frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 06 March 2023
DOI 10.3389/fenrg.2023.1121639

OPEN ACCESS

EDITED BY
Amrit Mukherjee,
University of South Bohemia in České Budějovice, Czechia

REVIEWED BY
Lei Shi,
Luliang University, China
Jun Zheng,
Baotou Teachers' College, China

*CORRESPONDENCE
Ye Zheng,
lbxjbzy@nwpu.edu.cn

SPECIALTY SECTION
This article was submitted to Sustainable Energy Systems, a section of the journal Frontiers in Energy Research

RECEIVED 13 December 2022
ACCEPTED 20 February 2023
PUBLISHED 06 March 2023

CITATION
Zheng Y, Li Z and Chai J (2023), Progress and prospects of international carbon peaking and carbon neutral research –based on bibliometric analysis (1991–2022).
Front. Energy Res. 11:1121639.
doi: 10.3389/fenrg.2023.1121639

Progress and prospects of international carbon peaking and carbon neutral research –based on bibliometric analysis (1991–2022)

Ye Zheng[1,2]*, Zhenmiao Li[1] and Jinlai Chai[1]

[1]School of Public Policy and Administration, Northwestern Polytechnical University, Xi'an, Shaanxi, China, [2]National Governance Collaborative Innovation Research Center, Northwestern Polytechnical University, Xi'an, Shaanxi, China

Carbon peak and carbon neutrality is an important strategic measure to tackle climate change and is of great significance to global climate governance, human development, and scientific and technological progress. In this paper, we used 3,824 papers in the core collection of Web of Science from 1991 to 2022 as a sample, and used bibliometric analysis and CiteSpace, a visual knowledge network analysis tool, to sort out the current status of international carbon peak and carbon neutrality research in terms of publication trends, temporal distribution, spatial distribution, keyword co-occurrence mapping, and research basis. And then the current hot topics of research are explored,including carbon neutralization technology, climate policy impact and performance evaluation, carbon pricing and carbon finance, citizen participation attitude and behavior, and climate governance and global cooperation. Research prospects have been presented in terms of four aspects: building the integrated research framework of carbon peak and carbon neutral research, establishing a comprehensive and efficient environmental policy system, expanding research cooperation, deepening research and application of carbon peak carbon-neutral technology.

KEYWORDS

climate change, carbon peak, carbon neutral, bibliometric analysis, research progress

1 Introduction

Reducing greenhouse gas emissions and tackling climate change has become an important issue for global sustainable development. A series of representative agreements, including the United Nations Framework Convention on Climate Change, Kyoto Protocol, and Paris Agreement, has been signed, outlining the goals and directions for global climate governance and carbon emission reduction. In 2015, 178 global parties signed the Paris Agreement, setting the target to "limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels" in the 21st century. Against this background, a new journey of global economic and social development led by the goal of "carbon peak and carbon neutrality" has begun. At the One Earth Summit in December 2017, 29 countries signed the Carbon Neutralization Alliance Statement, promising zero carbon emissions by the mid-21st century. As of May 2022, 127 countries have proposed or are prepared to set carbon-neutral targets, covering 90% of global GDP, 85% of the total population, and 88% of carbon emissions. The goals of carbon peak and carbon neutrality

require profound economic and social systemic change; therefore, global sustainable development is of great significance. Research on carbon peak and carbon neutrality has also received attention from scholars internationally.

Carbon peak refers to the stage of declining carbon emissions following a historical peak in CO_2 emissions during a certain period. Carbon neutrality, also known as "net zero carbon emissions," involves practicing afforestation, energy conservation, and emission reduction to offset the generated carbon emissions. Theoretically, carbon peak has been extensively researched worldwide; international action and strategic analysis, strategies to achieve carbon peak and carbon neutrality, carbon-neutral technology research, renewable energy, carbon emission trading, and carbon finance are important research interests. However, few studies have investigated the overall research status and trend of carbon neutrality in carbon peak, showing a state of fragmentation and decentralization. The existing review of research is subject to factors such as insufficient literature sources and data and a limited research perspective, fails to reveal the overall research status and dynamics of carbon peak and carbon neutrality research, and lacks a systematic review of phased results.

In view of this, this paper presents a bibliometric analysis of the international carbon peak carbon neutral research status and development trend of systematic exploration. We aimed to investigate the current carbon peak and carbon neutrality research hotspot and development trends to assist international climate governance and carbon peak and carbon neutrality field research. This paper would serve as a valuable reference for countries with similar emission targets.

2 Data sources and research methods

2.1 Data sources

The data were obtained from the Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI) databases in the Web of Science core collection. In terms of English journal retrieval, the retrieval type was set to TS = ("carbon neutral *" OR "carbon neutrality *" OR "carbon peaking *"). Climate change is an important challenge for all countries in the world, and achieving carbon neutrality, i.e., "net-zero CO_2 emissions", has become the consensus of all countries in the world. Carbon peaking refers to a point in time when carbon dioxide emissions stop growing and peak, and then gradually fall back. It marks the decoupling of carbon emissions from economic development, which is important for reducing greenhouse gas emissions and achieving the goal of carbon neutrality. Therefore, this study conducted a common search for "carbon peak" and "carbon neutrality" to ensure a more comprehensive study in the field of carbon emission management. In addition, the retrieval language and literature type were set to "English" and "Aritical," respectively, and the retrieval time was 28 July 2022. The search results showed that there were more than 4,000 papers distributed in different research fields.

Based on the initial sample, this study optimized the results by further excluding irrelevant research directions, such as ethics, history philosophy of science, communication, computer science cybernetics, etc. In addition, to ensure the validity of the visualization analysis, the abstracts of the retrieved papers were read and analyzed to exclude some articles that did not match the research topic, i.e., some articles did not include the concept of "carbon peaking" or "carbon neutrality" as their core research, although they contained the topics used in the search. The concept of "carbon peaking" or "carbon neutralization" was not included as a core research topic. Finally, a total of 3,824 valid articles were obtained after excluding invalid articles in this study.

