Journal of Infrastructure, Policy and Development 2024, 8(7), 4551.
https://doi.org/10.24294/jipd.v8i7.4551

Article

Visual analysis of international carbon emissions literature and study of evolutionary trends—Based on scientific knowledge mapping

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CITATION

Zhao S, Wang X, Li C, Cai R. (2024). Visual analysis of international carbon emissions literature and study of evolutionary trends—Based on scientific knowledge mapping. Journal of Infrastructure, Policy and Development. 8(7): 4551. https://doi.org/10.24294/jipd.v8i7.4551

ARTICLE INFO

Received: 4 February 2024
Accepted: 5 March 2024
Available online: 29 July 2024

Abstract: With the economic development and the carbon emissions cluster rise, this study uses CiteSpace, VOSviewer, and R-based Bibliometrix software to visualize and analyze the relevant literature on carbon emissions retrieved from the Web of Science database from 2014 to 2023. Through the analysis of the trend of publication volume, author co-citation analysis, institutional co-citation analysis, country co-citation analysis, literature co-citation analysis, thematic analysis of research, research evolution, and other related contents, it reveals the main academic forces, hot research areas, thematic focus changes and cutting-edge trends of international carbon emission research. The results of the study found that the themes of international carbon emissions research focus on carbon emissions, the drivers of carbon neutrality, and the impacts of climate change. An in-depth study of these aspects can help formulate more effective climate policies and emission reduction strategies to achieve global carbon neutrality and combat climate change.

Keywords: “dual-carbon” targets; carbon emissions; knowledge mapping; evolutionary trend analysis

1. Introduction

Since the Industrial Revolution, a large number of fossil fuels have been used, such as coal, oil, and natural gas. The combustion of these energy sources releases large amounts of carbon dioxide, which becomes one of the major greenhouse gases (Johny et al., 2018). The productivity of human society has increased unprecedentedly, but at the same time, it also brings serious environmental problems, the most prominent of which is the carbon emission problem (Pearson and Foxon, 2012). In the 1970s, scientists began to pay attention to the impact of the greenhouse effect on the global climate and started to conduct research related to carbon emissions (Mikhaylov et al., 2020). They found that greenhouse gases released by human activities can cause the surface temperature of the earth to rise, thus causing climate change (Chromec and Ferraro, 2008; Clarke, 2009; Xu et al., 2023). The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations in 1988 to assess the science of climate change, its impacts, and its adaptation measures. The IPCC’s reports have become an important reference for global climate change policymaking. In the past decades, the amount of carbon emissions caused by human activities has shown a significant growth trend (Li and Tang, 2017; Li et al., 2023). According to the International Energy Agency (IEA), global energy-related carbon dioxide emissions have increased by about 1.5 percent over the past decade to reach their peak in that year (Gnangoin et al., 2022). This trend has triggered an urgent need for sustainable

development and climate change adaptation, driving countries and international organizations to take more proactive actions to mitigate carbon emissions and seek greener development pathways (Kang et al., 2020).

With the growing problem of global climate change, the international community has been placing increasing emphasis on reducing carbon emissions (Djurovic et al., 2018). According to the Climate Change 2023 report released by the United Nations Intergovernmental Panel on Climate Change (IPCC), global greenhouse gas emissions have continued to grow over the past few decades, leading to global warming and the frequent occurrence of extreme weather. In response to this challenge, the Paris Agreement clarified the responsibility of countries for mitigating climate change, and governments have set emission reduction targets and taken a series of measures to reduce carbon emissions. Countries have begun to establish measurement and monitoring systems for carbon emissions and have collected a large amount of empirical data (Azevedo et al., 2018). Based on the international data, the gaps in carbon neutrality between China, the European Union, and the United States have been compared, and strategies and recommendations have been put forward (Zhao et al., 2022). Theoretical insights and practical countermeasures for China's future actions, key tasks, and policy measures to achieve carbon neutrality are presented, and research aspects of opportunities for achieving carbon neutrality are systematically identified (Dai et al., 2023; Wei et al., 2022). Meanwhile, the economic and social impacts of carbon emissions have also received more attention. Many scholars have begun to study the relationship between carbon emissions and economic development, energy consumption, policy environment, and other factors. Tran (2023) studied the impact of financial development on carbon dioxide emissions. Wang and Zhao (2019) analyzed the impact of a carbon tax on energy, the environment, and the economy in the coal industry. Cui et al. (2019) used regression models on economic and energy systems to analyze whether China's Shanxi can promote low-carbon development. Guo et al. (2023) understand the sources, respectively, and impacts of carbon emissions, as well as develop effective mitigation strategies. With the advancement of science and technology and the improvement of environmental awareness, international carbon emission research has entered a new stage. He et al. (2022) believes that science is closely related to carbon neutrality put forward the concept of the carbon energy index, and combined with green carbon science focus on the latest progress in petroleum refining. Sun et al. (2017) believe that modern scientific research should focus on detecting the level of carbon emissions. However, Ding et al. (2021) still need to understand the drivers behind them and explore effective ways to mitigate carbon emissions. Hu et al. (2022) seek a more sustainable development model. In this context, in-depth research on carbon emissions becomes particularly important. With the accumulation of theoretical and practical experience, researchers in related fields have conducted in-depth studies on carbon emissions in several neighborhoods. These include agriculture and land use (Houghton et al., 2012; Vleeshouwers and Verhagen, 2002; Wise et al., 2014), urban planning and construction (An et al., 2019; Fong et al., 2008; Pacheco-Torres et al., 2017), carbon emission problems in energy systems (Cheng et al., 2018; Hurwitz et al., 2020; Nian, 2015), and scientific and technological solutions to carbon emission problems (Chen et al., 2021). All these articles promote the development of carbon emissions.

However, although international carbon emissions research has achieved some important results, it still faces many challenges. Carbon emissions research has become a hotspot for academic research, and with the explosion of related literature, manual processing is no longer able to accurately extract valid information. Relevant researchers need to determine the best method to extract the required information quickly and accurately.

To gain a comprehensive understanding of the current status and development of international carbon emissions, this study integrated the use of CiteSpace, VOSviewer, and the R-based Bibliometrix tool to provide a comprehensive visual analysis of the academic literature related to international carbon emissions research. This comprehensive analysis method not only provides a comprehensive understanding of the current status of international carbon emissions research, but also reveals the research hotspots, key authors, and research institutes in the field, as well as clearly outlines the key themes and research trends in the field of international carbon emissions research. This helps researchers gain a deeper understanding of the core topics of carbon emissions issues and provides important reference directions for future research. It provides not only comprehensive insights into the international carbon emissions research field but also offers useful decision-making support and guidance for policymakers, research institutes, and enterprises. By analyzing research hotspots and development trends, we can more effectively formulate carbon management policies, promote technological innovation, and achieve more significant achievements in the field of carbon emission reduction.

