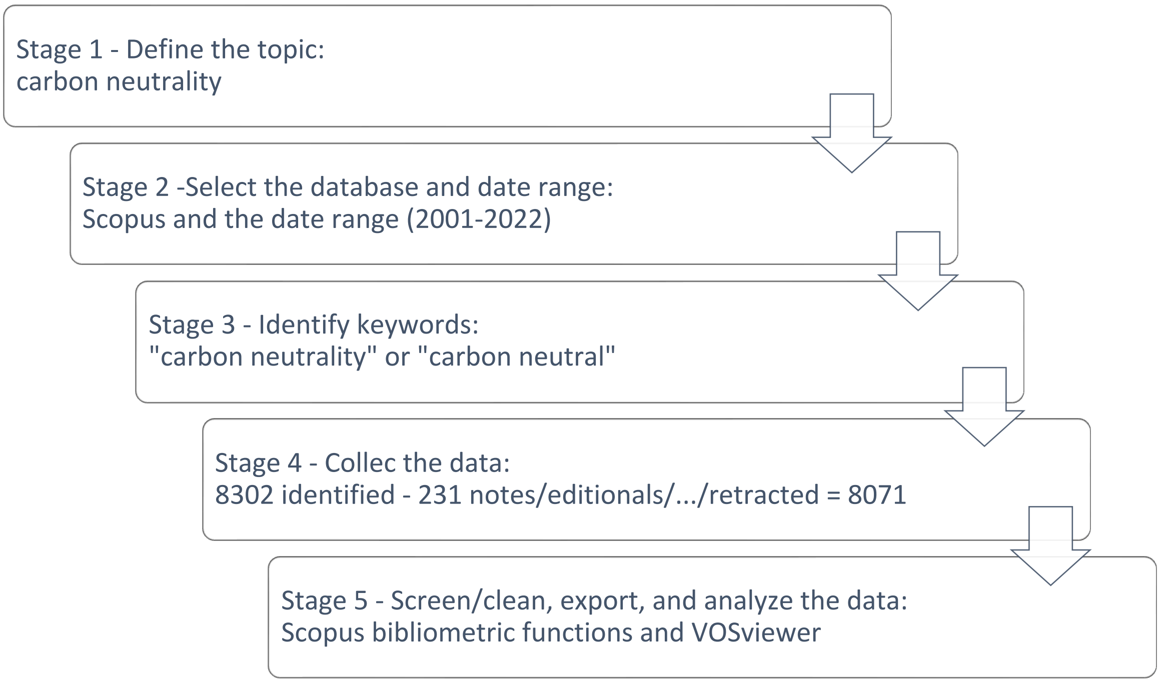


Figure 1. Process of the study.

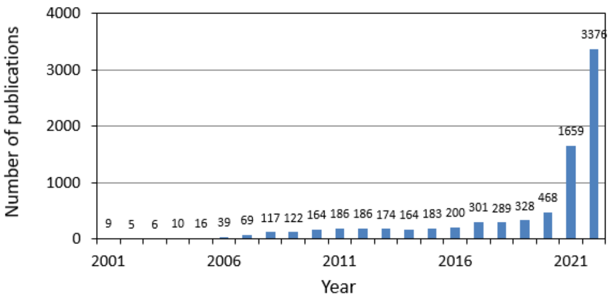


Figure 2. The number of carbon neutrality publications from 2001 to 2022 (up to 8 October 2022).

Scopus indicated that 143 authors had five or more publications on carbon neutrality. Among these authors, nine of them have produced 12 or more publications as shown in Table 1. T Spiegelhalter of Florida International University was ranked first with 18 publications including six journal articles, two review articles, and 10 conference papers. Y Zhou of HKUST (Guangzhou) was ranked second with 15 publications including nine journal articles, five review articles, and one book chapter. Y Geng of Shanghai Jiao Tong University and E E Kwon of Hanyang University were ranked third with 14 carbon neutrality journal publications each. D Blumberga of Riga Technical University, A Goeppert of University of Southern California, Y K Park of the University of Seoul, X Sun of the University of Electronic Science and Technology of China, and S Syri of Aalto University were ranked fifth with 12 publications each.

Table 1. Top 9 carbon neutrality authors.