2.2 Research methods

Bibliometric analysis was used for this study. The analysis used the literature system and bibliometric characteristics as the research object; mathematics and statistical methods were employed to study the distribution of literature information structure, quantitative relationship, and change law, following which the field of knowledge structure, characteristics, and laws of the research method were explored. This study adopted the general bibliometric analysis of carbon peak and carbon neutrality research countries and institutions and journal distribution analysis, including the volume of related research literature, research author and institutional information, journal information, and statistical summary of frequently cited literature. The research trend evolution and hot topics were analyzed based on keywords. Common word analysis (Co-word Analysis) is the most important analysis method in bibliometrics and sciometrics, performed primarily by building two keywords in the same literature frequency, performing cluster integration, and analyzing the density relationship between the common keywords to explore the keywords that reflect popular research topics, evolution path, and evolution trend, among others. Scientific knowledge graphs are a product of innovations in sciometrics that allow users to visualize the development, evolution, and internal logical relationship of discipline research. Compared with the traditional methods, the structure, context, and law of the discipline development can be found more objectively, scientifically, and efficiently. CiteSpace is a visual software for literature research and measurement analysis, with the advantages of quick data processing, visual effect, and convenient interpretation. Therefore, the research hotspots are displayed in an intuitive fashion, and the visual map shows corresponding literature content-specific analysis, leading to an objective understanding of the current situation of a research field and potential developments in the future. Therefore, this software can meet the analysis needs of countries, institutions, journals, and authors and promote the evolution of carbon neutrality.

3 Overall analysis of spatial and temporal distribution of international research

3.1 Time evolution of the number and changing trend of paper publications

Using statistics and sorting out the amount of carbon peak and carbon neutrality literature, the current development status and trends of carbon peak and carbon neutrality research could be

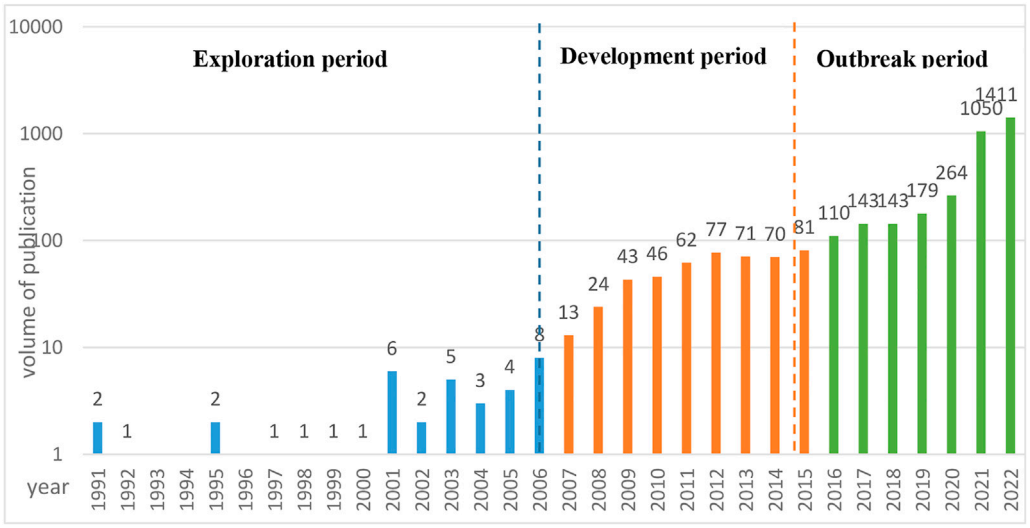

FIGURE 1
Statistics on the volume of publications on carbon peaking and carbon neutrality from 1991 to 2022.

understood. As can be seen from Figure 1, the number of publications on carbon peak and carbon neutrality shows a continuous upward trend, and the inflection point also reflects evident stage characteristics. The research on carbon peak and carbon neutrality continues to attract the attention of scholars and has shown explosive growth in the past 3 years.

Figure 1 shows that the number of international publications regarding carbon peak and carbon neutrality research has increased significantly since 1991, and its evolution can be divided into three stages. During the exploration period from 1991 to 2006, research papers on climate change and carbon neutrality were increasingly found; however, the topic still received low academic attention, with less than 10 publications annually. Since the 1980s, with a deeper understanding of earth science, climate change has become an important issue internationally. In 1990, the Intergovernmental Panel on Climate Change (IPCC) released its first assessment report, which confirmed the scientific basis of climate change issues and has impacted both governments and the general public globally. In 1992, the United Nations General Assembly adopted the United Nations Framework Convention on Climate Change, which established the ultimate goal of tackling climate change and the basic principles of international cooperation regarding the same. The publication of the IPCC Second Assessment Report in 1995 and the adoption of the Kyoto Protocol in 1997 increased academic attention to climate change and carbon emissions, thereby gradually promoting the study of carbon neutrality. The development period from 2007 to 2015 saw a steady increase in the number of internationally relevant research publications, with a total of more than 500 publications, indicating greater academic interest. In February 2005, the Kyoto protocol was enforced, and the Bali roadmap and Copenhagen climate conference in 2009 further defined the responsibilities of developed and developing countries. Most countries were interested in climate governance and carbon reduction. Since 2016, the field has witnessed exponential interest; the number of relevant research publications has increased sharply, with more than 1,000 publications annually until 2020. Recently, global warming caused by human activities and natural phenomena has seriously impacted the world. The continuous evaluation reports published by the IPCC show a cause for concern. The Paris agreement signed in 2016 for global climate governance provides a clearer direction, setting the goal to achieve net zero emissions by the second half of the century. Globally, most countries have carbon peak carbon neutrality as a national strategy or policy goal. Both the volume and thoroughness of research studies are expected to improve further.