2. Review of literature

With the growing problem of global climate change, carbon emissions, as a major source of greenhouse gas emissions, have attracted widespread attention in terms of their impacts and control strategies. The importance of studying carbon emissions is not only in terms of a deep understanding of climate change but also in terms of global sustainable development, environmental health, and all aspects of human existence. The following are some of the key aspects of studying the neighborhood of carbon emissions:

Carbon emissions, as one of the main drivers of global climate change, have raised profound concerns about climate sustainability on a global scale. Scholars have studied carbon emissions in the context of global climate change. Yang et al. (2022) argued that climate change has long-term impacts on agricultural carbon emissions. Xiong et al. (2016) studied the green pathway suitable for low-carbon development of the industry and argued that the government should formulate a regional low-carbon agricultural policy. Shen and Sun (2016) talked about climate change from the perspective of carbon emissions and low carbon. Ke and Pan (2011) elaborated on the main forestry action frameworks to address climate change in China. Wen and Wang's (2023) study assess the combined impact of climate change and traffic growth on asphalt pavement performance and carbon emissions of Chinese highways, providing a reference for future carbon reduction policies under climate change. By analyzing carbon emission data and studying the impact and relationship of climate change on carbon emissions, they have made a positive contribution to addressing climate change.

Transport is another major area of carbon emissions. Li et al. (2021) promote the sustainable development of the transport system by studying the influencing factors of carbon dioxide emissions in the transport sector and predicting its carbon emissions. Arasto et al. (2012) review and explore the effectiveness and problems of emission reduction measures in different ports to help ports with low emission reduction capacity learn and find the most suitable measures for emission reduction development. Li and Tang (2017) explore the development and challenges of the application of carbon trading mechanisms in the global transport sector. These researchers are focusing on carbon emissions from transport, looking for viable ways to reduce emissions, and exploring the challenges of carbon emissions in the transport sector. Building on the above, the latest system dynamics content further expands our understanding of carbon emissions in the transport sector. Latest research scholars (Wen and Wang, 2023) taking Beijing's public transport sector as an example, we use system dynamics modeling in conjunction with relevant policies and the current situation to advance the low-carbon development of public transport in the future.

Industry and energy production are some of the major sources of carbon emissions, with the main energy sources including coal combustion, oil, and natural gas, which are widely used in power generation, heating, and transport, releasing large amounts of carbon dioxide (Gür, 2022; Hunt et al., 2010). Sarker et al. (2013) studied the CO_2 emissions from electricity and fuel consumption consumed by the iron and steel industry sector in South Asian countries and made some policy recommendations. Wu et al. (2016) explored carbon dioxide emissions in industrial neighborhoods in conjunction with geographically weighted regression. These techniques aim to reduce carbon emissions from production processes and improve resource utilization. To promote the development and use of renewable energy sources, technological innovations to reduce carbon emissions during the combustion of conventional energy sources, as well as policy measures to encourage energy transition and sustainable industrial development (Lee et al., 2018; Naderipour et al., 2021). Shen et al. (2024) have studied the olefin industry under different development scenarios, revealing the carbon footprints of different olefin routes and then predicting their carbon emissions. The latest studies propose ways to reduce their carbon footprints, which provide important theoretical and practical basis for guiding sustainable development and making scientific decisions for governments and enterprises.

In terms of the development of carbon emissions, international research on carbon emissions has gone through different evolutionary stages, each focusing on different aspects and issues, presenting a continuous evolution of the carbon emissions issue in global attention and research.

In the first phase (embryonic stage), the focus of carbon emissions research was mainly on analyzing general trends on a global scale. Researchers are committed to understanding carbon emissions data across countries and regions to gain a comprehensive understanding of the sources and distribution of carbon emissions. At the same time, governments are actively responding to the challenge of climate change by formulating policies aimed at promoting low-carbon sustainable development laying the scientific foundation for mitigating greenhouse gas emissions and promoting environmental actions. Huang and Deng (2010) study the theory of low-carbon tourism, establish a development model of low-carbon tourism in the context

of leisure by choosing directions, paths, and methods, and further propose specific measures to develop low-carbon tourism. These measures not only contribute to the sustainable development of tourism but also have a positive impact on the mitigation of global carbon emissions. The research in this period provides strong support for combining theory and practice to promote low-carbon development.

The second phase is (developmental stage), in which countries strengthen the construction of carbon emissions trading, demonstrating a common concern for carbon markets and emission reduction mechanisms on a global scale. Attempts were made to make recommendations on operational accounting recognition and accounting measurement for the acquisition, use, purchase, or transfer of carbon emission permits (Yu, 2015). These efforts aim to be guided by market mechanisms and governments, thus contributing to the achievement of global carbon neutrality targets. Proposing a carbon performance evaluation standard is an important system to help companies achieve a low-carbon transition, and the standard helps to strengthen carbon reduction by companies, as well as to predict carbon trading and develop a market for carbon emission rights (Zhang et al., 2016). Government leadership and policy support in this area are crucial for the successful implementation of carbon emissions trading.

The third stage is (mature stage), using a variety of modeling methods, the third stage of carbon emission research is more focused on depth and refinement, with the help of advanced modeling methods and technological tools, the cost of controlling carbon dioxide emissions, and the economic modeling of the estimation (Zhang and Folmer, 1998). Shi et al. (2022) explored the current status of research and cutting-edge trends in the field of carbon neutrality, which can provide theoretical references for subsequent research on carbon neutrality as well as.

3. Data collection

In this study, the Web of Science Core Collection database was used as the source of the research data, and the advanced search mode was used with "TS = ("carbon emission" and "carbon neutrality" or "low carbon development")" as the combination of search terms, and the period was "2014–2023". "Neutrality" or "low carbon development" as the combination of search terms, and the period was "2014–2023". A total of 1907 documents were obtained through the precise search and cleaning filter, which were used as the finalized sample documents.

4. Research methodology

In this study, CiteSpace, VOSviewer, and Bibliometrics software based on R language are used to analyze the research literature on carbon emissions retrieved from the Web of Science database. Citespace can identify the hot topics and key terms in the research field by analyzing the keywords of the literature. At the same time, it can also perform cluster analysis on the literature to group similar topics or literature with strong correlations into one category, helping researchers to clarify the knowledge structure of the research field. Firstly, it reveals the important institutions and core authors of carbon emission research by using the analysis of authors, countries, and collaborating institutions' collaborative networks. Second, the academic influence and knowledge base of carbon emissions research are explored through co-citation

network analysis of related literature. Finally, the keyword co-occurrence network analysis was used to identify the major hot topics and development trends in the field of carbon emissions research.

4.1. Analyses of trends in the number of articles posted

The number of publications is an important indicator to measure the development trend of a certain field in a certain period, and it can intuitively observe the change of the heat of the research field, which is extremely important for analyzing the development trend of a certain field and predicting the future development of the field. The sample literature was statistically analyzed using Excel tools. As can be seen from **Figure 1**, the carbon emission literature research shows a significant growth trend, which shows that carbon emission has gained rapid development and attention in the past few years. The table starts in 2014, mainly because UNFCCC held its 20th Conference of the Parties (COP 20) in Lima, Peru, in 2014, and countries continued to negotiate a global agreement on mitigating climate change and coping with its impacts. Some countries adjusted their energy policies in 2014 to reduce carbon emissions.