Rank	Author name	Publications
1	Spiegelhalter, T	18 (6A, 2A, 10C)
2	Zhou, Y	15 (9A, 5R, 1BC)
3	Geng, Y	14 (14A)
3	Kwon, EE	14 (14A)
5	Blumberga, D	12 (7A, 5C)
5	Goepeert, A	12 (9A, 3R)
5	Park, YK	12 (5A, 7R)
5	Sun, X	12 (12A)
5	Syri, S	12 (10A, 2C)

Notes: A stands for Article, R stands for Review, C stands for Conference paper, and BC is a Book Chapter.

In terms of the number of carbon neutrality publications by affiliation, Table 2 shows that there were 377 publications with authors affiliated with the Chinese Academy of Sciences, followed by 320 publications with authors affiliated with China's Ministry of Education. All of the top 10 institutions were located in China with eight universities, one government department, and one state-owned corporation.

Table 2. Top 10 affiliations by the number of carbon neutrality publications.

Rank	Affiliation	Publications
1	Chinese Academy of Sciences	377
2	Ministry of Education, China	320
3	Tsinghua University	227
4	University of Chinese Academy of Sciences	171
5	Xi'an Jiaotong University	116
6	North China Electric Power University	114
7	Tianjin University	108
8	Shanghai Jiao Tung University	102
9	Zhejing University	81
10	State Grid Corporation of China	81

Table 3 shows the number of carbon neutrality publications by country. China was ranked first with 3,602 publications, followed by the United States and the United Kingdom with 1,234 and 527 publications, respectively. Japan, Germany, India and Australia were ranked fourth to seventh with over 300 publications each. Canada, South Korea, and Italy were ranked eighth to 10th with over 200 publications each.

Table 3. Top 10 countries by the number of carbon neutrality publications.

Rank	Country	Publications
1	China	3602
2	United States	1234
3	United Kingdom	527
4	Japan	385
5	Germany	379
6	India	351
7	Australia	304
8	Canada	282
9	South Korea	268
10	Italy	210

Table 4 shows the number of carbon neutrality publications funded by different sponsors. The authors of 1,633 publications acknowledged funding support from the National Natural Science Foundation of China while the authors of 418 publications acknowledged funding support from the National Key Research and Development Programme of China. Among the 10 top funding bodies, seven of them are funding bodies in China. Additionally, two U.S. funding bodies including the U.S. Department of Energy and U.S. National Science Foundation supported 281 publications while the European Union supported 129 publications through its European Commission.

Table 4. Top 10 funding bodies.

Rank	Funding Body (Region/Country)	Publications
1	National Natural Science Foundation of China (China)	1,633
2	National Key Research and Development Program (China)	418
3	Fundamental Research Funds for the Central Universities (China)	261
4	National Office for Philosophy and Social Sciences (China)	181
5	U.S. Department of Energy (the U.S.)	141
6	National Science Foundation (the U.S.)	140
7	Chinese Academy of Sciences (China)	130
8	European Commission (EU)	129
9	Ministry of Education (China)	126
10	China Postdoctoral Science Foundation (China)	123

Note: Some publications acknowledged more than one funding sponsor.

Table 5 shows the number of carbon neutrality publications by source title. Among the top 10 sources titles, Sustainability (Switzerland) was ranked first with 204 publications. Journal of Cleaner Production was ranked second with 185 publications. It was followed by three energy journals, namely Energies with 185 publications, Applied Energy with 141 publications, and Energy with 123 publications.

Table 6 shows the top 10 most highly cited carbon neutrality publications. Chisti's (2007) article entitled

Table 5. Top 10 source titles.

Rank	Source Title	Publications
1	Sustainability (Switzerland)	204
2	Journal of Cleaner Production	195
3	Energies	185
4	Applied Energy	141
5	Energy	123
6	Environmental Science and Pollution Research	122
7	Renewable and Sustainable Energy Reviews	112
8	Fuel	90
9	Journal of Environmental Management	85
10	IOP Conference Series – Earth and Environmental Science	73

"Biodiesel from microalgae" in Biotechnology Advances was ranked first with 7,071 citations. This review article argued that it is crucial to use biodiesel as transport fuels. However, biodiesel from oil crops, animal fat, and waste cooking oil cannot meet the growing demand for transportation. Thus, Christi (2007) suggested that microalgae appear to be a viable solution for producing biodiesel to meet the global demand for transport fuels. The second most highly cited publication was "Powering the planet: Chemical challenges in solar energy utilization" published in PNAS by Lewis and Nocera (2006) with 6,292 citations. The authors of this review article pointed out that solar energy is the largest exploitable source because one hour of solar energy reaching the Earth can theoretically support humans' energy consumption for one year. The authors suggested that an attractive approach is to convert

Table 6. Top 10 most highly cited carbon neutrality publications.