3.2 Distribution of core authors, institutions, and journals of international research

Table 1 respectively, show the top 10 authors who published the most articles in the international field of carbon peak and carbon neutrality research between 1991 and 2022. As can be seen from the Tables, in terms of international research, Chinese scholars predominate the top 10 authors of published papers, with Wei Li occupying the top position with 16 published articles. Professor Cui Qiang from Southeast University and Professor Sun Xuping from Sichuan University have both published more than 10 articles. Articles by the South Korean professor Eilhann E Kwon and the Bangladeshi scholar Muntasir Murshed, among others, were also published more frequently.

To explore the distribution and cooperation of carbon-neutral research institutions studying carbon peak, this study further generated the co-occurrence map of international research institutions in the field using CiteSpace, as is shown in Figure 2.

The Chinese Academy of Sciences published the highest number of articles (199) in foreign journals in the institution, followed by the Tsinghua University, University of Chinese Academy of Sciences, North China Electric Power University, University of California,

TABLE 1 Top 10 authors in terms of international publications.

Ranking	Author	No. of publications	Ranking	Author	No. of publications
1	WEI LI	16	6	PENG WANG	10
2	QIANG CUI	12	7	EILHANN E KWON	8
3	JUN LI	11	8	YANG LIU	8
4	LEI WANG	10	9	YANG ZHANG	8
5	XUPING SUN	10	10	MUNTASIR MURSHED	8

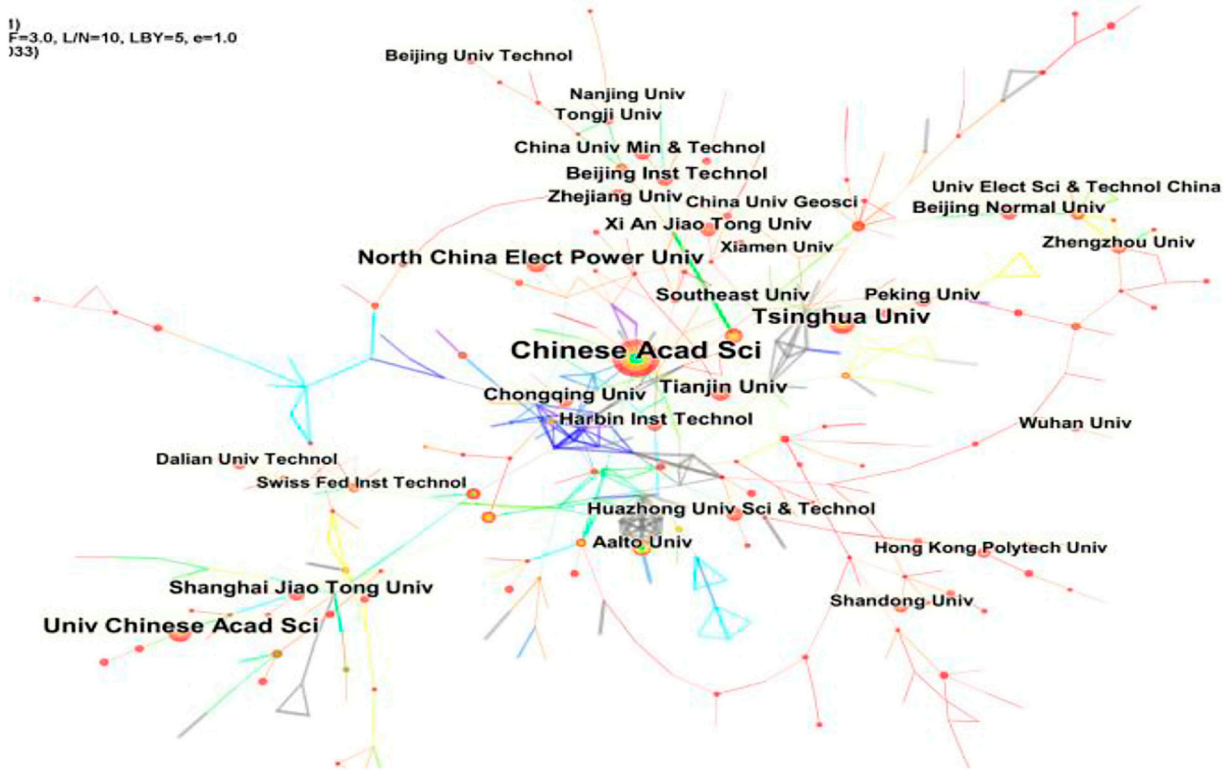

FIGURE 2
Institutional cooperation network.

and University of Alto, among others. Simultaneously, the Oak Ridge National Laboratory ORNL (Oak Ridge National Laboratory), as the largest scientific and energy research laboratory under the US Department of Energy, has also thoroughly studied carbon peak and carbon neutralization, with the highest centrality (centrality = 0.29), followed by Auburn University (centrality = 0.22), Federal Institute of Technology in Lausanne (centrality = 0.18), and Chinese Academy of Sciences (centrality = 0.16). These research institutions or organizations also play an important role in carbon peak and carbon neutralization research. In general, international research in the field of carbon peak and carbon neutrality is predominantly generated from institutions of higher learning and scientific research. Foreign research institutions and academic groups form a relatively close network, which facilitates the integration of academic resources and promotes cooperative innovation and achievement output.

To analyze the distribution of journals publishing research papers on carbon-peak and carbon neutrality, the number of journal publications was counted and the top 10 journals were ranked. The results are shown in Table 2. As can be seen from Table 2, the international carbon peak and carbon neutrality research published journals are primarily well-known journals with JCR1 region and high impact factors, such as *Sustainability*, *Journal of Cleaner Production*, *Energies*, and *Applied Energy*, with 177, 153, 151, and 113 publications, respectively. The carbon peak and carbon neutrality research involves a wide range of fields, covering environmental science, energy and fuel, industrial economy, green production, sustainable development, and other

TABLE 2 Top 10 international journals in terms of the number of publications.