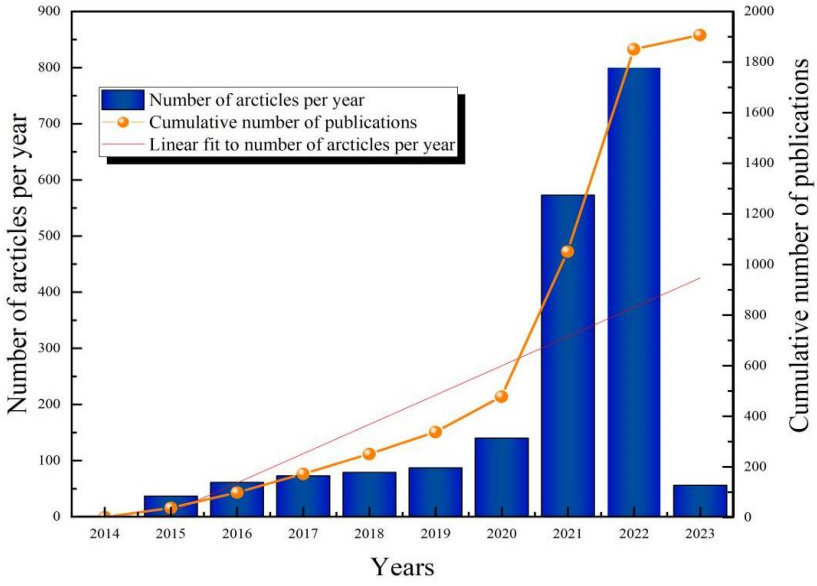

Figure 1. Trends in the volume of communications.

Several developed countries pledged to provide financial and technical support to developing countries to help them address the challenges of climate change. Afterward, the number of communications continued to increase as time progressed. 2016 saw a further escalation of international attention and efforts on carbon emission policies, with the most significant milestone being the Paris Agreement, which officially entered into force on 4 November 2016. The Paris Agreement was the first global agreement on climate change to be adopted by the United Nations on climate change. Afterward, it showed a continuous increase in the number of communications, and the number of communications began to double from 2020 to 2021, which shows that international carbon emission policies are mainly focused on countries actively seeking to reduce carbon emissions to slow down the trend of global warming. The

number of carbon emission communications continued to grow at a rapid trend in 2022, and the international community's efforts to combat climate change continued to be visible, and the International Energy Agency pointed out that, in 2002, global carbon dioxide emissions grew at a slower rate than global GDP, resuming the decade-long trend of decoupling global carbon dioxide emissions from economic growth that was broken in 2021.

4.2. Co-citation analysis

4.2.1. Author cited

The author co-occurrence graph captures the intensity of collaboration between authors by analyzing authors in the field. The number of publications is presented in the form of the size of nodes, and the sparsity of cooperation between authors is presented in the form of the thickness of connecting lines. According to **Figure 2**, the network mapping of authors' cooperation in this research field contains 335 nodes and 221 connecting lines, in general, most of the nodes have connecting lines, and it can be seen that the authors appearing in the graph are closely connected. Cai, Bofeng, Geng, Yong and Shan, Yuli form a group of authors, in addition, there are also some small cooperation teams between Li, Zheng, and There are also small collaborations between Li, Zheng, and Zhu, Jiao, are weak due to the small number of collaborators. According to **Table 1**, the first ranked is Cai, Bofeng node with the largest number of publications, with a total of 16 publications, mainly concentrated in 2017. Dong, Feng, Shan, and Yuli each published 11 articles in 2021 and 2018. There are four authors with more than 10 or more publications in this research area, with a total of 48 publications, of which the top five authors are Cai, Bofeng, Dong, Feng, Shan, Yuli, Li, Zheng, Li, Yan, in order, with 16, 11, 11, 10, and 9 publications, respectively. authors ranked in the top 10 have published six or more publications. The period is concentrated in 2017–2022. and the reason why scholars focus on the field of carbon emissions is mainly due to climate change, economic growth and carbon emissions constitute a contradictory pair of relationships, and these factors together promote the in-depth study of global carbon emissions.

Table 1. Scale of author's publications.

Frequency	Vintages	Name (of a thing)
16	2017	Cai, Bofeng
11	2021	Dong, Feng
11	2018	Shan, Yuli
10	2020	Li, Zheng
9	2022	Li, Yan
8	2019	Lin, Boqiang
8	2022	Li, Wei
7	2020	Wang, Can
7	2017	Geng, Yong
6	2017	Cai, Bofeng

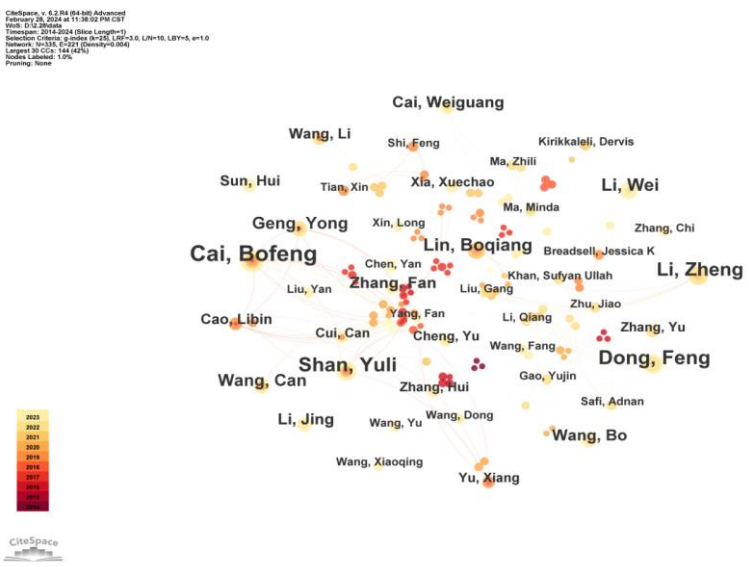

Figure 2. Author co-occurrence diagram.

4.2.2. Institutional citations

The node size and centrality of the research network in CiteSpace enable rapid identification of current research hotspots in the field. A total of 301 nodes with 1170 connections are shown. The size of the nodes visually demonstrates how active the institution is in research in a particular area, in addition, the centrality calculation is used to measure the importance of the nodes in the overall research network. Higher centrality of a node implies that the institution has a more central position in the research network and its research has a relatively greater degree of influence on the field as a whole. The visualization results from the analysis of 1907 documents can be derived from the main institutions of research in the field of editing and publishing, and at the same time, the cooperation between institutions can be more intuitively seen based on the connectivity between the nodes. In terms of issuing institutions, a representative issuing institution centered on the Chinese Academy of Sciences, Tsinghua University, North China Electric Power University, etc. is formed (see **Table 2**). The first institution is the Chinese Academy of Sciences, with 153 articles, which mainly focuses on the national "dual-carbon" strategic goal, innovates the institutional mechanism, integrates resources and advantageous strengths, and organizes a multidisciplinary research team on the "dual-carbon" strategy to continue to work on the "dual-carbon" strategy. The main purpose is to innovate the institutional mechanism, integrate resources and advantageous strengths, organize multi-disciplinary "dual-carbon" strategy research teams, and continuously promote the "action plan" to provide strong scientific and technological support for achieving the strategic goals of carbon peak and carbon neutrality. The second is Tsinghua University with 99 articles. The Carbon Neutral Research Institute of Tsinghua University will be driven by innovative concepts and mechanisms, and will actively build a new type of strategic platform to provide support for the new pattern of national development. These two institutions account for about 13% of the total number of articles issued, which is extremely influential. As can be seen from **Table 2**, most of the institutions are located in China through the geography of the research institutions.