Author(s)	Title	Year	Source	Citations
Chisti, Y	Biodiesel from microalgae	2007	Biotechnology Advances	7071
Lewis, NS & Nocera, DG	Powering the planet: Chemical challenges in solar energy utilization	2006	PNAS	6292
Ragauskas et al.	The path forward for biofuels and biomaterials	2006	Science	4603
Brennan, L & Owende, P	Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products	2010	Renewable and Sustainable Energy Reviews	3278
Klemm et al.	Nanocelluloses: A new family of nature-based materials	2011	Angewandte Chemie	3119
Logan, BE	Microbial Fuel Cells [book]	2008		1388
Luyssaert et al.	Old-growth forests as global carbon sinks	2008	Nature	1129
Olah et al.	Chemical recycling of carbon dioxide to methanol and dimethyl ether: From greenhouse gas to renewable, environmentally carbon neutral fuels and synthetic hydrocarbons	2009	Journal of Organic Chemistry	1099
Tu et al.	Photocatalytic conversion of CO_2 into renewable hydrocarbon fuels: State-of-the-art accomplishment, challenges, and prospects	2014	Advanced Materials	1066
Sivula, K & van de Krol, R	Semiconducting materials for photoelectrochemical energy conversion	2016	Nature Reviews Materials	906

and store solar energy in the form of chemical bonds using photosynthetic processes rather than relying on plants and algae that demands an enormous surface area and highlighted the challenges involving these photosynthetic processes. The third most highly cited publication was "The path forward for biofuels and biomaterials" published in Science by Ragauskas et al. (2006) with 4,603 citations. This review article suggested that biomass is a carbon-neutral renewable resource for bioenergy and biomaterials. The authors argued that biorefinery should be used an approach in which biomass can be utilised in an optimal manner to produce sustainable energy and multiple biomaterials and products. The fourth most highly cited publication was "Biofuels from microalgae-A review of technologies for production, processing, and extractions of biofuels and co-products" published in Renewable and Sustainable Energy Reviews by Brennan and Owende (2010) with 3,278 citations. This review article was focused on the technologies underpinning microalgae-to-biofuels systems. It explained how biomass was produced by microalgae, and how biomass could be harvested and converted to biofuels and other bio-products. The fifth most highly cited publication was "Nanocelluloses: A new family of nature-based materials" published in Angewandte Chemie by Klemm et al. (2011) with 3,119 citations. This review article suggested that nanocelluloses as an abundant, renewable, and potential carbon-neutral source have vast applications such as sustainable nanocomposites, medical and life-science devices, and natural polymeric materials. The sixth to tenth most highly cited publications attracted 906 to 1,388 citations. They included two review articles (Olah et al., 2009; Tu et al., 2014), two journal articles (Luyssaert et al., 2008; Sivula and van de Krol, 2006), and one book (Logen, 2008).

3.2. Co-authorship analysis using VOSviewer

When co-authorship analysis was conducted at the individual level with five publications or more, 143 authors met the threshold. As expected, the authors listed in Table 1 produced most publications. T Spegelhalter published eight documents alone and co-authored another 10 documents with different researchers as shown in Figure 3. D Blumberga published carbon neutrality journal and conference papers with different researchers in Riga Technical University, Latvia while A Goeppert co-authored 10 publications with his colleague - G K S Prakash in the University of South California. Additionally, most Chinese researchers including Y Zhou, Y Geng, X Sun, etc. co-authored publications with researchers in China while researchers in South Korea such as E E Kwon and Y K Park co-authored publications with each other and some researchers in Hong Kong, People's Republic of China .