Ranking	Journal name	No. of publications	Impact factor	JCR subregion
1	*SUSTAINABILITY*	177	3.889	Q2
2	*JOURNAL OF CLEANER PRODUCTION*	153	11.072	Q1
3	*ENERGIES*	151	3.252	Q3
4	*APPLIED ENERGY*	113	11.446	Q1
5	*ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH*	103	5.19	Q2
6	*ENERGY*	101	8.857	Q1
7	*FUEL*	74	8.035	Q1
8	*JOURNAL OF ENVIRONMENTAL MANAGEMENT*	74	8.91	Q1
9	*SCIENCE OF THE TOTAL ENVIRONMENT*	57	10.753	Q1
10	*RESOURCES CONSERVATION AND RECYCLING*	55	13.716	Q1

fields; the research on carbon peak and carbon neutrality is complex and systematic and the realization of carbon peak and carbon neutrality goals requires interdisciplinary and multi-field cooperation.

4 Knowledge basis and hot topic analysis of international research on carbon peak and carbon neutrality

4.1 High co-citation analysis on international research on carbon peak and carbon neutrality

The research frontier of a certain field is believed to represent the development status of a research field; therefore, the quotations of the research frontier will form the corresponding knowledge basis. The analysis must first be performed from the knowledge base level to understand the essence of carbon neutrality research frontier at home and abroad. With the help of CiteSpace, this paper expresses the structure, hot spots, and direction of the international carbon peak and carbon neutrality research knowledge basis through the high co-citation analysis. Additionally, the paper arranges the citation times in descending order and further arranges the top ten literature information, as shown in Table 3.

According to Figure 3 and Table 3, the most extensive literature on carbon neutrality is The Special Report on Global Warming of 1.5°C published by the IPCC (Change, 2018). Other core literature was mainly published between 2017 and 2020, exploring net zero-emission energy systems, biomass energy, carbon capture, carbon storage, and carbon utilization technology routes and application prospects, and China's carbon-neutral targets.

Promoting energy system transformation has always been a key driver of carbon reduction and decarbonization. Davis SJ (2018) showed that the successful transition to future net zero emission energy systems may depend on large amounts of cheap, emission-free electricity, mechanisms which is quickly and cheaply to balance the large and uncertain timing differences between demand and generation and electrification alternatives for most fuel-using equipment, alternative materials and manufacturing processes for structural materials, and carbon-neutral fuels (Davis et al., 2018). Forest bioenergy is a good alternative to fossil fuels, but the potential of forest bioenergy to reduce greenhouse gas emissions must be balanced with the forest carbon impacts associated with biomass harvesting. Mckechnie J (2018), performed a life cycle assessment (LCA) and forest carbon analysis to evaluate the total greenhouse gas emissions of forest bioenergy over time (McKechnie et al., 2011).

In addition, negative emission technologies also play an important role in achieving climate change goals. Bui M (2018) showed that negative emission technologies also play an important role in achieving climate change goals (Bui et al., 2018). Carbon capture and storage (CCS) technologies were reviewed, and the research scope was expanded to include key negative emission technologies (NETs) and CCS (BECCS) and direct air capture (DAC) for bioenergy. Subsequently, Hepburn C (2019) further reviewed the ten ways of CO_2 utilization (Hepburn et al., 2019). In addition, scientists have found that CO_2 can be electrocatalytically converted into chemical materials, which could help reduce the dependence of the chemical industry on fossil fuels and potentially contribute to reducing carbon emissions. Seh et al. (2017) have discussed the design strategy of advanced heterogeneous electrocatalysts and related materials, and efforts to extend this research to new clean energy reactions and develop novel catalysts in clean energy conversion can further promote the sustainable production of fuels and chemicals. Subsequently, (Nitopi et al., 2019) (De Luna et al., 2019) have also provided new insights and perspectives for the future prospects of electrocatalysis and biocatalysis.

China is the largest energy consumer and CO_2 emitter, accounting for 30% of global emissions; therefore, the attainment of carbon peak and carbon neutrality by China is of great significance. Mallapaty (2020) concluded that for China to achieve its carbon-neutral goal, it must increase electricity production and develop and expand the use of renewable energy, such as switching from gasoline cars to electric cars. And CCS should also be further developed. In the study by Shan et al. (2020), CO_2 emission and energy inventories were constructed for China and its 30 provinces,which providing data support for further emission-related research and emission reduction policy formulation.

TABLE 3 Statistical analysis of highly Co-cited literature (top 15).