It is a research pattern dominated by universities and supported by research institutes. In terms of the volume of publications, among the top ten institutions, there are eight universities and two research institutes. The top ten institutions with centrality greater than 0.1 are the Chinese Academy of Sciences (0.26) and Tsinghua University (0.28), totaling two. As can be seen from **Figure 3**, most of the institutions are closely linked, and all of them are universities and research institutes in China. The research institutions have transformed the inertia of single-discipline development, given full play to the advantages of basic research and cross-fertilization of the university, realized multi-institution, multi-department, and multi-discipline joint innovation, and concentrated their advantageous resources to accelerate the breakthrough of the key core technologies in the field of carbon-neutralization.

Table 2. Scale of institutional issuance.

Quantities	Centrality	Vintages	Mechanism
153	0.26	2016	Chinese Academy of Sciences
99	0.28	2016	Tsinghua University
72	0	2017	North China Electric Power University
60	0.04	2016	University of Chinese Academy of Sciences
59	0.05	2017	China University of Mining & Technology
52	0.04	2018	Institute of Geographic Sciences & Natural Resources Research
42	0.05	2016	Beijing Normal University
37	0.07	2017	Chongqing University
36	0.08	2017	Shanghai Jiao Tong University
35	0.09	2017	Peking University

Figure 3. Institutional co-occurrence diagram.

4.2.3. National citation

In the country co-occurrence **Figure 4**, a total of 90 countries appears, of which there are 4 countries with more than 50 articles in the literature. According to the countries shown in the figure, there are 4 countries in Europe, namely Netherlands, Germany, Russia, and England, 6 countries in Asia, namely People R China, Japan, Malaysia, India, Pakistan, and South Korea, and 2 countries in North America, USA and Canada, and 1 country in Australia. In North America, there are 2 countries, the

USA and Canada, and in Australia, there is 1 country, Australia, which are closely linked to each other, mainly to reduce greenhouse gas emissions and respond to the challenge of climate change, and each country is trying to grasp the dynamic balance between development and environmental protection and is actively narrowing the carbon neutral gap. As shown in **Table 3**, Peoples R China ranks first with 1706 articles, followed by the United States with 117 articles, England with 77 articles, and Australia with 52 articles. According to the centrality, Peoples R China 0.69, still ranked first, indicating that China's carbon emissions are very influential. It is followed by the United States, with a publication number of 117 and a centrality of 0.33, indicating that the articles published in the United States are popular and enjoy a great reputation in the international arena. Most of the articles in the table are from developed countries, and from a historical perspective, the developed countries that were the first to enter industrialization are more indebted to the "climate deficit". Secondly, major developed countries such as the United States, Germany, the United Kingdom, and Japan have formulated low-carbon development strategies in search of more sustainable development strategies.

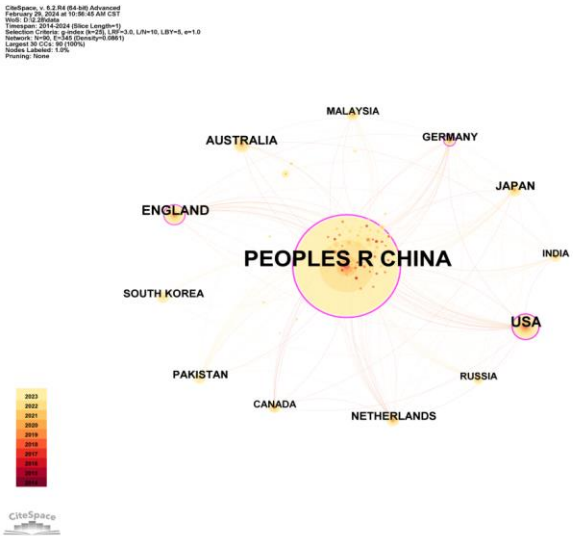

Figure 4. Country co-occurrence map.

Table 3. National Communications scale.

Quantities	Centrality	Vintages	Nations
1706	0.69	2016	PEOPLES R CHINA
117	0.33	2016	USA
77	0.19	2016	ENGLAND
52	0.06	2016	AUSTRALIA
37	0.04	2016	JAPAN
36	0.08	2016	NETHERLANDS
30	0.13	2016	GERMANY
30	0.01	2020	SOUTH KOREA
29	0.09	2016	PAKISTAN
23	0.02	2017	MALAYSIA

4.3. Literature co-citation analysis

Literature co-citation is an analytical method used to study the relevance of literature to each other. It refers to the fact that if multiple articles are cited by one or more later papers at the same time, the two papers are said to constitute a co-citation relationship. By analyzing the co-citation of literature, it is possible to find out information about important literature in the field of study, trends in the discipline, and so on. From **Figure 5**, it can be seen that most of the cited articles are those of Shan YL. This is followed by Chen (2020), Shan (2020), Mallapaty (2020), and Dong (2018). **Table 4** lists the 10 most cited articles on the topic of carbon emissions. Journals ranked 1, 2, 3, and 7 belong to scientific disciplines, journals ranked 5, 6, 8, and 9 belong to environmental disciplines, and journals ranked 4 and 10 belong to nature journals. The research topics are all centered on in-depth discussions of the carbon emissions situation, the factors influencing it, and the strategies for achieving carbon neutrality goals, through which the carbon emissions problem can be better addressed. The ranked 1 document, with 70 citations, used the Intergovernmental Panel on Climate Change (IPCC) emission accounting methodology to construct the quantity of China's 1997–2015 carbon emissions (Shan et al., 2018). Similar to #1 are #2, #3, and #10, all of which are scientific studies focusing on carbon dioxide emissions and whose results have contributed to the development of carbon mitigation policies (Chen et al., 2020; Shan et al., 2020; Zhou et al., 2021)

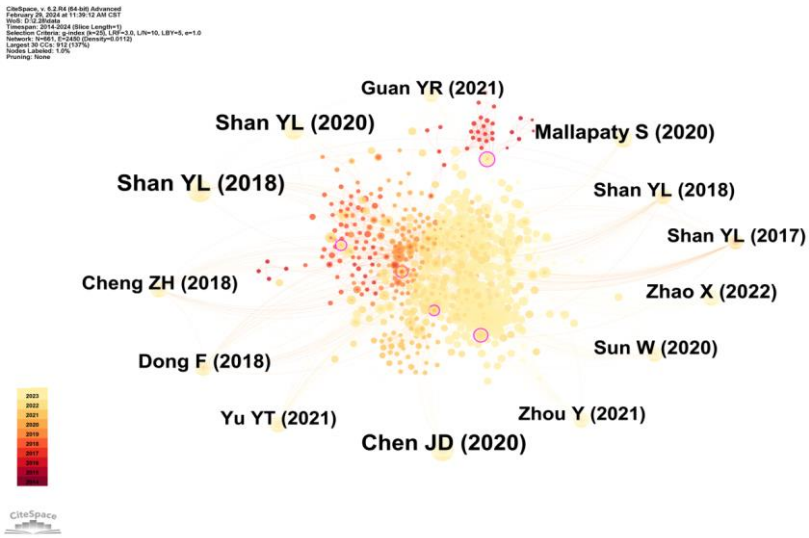

Figure 5. Literature co-citation graph.