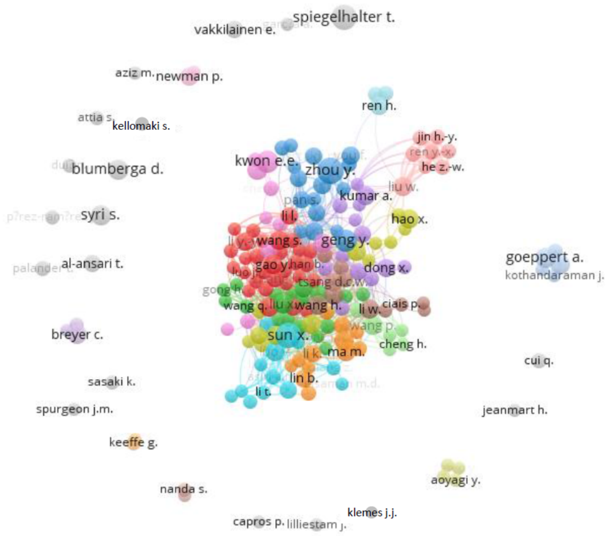


Figure 3. Co-authorship analysis at the individual level (threshold: five publications or more).

When co-authorship analysis was conducted at the country level with 10 publications or more, it was found that 60 countries out of the total 213 countries met the threshold. Figure 4 shows that these 60 countries formed four clusters. The first cluster (red in colour) had 25 countries in which Germany produced the largest number of publications (379), followed by Italy (210), Finland (196), Spain (159), France (155), and Sweden (146). The second cluster (green in colour) included 19 countries in which Japan produced the largest number of publications (385), followed by India (351), South Korea (268), and Malaysia (108). The third cluster (blue in colour) included 12 countries in which the U.S. produced the largest number of publications (1234), followed by the United Kingdom (527), Canada (282), and Netherlands (160). The fourth cluster (yellow in colour) had only four countries in which China produced most of the publications (3602), followed by Australia (304), Hong Kong – China (137) and Singapore (88).

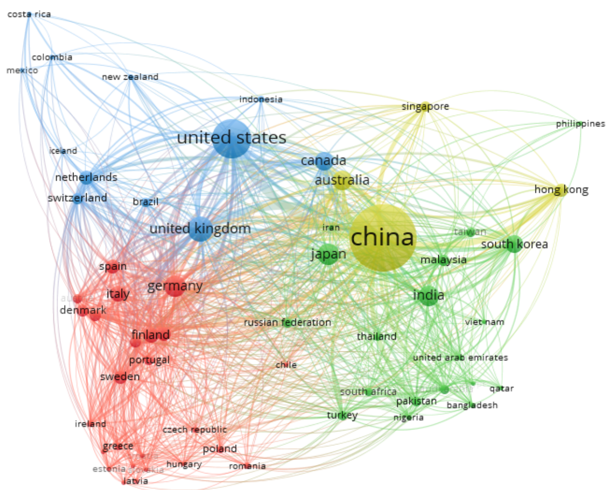


Figure 4. Co-authorship analysis at country level (threshold: 10 publications or more).

3.3. Co-citation analysis using VOSviewer

Co-citation analysis was conducted at the cited source level. When the minimum number of citations was set to 200, 199 sources out of the 73,424 cited sources met the threshold. Table 7 shows the top 10 most highly cited sources from carbon neutrality publications. Many of them are well-established energy journals.

Table 7. Top 10 source titles by co-citation analysis based on the source level.

Rank	Source Title	Citation counts
1	Energy	5311
2	Science	3655
3	Energy Policy	3578
4	Journal of the American Chemical Society	3550
5	Fuel	3502
6	Applied Energy	2755
7	Bioresource Technology	2724
8	Nature	2705
9	Journal of Cleaner Production	2649
10	Applied Energy	2452

3.4. Co-occurrence of keywords analysis using VOSviewer

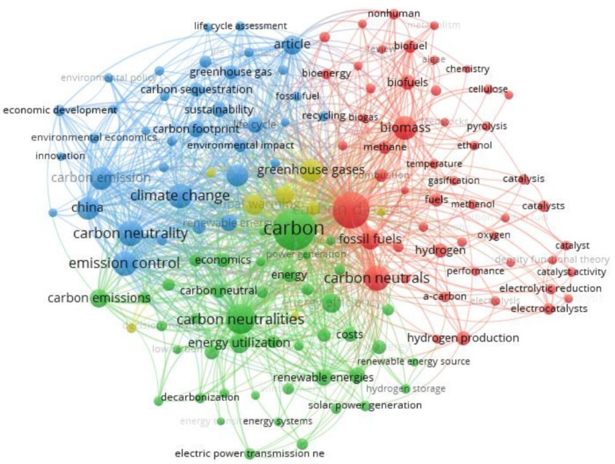


Figure 5. Co-occurrence of keywords (threshold of occurrences of a keyword: 100).