No.	Author	Title	Co-citation frequency	Impact factor	Journal name	Year of publication
1	Intergovernmental Panel on Climate Change (IPCC)	Global Warming of 1.5°C	55	--	--	2018
2	Mallapaty, Smriti	How China Could Be Carbon Neutral By Mid-century	52	69.504	*NATURE*	2020
3	Shan, YL; Guan, DB; Zheng, HR; et al.	Data Descriptor: China CO_2 emission accounts 1997–2015	37	8.501	*SCIENTIFIC DATA*	2018
4	Bui, M; Adjiman, CS; Bardow, A; et al.	Carbon capture and storage (CCS): the way forward	37	39.714	*ENERGY & ENVIRONMENTAL SCIENCE*	2018
5	Seh, ZW; Kibsgaard, J; Dickens, CF; et al.	Combining theory and experiment in electrocatalysis: Insights into materials design	35	63.714	*SCIENCE*	2017
6	Nitopi, S; Bertheussen, E; Scott, SB; et al.	Progress and Perspectives of Electrochemical CO_2 Reduction on Copper in Aqueous Electrolyte	34	72.087	*CHEMICAL REVIEWS*	2019
7	Shan, YL; Huang, Q; Guan, DB; et al.	China CO_2 emission accounts 2016–2017	30	8.501	*SCIENTIFIC DATA*	2020
8	Dinh, CT; Burdyny, T; Kibria, MG; et al.	CO_2 electroreduction to ethylene *via* hydroxide-mediated copper catalysis at an abrupt interface	27	63.714	*SCIENCE*	2018
9	De Luna, P; Hahn, C; Higgins, D; et al.	What would it take for renewably powered electrosynthesis to displace petrochemical processes?	26	63.714	*SCIENCE*	2019
10	Mckechnie, J; Colombo, S; Chen, JX; et al.	Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels	25	11.357	*ENVIRONMENTAL SCIENCE & TECHNOLOGY*	2018
11	Hepburn,C; Adlen, E; Beddington, J; et al.	The technological and economic prospects for CO_2 utilization and removal	23	69.504	*NATURE*	2019
12	Davis, SJ; Lewis, NS; Shaner, M; et al.	Net-zero emissions energy syste ms	23	63.714	*SCIENCE*	2018
13	Birdja, Y Y; Pérez-Gallent, E; Figueiredo, MC; et al.	Advances and challenges in understanding the electrocatalytic conversion of carbon dioxide to fuels	22	67.439	*NATURE ENERGY*	2019
14	Morales-Guio, CG; Cave, ER; Nitopi, SA; et al.	Improved CO_2 reduction activity towards C_{2+}alcohols on a tandem gold on copper electrocatalyst	21	40.706	*NATURE CATALYSIS*	2018
15	Khan, Z; Ali, S; Umar, M; et al.	Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy	20	10.753	*SCIENCE OF THE TOTAL ENVIRONMENT*	2020

Therefore, the aforementioned high co-cited literature lays an important knowledge foundation for current and future scholars, provides potential and feasible technical routes, and indicates areas for further research.

4.2 Hot topic analysis of international research on carbon peak and carbon neutrality

Keywords reflect the central information of a document and indicate its theme. This study combined the keywords and word frequency to explore the carbon peak and carbon neutrality research field at home and abroad. Specifically, this study imported the retrieved literature information into CiteSpace; the analysis period, time slice, and Node Type were 1991–2022, 1 year, and Keywords, respectively, following which the knowledge map of foreign high-frequency keywords was obtained, as is shown in Figure 4. The analysis results showed that from 1991 to 2022, foreign carbon peak and carbon neutrality research hotspot high-frequency keywords were: energy (329 times), impact (321 times), performance (298 times), system (226 times), emission (223 times), CO_2 emission (221 times), model (205 times), carbon dioxide

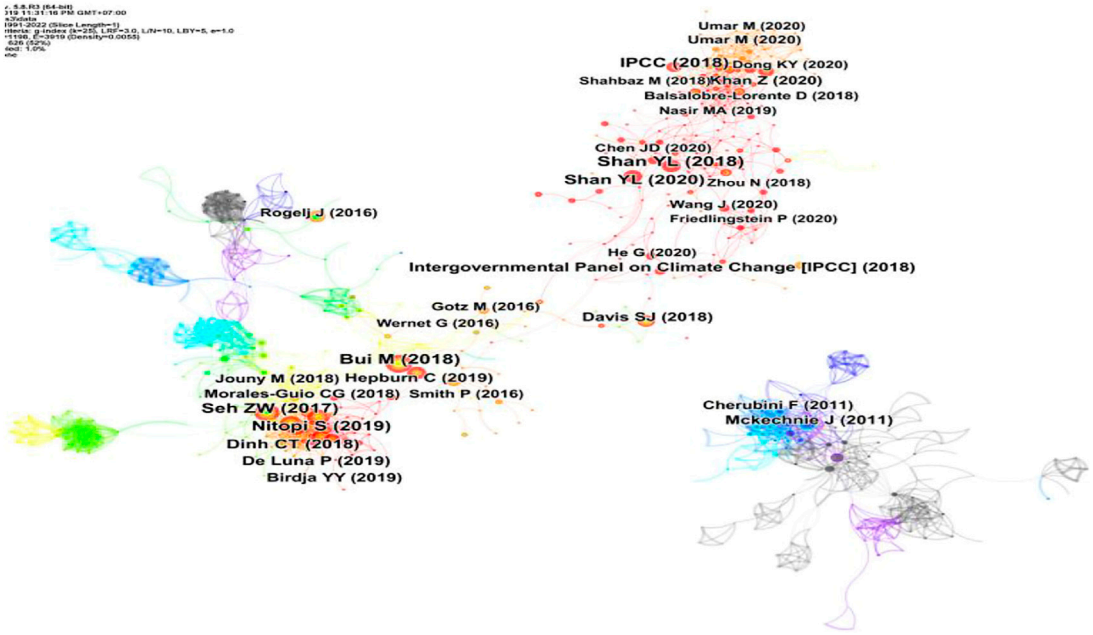

FIGURE 3
Statistical analysis of highly co-cited literature.

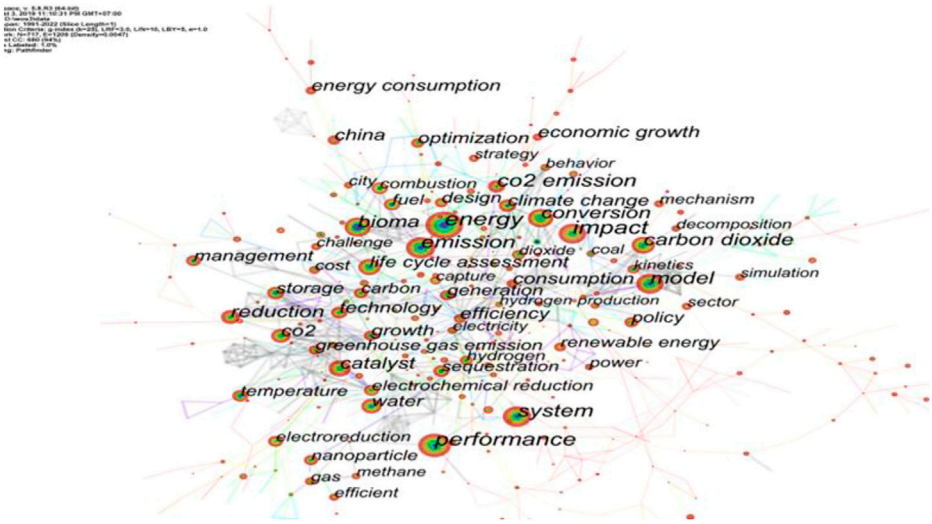

FIGURE 4
Keyword co-occurrence network.