Table 4. Scale of literature co-citation.

Frequency	Centrality	Label	Source	Titel
70	0.03	Shan (2018)	SCI DATA	Data Descriptor: China CO_2 emission accounts 1997–2015
60	0.01	Chen (2020)	SCI DATA	County-level CO_2 emissions and sequestration in China during 1997–2017
52	0.03	Shan (2020)	SCI DATA	China CO_2 emission accounts 2016–2017
41	0	Mallapaty (2020)	SCI DATA	How China could be carbon neutral by mid-century
32	0.07	Dong (2018)	RESOUR CONSERV RECY	Drivers of carbon emission intensity change in China

Table 4. (*Continued*).

Frequency	Centrality	Label	Source	Titel
34	0.03	Zhao (2022)	RESOUR CONSERV RECY	Challenges toward carbon neutrality in China: Strategies and countermeasures
33	0.05	Shan (2018)	SCI ADV	City-level climate change mitigation in China
33	0.08	Cheng (2018)	RENEW SUST ENERG REV	Industrial structure, technical progress and carbon intensity in China's provinces
32	0.06	Sun (2020)	J CLEAN PROD	How does urbanization affect carbon emission efficiency? Evidence from China
31	0.03	Zhou (2021)	SUSTAIN CITIES SOC	Urbanization, land use change, and carbon emissions: Quantitative assessments for city-level carbon emissions in Beijing-Tianjin-Hebei region

Author co-citation is the number of times an author's paper has been cited by other scholars in academia. It is an important indicator of a scholar's influence and academic contribution. As can be seen from **Figure 6**, each node represents an author, and the larger the node indicates that the corresponding author has published more literature, and vice versa, the less; different node colors as well as thinness and thickness represent the frequency of the author's appearance in different periods. The connecting lines between the nodes indicate the existence of a collaborative relationship between the authors. The upper left corner of **Figure 6** shows 813 nodes (N) and 4941 connecting lines (E) Among the many author nodes, Shan, Chen, Mallapaty, etc. are located in the nodes are more prominent, which represents that they also have more publications. Secondly, from the situation of connectivity presented in the figure for cooperation network analysis, from the number of cooperation, connectivity is complex, the researchers cooperate frequently, the outermost circle of scholars as the core researchers in the field of carbon emissions research, the pivotal role in carbon emissions research, and the inner circle of scholars in close contact with the inner circle of scholars, the formation of the outer circle of scholars as the center of the huge authors of the network of cooperation.

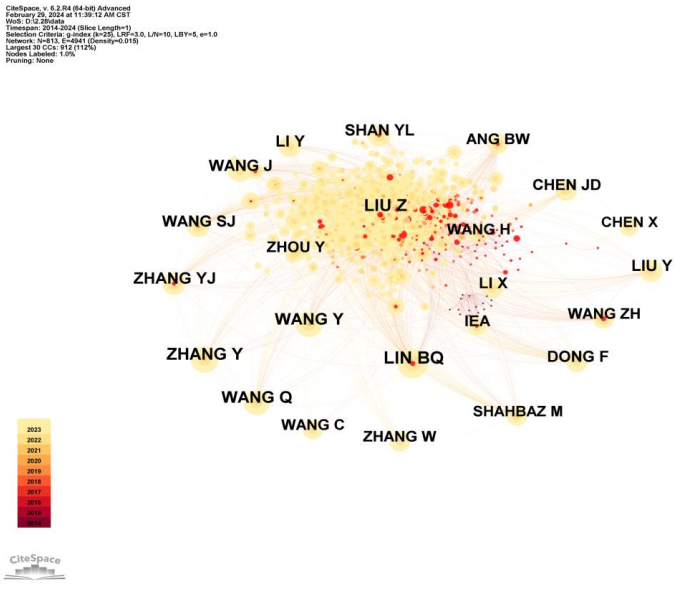

Figure 6. Author co-citation graph.

As can be seen in **Figure 7**, there are many journals involved in the field of carbon emissions, and the size of the nodes shows that J CLEAN PROD, ENERGY POLICY, APPL ENERG, RENEW SUST ENERG REV, ENERGY has a high number of articles issued, and the journals are closely linked. These journals mainly focus on the field of energy and technology and mainly study resource utilization and environmental protection. As can be seen from **Table 5**, there are three journals with more than 1000 articles in the top 10 journals, carrying a total of 3706 articles. However, the centrality of these mediators is less than 0.1, indicating that these journals are not broad enough in terms of influence. Most of these journals were published in 2016, and scholars are paying more attention to the issue of carbon emissions. This is mainly because the Paris Agreement officially came into effect in 2016, and countries proposed emission reduction targets and implementation strategies according to their national conditions, stimulating more research activities. Scholars' research can provide policymakers with a scientific basis to better set realistic and feasible emission reduction targets, which is of great significance to solving the global climate change problem.

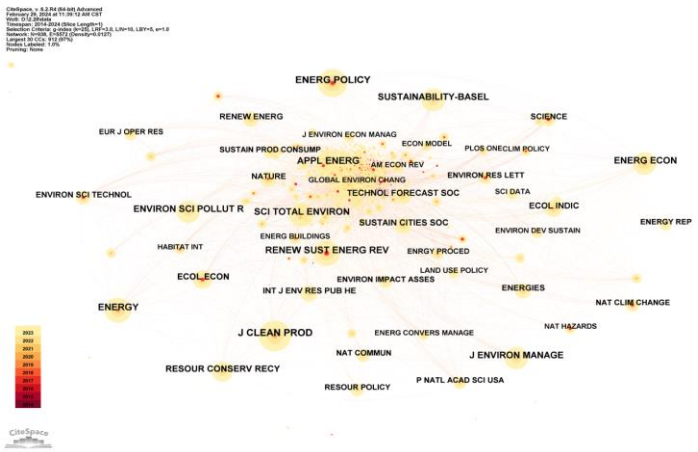

Figure 7. Journal co-citation graph.

Table 5. Journal co-citation scale.