Co-occurrence of keywords analysis (i.e., all keywords) was conducted on all the identified publications using VOSviewer. When the number of keyword co-occurrences was set to 100, 140 keywords were identified that formed four clusters. Table 8 shows the frequency of the top six keywords in each of the clusters. Cluster 1 covers carbon dioxide, carbon neutrals, biomass, and fossil fuels. Cluster 2 covers carbon, carbon neutralities, energy efficiency, and energy utilisation. Cluster 3 covers carbon neutrality, climate change, emission control, and China. Cluster 4 focuses on greenhouse gases, global warming, gas emissions, and coal. Figure 5 shows that Cluster 1 was red in colour with 52 keywords, Cluster 2 was green in colour with 43 keywords, Cluster 3 was blue in colour with 37 keywords, and Cluster 4 was yellow in colour with eight keywords.

Table 8. Top 6 keywords (with the frequency of occurrences) in each cluster.

Cluster 1	Cluster 2	Cluster 3	Cluster 4
Carbon dioxide (1,837)	Carbon (2,424)	Carbon neutrality (874)	Greenhouse gases (744)
Carbon neutrals (915)	Carbon neutralities (1,238)	Climate change (842)	Global warming (560)
Biomass (807)	Energy efficiency (543)	Emission control (839)	Gas emissions (484)
Fossil fuels (535)	Energy utilisation (536)	China (700)	Coal (277)
Biofuels (306)	Carbon emissions (489)	Carbon emission (698)	Carbon dioxide emissions (129)
Hydrogen (294)	Renewable energies (392)	Sustainability development (661)	Greenhouse gas emissions (126)

4. Discussion

The study's results indicate that carbon neutrality has been a hot topic in the past two years. Before 2021, there were less than 500 publications each year, i.e., less than one or slightly over one paper per day. On 22 September 2020, China's President – Xi Jinping – announced in the UN General Assembly via videolink that China aims at reaching peak emissions before 2030 and becoming carbon neutral by 2060 (now known as the 30-60 goals). Since then, researchers, particularly those in China and other Asian regions, have redirected many of their research efforts to help reach these goals. Therefore, the number of carbon neutrality publications increased sharply from 468 in 2020 to 1,659 in 2021, then to 3,376 in 2022 (up to 8 October 2022) as shown in Figure 1. When the identified publications were analysed by author, T Spiegehalter of Florida International University was found to be the most prolific author (see Table 1). Nevertheless, with the great effort supported by many Chinese funding bodies (see Table 4), it is expected that many top Chinese researchers such as Y Zhou of HKUST (Guangzhou), Y Geng of Shanghai Jiao Tong University, X Sun of University of Electronic Science and Technology of China, etc. will produce many more carbon neutrality publications in the coming years. Additionally, it was found that China strives to achieve its 30-60 goals through not only research in higher education institutions but also in government departments such as China's Ministry of Education and utilities such as the State Grid Corporation of China as shown in Table 2. Therefore, carbon neutrality publications have been dominated by China, followed by the U.S., the U.K., Japan, Germany, and India (see Table 3 and Figure 4) – similar to what was reported by To and Yu (2020). When the number of publications was counted by source title, Sustainability (Switzerland) was identified as the top journal having the largest number of carbon neutrality publications, followed by the Journal of Cleaner Production and Energies (see Table 5). Sustainability (Switzerland) is an open access and multidisciplinary environmental journal covered by both the Science Citation Index Expanded and Social Sciences Citation Index, meaning that researchers have approached carbon neutrality not only from the science and engineering perspectives, but from the perspectives of social sciences and psychology because energy saving involves human behavioural change (Lebrouhi et al., 2022; Mustafa et al., 2022). In fact, there have been a large number of publications (320) from researchers affiliated with the Ministry of Education in China (see Table 2) and the fourth most active funding body was the National Office for Philosophy and Social Sciences in China (see Table 4).