(175 times), reduction (161 times), and conversion (160 times). According to the results of the centrality analysis, the top ten keywords with the highest centrality were: CO_2 (0.52), bioma (0.24), hydrogen (0.18), storage (0.17), model (0.16), agriculture (0.16), growth (0.15), land use (0.14), water vapor exchange (0.14), and biodiesel (0.13). The current foreign carbon peak and carbon neutrality research hotspots cover many fields with broad research scope.

To clearly present foreign double carbon research topics, this study used the CiteSpace software cluster analysis method to generate cluster labels and the foreign double carbon research topic cluster map, as shown in Figure 5. Combined with the software export "cluster theme information summary table." Foreign carbon peak and carbon neutrality research topics contained the keywords "water (water)," "conversion (transformation)," "CO_2 reduction (CO_2 reduction)," "extreme

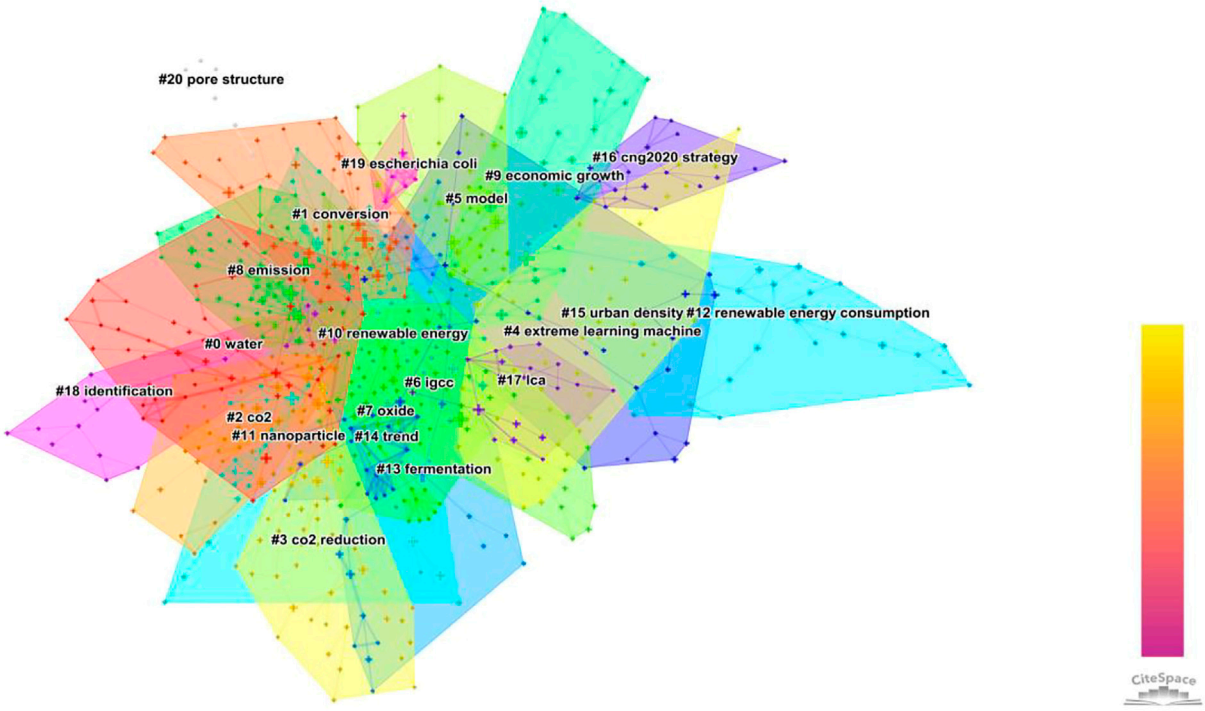

FIGURE 5
Keyword clustering graph.

learning machine (extreme learning machine)," "model (model)," "IGCC (overall coal gasification combined cycle power generation system)," "oxide (oxide)," "economic growth (economic growth)," "renewable energy (renewable energy)," and 20 other clusters. Different degrees of the intersection of the study subject under each cluster existed. After a Secondary reading and an inductive summary, international research on carbon neutrality can be roughly summarized into five areas, including carbon peak attainment, carbon neutralization technology, climate policy impact and performance evaluation, carbon pricing and carbon finance, citizen participation attitude and behavior, climate governance, and global cooperation.

4.2.1 Field 1. Technologies to achieve carbon peak and carbon neutrality

The prominent keywords in this field were "conversion," "energy consumption," "biomass," "fuel," "renewable energy," "hydrogen energy," and "electrochemical reduction." Technological innovation is key to achieving carbon neutrality. To achieve the goals of carbon peak and carbon neutrality, we should understand and adapt to the natural conditions of the earth, and technically, we need to grasp the two key routes of "energy saving and carbon emission reduction" and "carbon sequestration and carbon sinks expansion."