Count	Centrality	Year	Cited journals
1480	0.03	2016	J CLEAN PROD
1213	0.02	2016	ENERG POLICY
1013	0.04	2016	APPL ENERG
993	0.01	2016	RENEW SUST ENERG REV
993	0.01	2016	ENERGY
932	0.05	2016	SCI TOTAL ENVIRON
824	0.03	2016	SUSTAINABILITY-BASEL
817	0.04	2016	J ENVIRON MANAGE
800	0.04	2016	ENERG ECON
777	0.02	2016	ENVIRON SCI POLLUT R

To further understand the latest developments and research directions of carbon emission research, the CiteSpace mutation detection algorithm was used. Based on the

information of titles, abstracts, and keywords of the selected database papers, mutation keywords were extracted and a mutation keyword word list was generated. Through the keyword analysis in **Figure 8**, there are 25 mutant keywords. From the chart, it can be seen that the keywords with high mutation values from 2016 to 2019 are low-carbon development, climate change, greenhouse gas emissions, framework, and urban. mainly because the international community has adopted a series of important in response to climate change. The main reason is that the international community has adopted a series of important policies to deal with climate change, and many countries have taken active measures for low-carbon development. The frequent occurrence of mutated terms usually reflects the foremost dynamics of a particular research field to a certain extent. The research hotspots keep changing, combining the keyword frequency, centrality, and abruptness, it can be seen that the research hotspots of carbon emission have shifted from low-carbon development, greenhouse gas emission, scenario analysis, etc. to carbon dioxide emissions, it can be seen that low-carbon transformation has far-reaching impacts on the realization of sustainable development goals. Among them, low-carbon development has frequently appeared from 2016 to 2020, which is mainly closely related to global carbon emission concerns, efforts to combat climate change, and sustainable development. The emergent words started in 2016, with most of the words revolving around low carbon, and climate change in these directions due to the Paris Agreement's proposal to mitigate greenhouse gas emissions. In 2017–2018 the emergent world began to shift towards specifics, such as residential buildings, waste management, and other specific areas. In 2019 and beyond, academics are using data to do more in-depth research and more accurate analysis in their research areas to provide more rigorous scientific evidence for national governments.

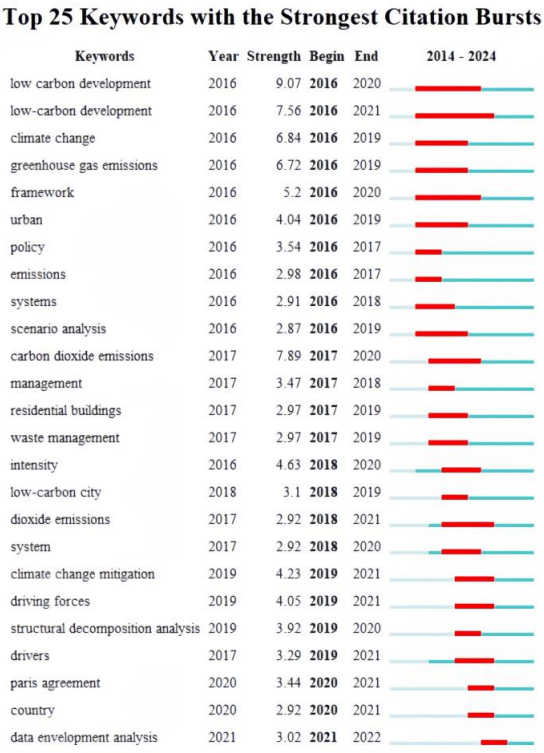

Figure 8. Keyword bursting map.

4.4. Analysis of research themes

Now, VOSviewer software is used to construct a knowledge graph in the field of carbon emissions with the analysis of subject terms, aiming to reflect the research hotspots in this field. As found in **Figure 9**, the research hotspots on carbon emissions start to develop in 2021 as climate change, mainly due to the seriousness of the global climate change situation, the increase of extreme weather events, and the increase of greenhouse gas concentrations pose a great challenge to human society and the natural environment. Then in May 2021, it will be energy consumption, CO_2 emission, and sustainable development, more because the peak of carbon emissions and carbon emission pathways have attracted widespread attention, and the improvement of energy efficiency and renewable energy development is regarded as an important means of realizing the transition to green and low-carbon development. 2022, it will be carbon neutrality. In 2022, it will be developed into carbon neutrality, and in 2023, it will gradually shift to the digital economy, mainly to improve the institutional mechanism and policy measures for low-carbon energy transition. The research field will gradually develop from climate change and low carbon to carbon emission and carbon neutrality. From experience, after the carbon summit, there will be a plateau period, after which, with technological progress, carbon capture technology and negative emission technology will be more and more widely used, and the level of carbon emission will continue to decline, enter into a virtuous cycle, and eventually achieve carbon neutrality.

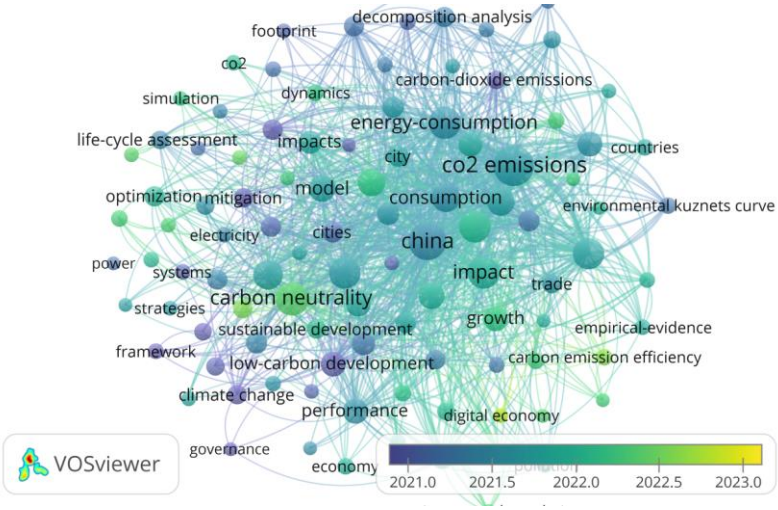

Figure 9. Keyword clustering map.

According to the density clustering map, there are 137 high-frequency keywords with a frequency of not less than 7. As shown in **Figure 10**, carbon neutrality has the highest density, and the reason why "carbon neutrality" has the highest density in carbon emission research is that it is driven by scientific and technological innovations, as well as the attention of international initiatives, enterprises, and the financial sector, and more importantly, it is in line with the sustainable development goals. Sustainable Development Goals (SDGs). Together, these factors have led to research and practice to find the most effective ways to achieve carbon neutrality. This is followed by China, CO_2 emission. These terms indicate that carbon neutrality is highly researched in the

field of carbon emission. The density of climate change in the figure shows that it is mainly caused by human activities that lead to greenhouse gas emissions, and there has been a wide range of concerns about how to reduce greenhouse gas emissions, improve energy efficiency, and develop renewable energy and other technologies.

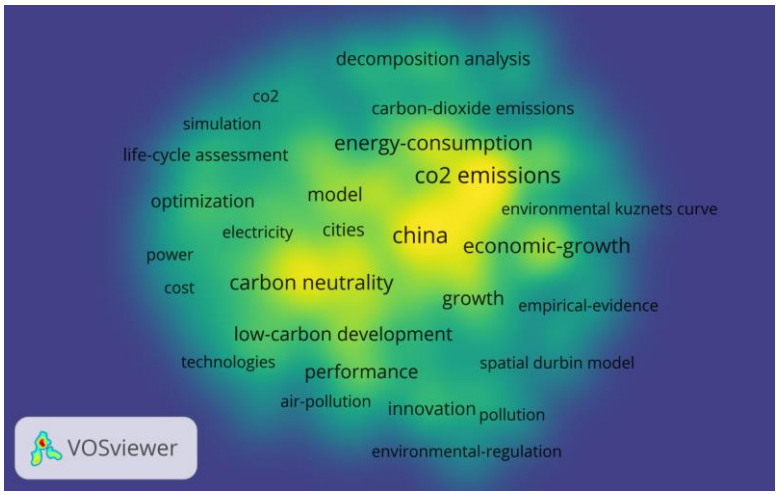

Figure 10. Keyword density map.