The most highly cited publications illustrated that review articles have attracted many more citations than regular journal articles (see Table 6). This is not a surprising finding as To (2022) reported a similar situation for world issues-related publications. Additionally, four out of the top 5 most highly cited publications indicated that biomass – particularly microalgae and nanocelluloses – should be considered as one of the viable solutions for carbon neutrality because biomass is carbon neutral in nature. Lewis and Nocera (2006), on the other hand, suggested that people should explore other chemical-based photosynthetic processes to collect and store solar energy rather than rely on plants and algae which demands a huge surface area. The authors fully agree with these research suggestions but also like to highlight that carbon neutrality should focus on finding alternative and renewable energies (Chisti, 2007; Klemm et al., 2011; Ragauskas et al., 2006), changing people's life style, and improving energy efficiency and utilisation (Che et al., 2019; Lin et al., 2022; Zhang et al., 2022a). Carbon offsetting seems to be part of the solution to achieve carbon neutrality but its implementation should be carried out with great caution. As we mentioned in the Introduction, the fast carbon cycle takes a million years for one cycle while the slow carbon cycle takes tens/hundreds of years for one cycle. Carbon offsetting may overlook the fact that nature takes millions of years to turn biomass into fossil fuels under complex geothermal-chemical processes. Carbon offsetting may blind people into believing that we can somehow remove "new" CO_2 due to the burning of fossil fuels, i.e., "old" biomass (McKendry, 2002) by capturing CO_2 using plants, i.e., "new" biomass and other sequestration technologies. From the system perspective, humans should stop using fossil fuels. In other words, humans should stop injecting CO_2 from "old" biomass into the current climate system.

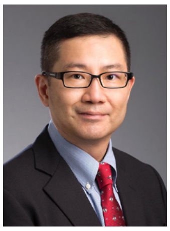
Finally, co-occurrence of keywords analysis revealed that carbon neutrality publications can be broadly classified into four clusters, namely carbon neutrals using biofuels and hydrogen, carbon neutralities focusing on energy efficiency, energy utilisation and renewable energies, carbon neutrality aiming to achieve sustainable development, and greenhouse gas emissions from coal (see Figure 5 and Table 8). Cluster 1 (red in colour) contained 52 keywords including carbon dioxide, carbon neutrals, biomass, fossil fuels, biofuels, and hydrogen and as such it was labelled as carbon neutrals using biofuels and hydrogen. Cluster 2 (green in colour) contained 43 keywords including carbon, carbon neutralities, energy efficiency, energy utilisation and renewable energies and thus was labelled as carbon neutralities focusing on energy efficiency, energy utilisation and renewable energies. Cluster 3 (blue in colour) contained 37 keywords including carbon neutrality, climate change, China, and sustainability development and thus was labelled as carbon neutrality aiming to achieve sustainable development. Cluster 4 (yellow in colour) contained eight keywords including greenhouse gases, global warming, gas emissions and coal. Therefore, it was labelled as greenhouse gas emissions from coal. It should be noted that cluster analysis provides a general idea of how academic publications can be broadly classified into some key research themes such as the ones – carbon neutrality themes – that we explored in the present study. Nevertheless, many links were also observed between keywords in different clusters as shown in Figure 5.

5. Conclusions

The study reviewed the emergence and development of carbon neutrality research in the past two decades. Using the bibliometric data obtained from Scopus, it was found that the number of carbon neutrality publications has increased exponentially since 2020. Specifically, China has put in enormous resources and efforts to support carbon neutrality-related research through its higher education institutions, government departments, and state-owned corporations. Co-authorship analyses at the individual and country levels support the aforementioned statement. Four out of the top 5 most highly cited publications suggested that biomass – particularly microalgae and nanocelluloses – should be a viable solution for carbon neutrality as it is both an energy source and a source of biomaterials and bioproducts. Future research should pay great attention to this area. Overall, co-occurrence of keywords analysis revealed that four clusters have emerged from the past research efforts. The clusters include carbon neutrals using biofuels and hydrogen, carbon neutralities based on energy efficiency, energy utilisation, and renewable energies, carbon neutrality aiming at achieving sustainable development, and greenhouse gas emissions from coal.

This study has two main limitations. First, it was a cross-sectional study focusing on carbon neutrality publications during the period 2001-2022 (up to 8 October 2022). As the rate of carbon neutrality research accelerates, it is expected that many new publications – possibly with new research directions and findings will appear in the near future. Thus, researcher(s) can carry out another bibliometric study near the end of 2023. Second, the present study used Scopus as the source of data. As other academic indexing databases such as Dimensions and CNKI (China National Knowledge Infrastructure) contain a very different kind of data, it is worthwhile to carry out a similar bibliometric study using CNKI so that the emerging themes of carbon neutrality in China can be identified.

Notes on contributors



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