Energy conservation and carbon emission reduction mainly rely on technological innovation and low-carbon production to promote energy efficiency and zero carbonization of energy systems. Energy efficiency improvement technologies include the use of energy-saving equipment, energy echelon utilization, and circular economy realization, such as the use of hydrogen injection in the steel industry, solid biomass replacement, zero-carbon power replacement, and other technologies (Fan and Friedmann, 2021). While solar and wind energy, hydropower, and other renewable sources are regarded as reliable alternatives to traditional energy. Besides, Biomass is a rich and carbon-neutral renewable energy source (Dhyani and Bhaskar, 2018) and could help reduce global warming when used as a substitute for fossil fuels. Additionally, biomass can be used to generate electricity and heat, produce fuels, and make bio-based and chemical materials (McKendry, 2002a). Currently, research on biomass mainly includes the background principle of biomass energy development and utilization (McKendry, 2002b; Cherubini, 2010; Srivastava et al., 2021), biomass energy development and utilization technology (McKendry, 2002c; Dhyani and Bhaskar, 2018; Boujjat et al., 2020; Pattanayak et al., 2020), biomass energy development and utilization prospects (Demirbas, 2005; Dutta et al., 2014; Kwon et al., 2015; Ma et al., 2021; Wang et al., 2021), and the impact of using biomass energy on the environment and society (Cherubini et al., 2011; Mäkipää et al., 2015; Majava et al., 2022; Yang et al., 2022).

"Carbon sequestration and carbon sinks expansion" can primarily be achieved through carbon sequestration and ecological carbon sequestration, with NETs being the most important. NETs mainly involve an ecological carbon sink, carbon capture, carbon utilization, and carbon storage technology (CCUS), BECCS, and DAC. Firstly,forest, grassland, lakes, green space, and wetlands can serve as ecological carbon sinks, which can help absorb and store green carbon; blue carbon reserves in mangroves, salt marsh wetlands, and seaweed beds can also be

enriched (Man et al., 2021; Liu et al., 2022a). Secondly,CCUS is important for potentially reducing emissions, is important in reducing carbon emissions and promoting industrial decarbonization, and has attracted international research attention (Bui et al., 2018). CCUS involves separating CO_2 from industrial or related emission sources and storing it in the natural basement layer for a prolonged period, thus reducing greenhouse gas emissions (Asif et al., 2018). The current deployment of CCUS technology lags behind global expectations, and the large-scale commercialization of CCUS technology also faces high project failure rates and a lack of financial support and market stimulus, in addition to insufficient geological potential exploration with incomplete regulatory frameworks and risk-sharing mechanisms (Chen et al., 2022). Thirdly,BECCS is a combination of biomass energy and CCS technology to achieve negative CO_2 emissions. The model analysis performed by Fajardy and Mac Dowell (2017) showed that BECCS is a reliable choice to permanently and sustainably remove atmospheric CO_2. Additionally DAC refers to the technique of extracting CO_2 directly from the atmosphere. CO_2 can be stored in deep geological structures or used in industrial production. (Shi et al., 2022). DAC is an ideal negative emission technology; however, large-scale deployment is difficult to achieve due to the high cost and small market demand.

4.2.2 Field 2. Climate policy impact and performance evaluation

The keywords in this field were: “policy,” “impact,” “performance,” “reduction,” and “economic growth,” and the related papers discussed the policy effect and impact assessment of climate policy. In view of impact evaluation of environmental policy, (Chen and Lin, 2021)pointed out that the policy can significantly improve carbon/energy-carbon performance, promote green technology innovation, promote the development of emission reduction technology, and thereby achieve the strategic goal of carbon peak and carbon neutrality. Liu et al. (2022b) discussed the impact of low carbon policy on the green development of China’s manufacturing industry. The results showed that implementing a low-carbon policy can significantly reduce pollutants and improve production efficiency. In addition, manufacturers usually use recycling to reduce emissions rather than restrictions or production cuts. Through empirical analysis, the study by He et al. (2021) explored how the national climate policy affects the impact of enterprise carbon reduction investment (CAI). The study also found that national climate policies can stimulate individuals and businesses to regulate and innovate rather than only follow policy regulations.

Some scholars have demonstrated the impact of policies such as low-carbon cities and innovative cities on carbon emissions based on the urban development perspective of. (Du et al., 2022) empirically verified that low-carbon urban policies can significantly improve carbon emission efficiency by optimizing resource allocation, energy conservation, and green technology innovation, and the effect of pilot policies is radiation. The impact on carbon emission efficiency may vary according to urban differences. Using a quasi-natural experiment, (Yang and Shi, 2022) shown that innovative cities are conducive to reducing the carbon emission intensity of enterprises and have a more significant impact on private enterprises, non-export-oriented enterprises, polluting enterprises, and capital-intensive enterprises. Considering the perspective of a civilized city. Qi et al. (2022) found that the civilized city policy considerably promotes the enterprise’s ESG performance and has a stronger effect on promoting state-owned enterprises, which was further amplified by media attention.

Furthermore,Some scholars have investigated, reviewed, and sorted out relevant national climate policy measures from the perspective of policy implementation. Through interviews, (Yangka et al., 2019) studied the Bhutan carbon-neutral climate policy formulation and implementation process and identified twelve key themes, including carbon neutrality, gross national happiness, and sustainable development goals policy framework, which allowed Bhutan to achieve carbon-neutral goals. The results would also be useful for other countries working towards carbon neutrality.

4.2.3 Field 3. Carbon pricing and carbon finance

The keywords in this field included: “carbon finance,” “carbon trading market,” “carbon trading mode,” “carbon emission trading,” and “clean development mechanism.” Carbon pricing plays an important role in regulating the peak of carbon emissions (Duan et al., 2018). Carbon financial market is the general term for greenhouse gas emission trading and its related financial activities and transactions. Ren et al. (2018) explained that different types of environmental regulation show different effects on ecological efficiency. In contrast, the market has more advantages than administrative control and is conducive to improving ecological efficiency, promoting green technology innovation, and mobilizing the enthusiasm of economic subjects. As the core of the carbon financial system, the carbon emission trading mechanism is a market-oriented carbon emission reduction process, which can effectively reduce carbon emissions and environmental pollution. The carbon emission quota allocation is central to the stable operation of the carbon market. According to the actual delivery of carbon credit units in the trading process, the carbon emission right trading market can be divided into two categories: the quota (allowance) market under the “total-trading” (cap and trade) mechanism and the market with the carbon credit unit trading generated by the project (the project market). The key to implementing the total amount trading quota market is determining the total amount and the initial quota allocation. eduction transaction generated through the state-to-state cooperative emission reduction plan. After calculating the actual emission volume, if the actual emission is less than the baseline, it can be sold after verification (Carmona et al., 2010).