5. Evolutionary analysis of the study

In order to further understand the research trend of scholars' information retrieval behavior, the trend of high-frequency keyword changes was plotted using the R-based Bibliometrix program. As can be seen from **Figure 11**, from 2012 to 2014, carbon emission research was just starting and the focus was mainly on affluence, and it started to shift to government and developing-country in 2014, which was mainly due to the fact that 2014 was the 20th Conference of the Parties (COP 20) under the United Nations Framework Convention on Climate Change (UNFCCC) of the United Nations Framework Convention on Climate Change (UNFCCC). During this period, international attention to the issue of climate change grew and governments began to engage more actively in carbon emission mitigation and efforts to combat climate change. Thus, the shift in keywords from carbon emissions to governments and developing countries may reflect researchers' focus on national-level policies and actions. In 2015 some scholars focused on adaptation, benefits, which reflected a trend toward more practical, integrated, and socioeconomic interest in climate change research. In 2018 the keywords shifted to inventory, urban, framework, with researchers paying more in-depth and granular attention to carbon emissions issues in 2018. Scholars may gradually shift from a more macro level, such as global climate change, to more specific directions, such as inventory development, urban emissions, and the establishment of research frameworks. This change contributes to a more comprehensive understanding of the carbon emissions issue and the development of more practical responses. Beyond 2020, the focus is clearly on 'CO_2 emissions', especially, 'energy consumption' and its 'intensity', reflecting a growing interest in the accuracy of emission inventories, the issue of carbon emissions in the context of urbanization, and the design of overall structures. intensity", reflecting the global urgency to address climate change and achieve peak carbon and carbon neutrality.

These changes in keywords reveal a central trend: as understanding of the impacts of climate change deepens, research is focusing on energy production and consumption activities as the main source of carbon dioxide emissions, underscoring the importance of strengthening carbon mitigation efforts in the energy sector.

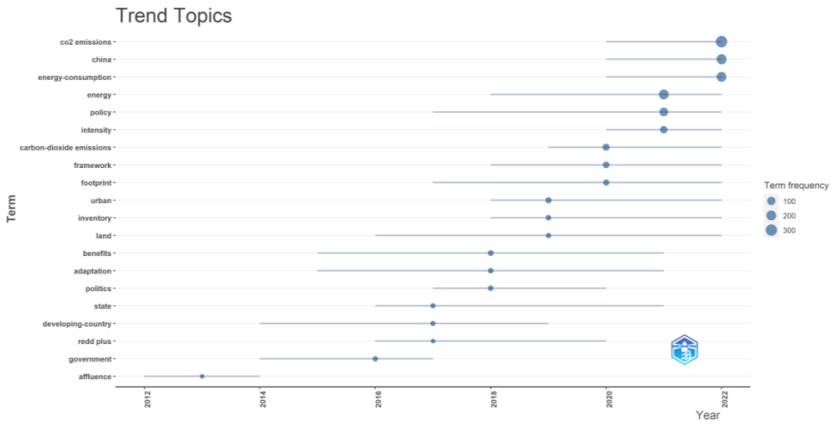

Figure 11. Trends in keywords.

The coupled clustering diagram presented in **Figure 12** provides insight into the key themes and trends in the current research area. In the first quadrant in the upper right corner, it is noted that the calibrated themes are not only of high importance but have also made significant progress. In particular, the location of the circles reveals that issues regarding CO_2 emissions and energy consumption in low-carbon cities have received a lot of attention and milestones have been achieved in this area. This trend is closely linked to global policy orientations, reflecting a concerted international effort to combat climate change and promote sustainable development. In the second quadrant from the top left, there is a relative lack of research in this region, although there are scholars who have already conducted extensive research in this area. This suggests that although there is a certain amount of research based on topics such as carbon emissions and energy efficiency, they still need to be deepened and improved. The third quadrant reveals the so-called 'marginalized topics', including the impact of carbon emissions on economic growth and some fragmented research activities. These themes are currently marginalized in mainstream research and lack sufficient attention. However, they are critical to a comprehensive understanding of the interaction between the economy and the environment. Therefore, the academic community needs to conduct more systematic and in-depth research on these topics to more accurately assess the impacts of carbon emissions on economic growth and formulate corresponding response strategies. Quadrant 4 identifies several areas that are important but underdeveloped research topics, such as energy consumption and decomposition analyses. These potential hotspot areas are full of challenges and opportunities, and their development may lead to new directions in academic research in the future. Therefore, encouraging more researchers and institutions to devote themselves to exploring these areas will not only help to promote the advancement of the discipline but also help to provide innovative solutions to the energy and environmental problems facing the world. Future research should actively seek new

theoretical perspectives and methodologies to grasp and interpret the deeper significance of these complex topics.

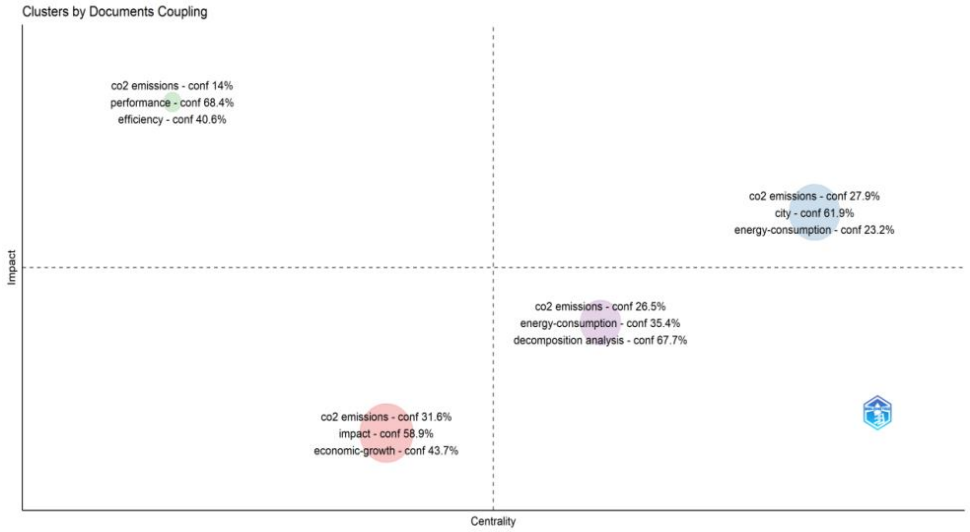

Figure 12. Keyword coupling clustering diagram.

The analysis of the data in **Figure 13** reveals an evolutionary trend in carbon emissions research that is closely linked to global policy orientations, theoretical frameworks, and practical applications. From 2014 to 2020, research focused mainly on the core topics of energy, mortality, sustainable development, and CO2 emissions. These concerns reflect the joint efforts of the international community to combat climate change and promote the development of a low-carbon economy. The concept of sustainable development, in particular, not only reflects the depth of theoretical research, but also points to the integrated consideration of economic, social, and environmental dimensions in practical policymaking. Entering 2021–2022, the research field begins to expand, with content focusing more on the impacts of energy consumption and carbon emissions, as well as related policy responses. The diversity of research in this period indicates that scholars are exploring multiple dimensions of the carbon emissions issue and are committed to providing a more comprehensive scientific basis for policymaking. For example, research in the energy sector has expanded to include the use of renewable energy, energy efficiency strategies, and green technology innovations. By 2023, carbon research will be further diversified to cover transport, sustainability, and management. These new keywords highlight the intersectionality of carbon emission issues with other fields, such as emission reduction measures in the transport sector, environmental management strategies for businesses, and sustainability assessment of public policies. This multidisciplinary convergence helps deepen our understanding of the complexity of carbon emissions and promotes cross-disciplinary solution innovation. Taking an overview of the development trend of the keywords, it can be seen that carbon emissions research has always maintained a high level of interest and has expanded and enriched its research fields and directions over time. This not only helps the global community to better understand and address the carbon emission challenges but also provides researchers with a wide range of exploration space to support the global long-term goal of carbon peaking and carbon neutrality.

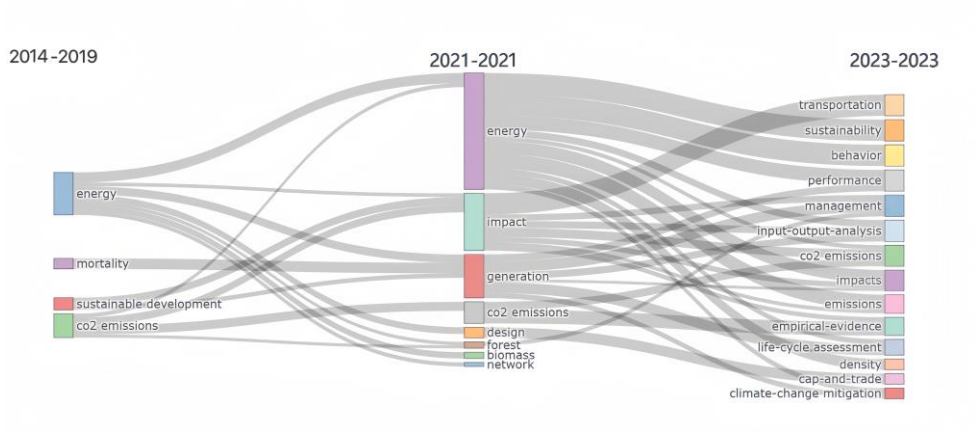

Figure 13. Keyword Sankey diagram.

6. Conclusions and outlook of the study

By analyzing data from 1907 carbon emission papers from 2014–2023 with the visualization tool CiteSpace, we constructed and generated author, institution, and country partnership maps, keyword clustering, and emergent word detection, literature co-citation, keyword evolution, keyword coupling clustering map, keyword Sankey map, and many other maps.

In terms of the basic situation of global carbon emission research, the overall trend of literature publication shows an upward development, and the number of highly cited authors in carbon emission research is relatively small. Research institutions are mostly universities, most of which are institution-level corporations, and there is less cooperation between universities and research government agencies.

In terms of the trend of the evolution of the research field, it can be divided into 3 phases, the first phase is 2016–2018, in which the global attention to the issue of carbon emissions gradually increased. Governments and international organizations began to recognize the impact of climate change on the global economy, ecology, and society, and the research direction of scholars was more concentrated, mainly focusing on the perspective of carbon emissions, climate change, and low-carbon development. The second stage is from 2018 to 2021, countries have strengthened the construction of the carbon emissions trading market to reduce carbon emissions through the market mechanism, and scholars' research areas are mostly focused on developing countries, government strategies, energy consumption, and other aspects. The third stage is 2019–2023, in which the global carbon emission problem enters a new stage. In the face of the economic and social impacts of the new crown epidemic, governments have taken a more active attitude in addressing climate change. The research direction of scholars at this stage shows a decentralized trend, with studies focusing on various aspects, carbon neutrality, drivers, carbon dioxide emissions, and a more targeted approach to the field of carbon emissions. Based on the findings so far, it is proposed to focus on analyzing three key sectors: Energy, manufacturing, and transport. By analyzing the carbon emission patterns and trends in these sectors, we can more precisely formulate a well-targeted carbon reduction strategy, while providing a scientific basis for policy formulation. For the energy sector, we can study the changes in carbon footprint during the conversion of traditional fossil fuels to renewable energy;

for the manufacturing sector, the analysis can focus on process optimization and the promotion and application of energy-saving and emission-reduction technologies; and for the transport sector, the study should focus on the transformation of electrification, the improvement of logistic efficiency, and the use of low-carbon fuels. Such industry-specific analyses will help advance more effective carbon emissions research.

Future research can build on this foundation and further explore the following directions in depth: First, interdisciplinary cooperation is a trend in modern scientific research, and the issue of carbon emissions involves several disciplinary fields, such as environmental sciences, economics, sociology, and so on. In the future, the research and practice of interdisciplinary cooperation can be strengthened to promote communication and cooperation among different disciplines to jointly solve the carbon emission problem. Secondly, technological innovation is a key driver for in-depth research. With the emergence of cutting-edge technologies such as artificial intelligence and big data, we have the opportunity to collect, analyze, and interpret data on carbon emissions in an unprecedented way. This not only improves the efficiency of research but also helps to discover new emission reduction strategies as well as optimize existing ones. Finally, in-depth analyses of domestic and international carbon emission reduction policies and assessment of their effects are crucial to the formulation of effective policies. Policies in different countries and regions reflect a variety of values, economic conditions, and social needs, and understanding these differences can help design emission reduction strategies that are more adaptable to local conditions.

This paper analyses trends in literature publication and keyword evolution, identifies current patterns of academic collaboration in carbon emissions research, and points to the problem of insufficient cross-institutional collaboration, which provides a direction for improvement in future collaboration. Meanwhile, the research hotspots at different stages are analyzed according to the evolution of the research field over time, which provides a scientific basis for the government and policymakers to formulate relevant policies and offers new perspectives to explore the development trend of carbon emissions. In addition, the discovery of emerging research themes and technological applications has promoted scientific and technological innovations, especially advances in carbon neutral and low carbon technologies, which are crucial for the global response to the challenge of climate change.

The research in this paper still has some limitations, and in the future field of carbon emission research, it is necessary to improve the theoretical framework and expand the distribution of research disciplines to examine carbon emissions in different fields, to make the article logically meticulous and better structured.

Author contributions: Conceptualization, SZ and RC; methodology, SZ; software, XW; validation, CL, XW and RC; formal analysis, SZ; investigation, CL; resources, XW; data curation, RC; writing—original draft preparation, SZ; writing—review and editing, XW; visualization, CL; supervision, XW; project administration, CL; funding acquisition, RC. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by Zhejiang Provincial Philosophy and Social Science Planning Project (ZX2023000228).

Conflict of interest: The authors declare no conflict of interest.

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