Additionally, an important way to reduce carbon emission reduction is to participate in carbon emission right trading, and the individual carbon trading mechanism is an important means to reduce carbon emissions at the consumer end. Fawcett (2010) showed that implementing individual carbon trading will damage the welfare of high-income groups and increase the welfare of low-income groups, which will help to promote social equity. The paper by Fleming (2005) proposed that for individual carbon emission trading in China, the government organization sets carbon emission reduction targets and distributes the quotas to consumers and institutions, thereby encouraging consumers to take the initiative to reduce carbon emissions through the market trading mechanism.

By comparing the public acceptability of individual carbon trading and carbon tax, (Bristow et al., 2010) pointed out that establishing an individual carbon trading mechanism requires considering individual carbon account management, market operation, regulation, license distribution, and trading costs.

4.2.4 Field 4. Citizen participation and behavior

This field included the words "personal carbon trading," "behavior," "stakeholders," and "consumption." Coping with climate change is a common challenge for all humankind. Energy consumption and carbon emissions due to personal requirements are important sources of global greenhouse gas emissions. Therefore, a sound personal carbon trading mechanism is an effective solution to reduce greenhouse gas emissions (Zhang and Feng, 2022). More scholars are studying the impact of individuals on the effect of carbon emission reduction, mainly including the individual consumption of carbon emission measures, individual carbon emissions, and the impact of low-carbon policies on residents' low-carbon behavior. Understanding individual preferences and how they affect energy-related behaviors is critical. Itaoka et al. (2022) investigated household consumer preferences and behaviors for changing their energy supply companies. The policy impacts identified include the need to increase energy options and determine the economic and environmental benefits of market participation. Cheng A W (2022) (Cheng and Lee, 2022) found that while both the internal psychosocial variables and external socioeconomic background were positively associated with the behaviors supporting the energy transition, psychosocial variables had a greater impact on the individual participation in the energy transition. Citizens abide by relevant policies or make energy transition easier than when the government enforces requirements. Quimby and Angelique (2011) found that individual environmental behaviors can be influenced by psychological factors, situational factors, and sociodemographic characteristics. Psychological factors including attitude, environmental values, and environmental responsibility awareness; situational factors include interpersonal influence, social norms, laws and regulations, and environmental pollution status; and social and demographic characteristics mainly include the influence of age, income, gender, education level, and family size on citizens' environmental behavior.

4.2.5 Field 5. Climate governance and global cooperation

The field includes "Climate change," "Climate Policy," "Global Governance," and "Environmental Policy." Climate change is a typical global public problem involving a wide range and high socioeconomic impact. It requires the active participation of various governments, international organizations, non-governmental organizations, and individual citizens (Nordhaus, 2015). Therefore, to address and solve global environmental problems, multiple global environmental entities must be developed and a global multi-center environmental governance mechanism designed. At the international level, the UNFCCC of 1992 and the 2016 Paris agreement addressed the need for mitigation and adaptation to climate change and formulated the overall rules. In this context, transnational climate governance (TCG), local urban climate governance, and the involvement of non-governmental organizations and public climate governance action also gradually increased (Tan et al., 2022). Based on the perspective of transnational climate governance and cooperation, (Da Zhu, 2022) built the climate policy and climate cooperation model of China, the United States, and the European Union, and to predict that the most balanced choice is the strategic combination of collective cooperation. To some extent, humankind has formed a joint force of decarbonization, and more countries and regions should be part of this in the future.

From the perspective of international organizations and public participation, from the end of the 20th century to the beginning of this century, many international organizations have introduced a series of plans and strategies to tackle international climate change, involving many aspects of natural science and social science (Biermann, 2007). The International Biodiversity Program (DIVERSTAS), International Geosphere-Biosphere Program (IGBP), World Climate Research Program (WCRP), and International Human Factors Program for Global Environmental Change (IHDP) are aimed at strengthening cooperation by establishing an overall Earth systems science partnership. The 2016 Paris Agreement included all countries in a community with a shared future to protect the earth's ecology and ensure human development, including all national commitments to reduce emissions and make joint efforts to adapt to climate change The conclusion of the Paris Agreement indicates that global climate governance has entered a new stage of a coordinated response to climate change through state-determined contributions. The World Environment Day 2022 saw the participation of more than 150 countries, including governments, businesses, civil society, schools, celebrities, cities, and communities, raising awareness and celebrating environmental initiatives and increasing the depth and breadth of environmental governance initiatives.

5 Research conclusions and recommendations

5.1 Research conclusions

This paper summarizes and analyzes the current research status and hot topics of international literature in the field of carbon peaking and carbon neutrality using the literature selected from the Web of science core collection database as a research sample, and proposes the development directions and trends of future research. Specific research findings are as follows.

From the perspective of time distribution, the amount of research published on carbon peak attainment and carbon neutrality has gone through three development stages from 1991 to the present, with an overall upward trend. Overall, the current research is flourishing, with increasing attention being paid to carbon-neutral research. The research in this field has broad prospects and strong theoretical and practical value.

From the perspective of spatial distribution, the research institutions are mainly universities and research institutes and the research force is mainly concentrated in developed countries, and the number of publications from developing countries represented by China is also increasing daily, showing a general

multi-polar development trend. From the perspective of the distribution of research fields, the current research is mainly in the field of natural science, including energy, economy, production, and environment.

From the perspective of research hotspots, The International Carbon peaking and carbon neutrality study covers four aspects: technologies to achieve carbon peaking and carbon neutrality, climate policy impact and performance evaluation, carbon pricing and carbon finance, Citizen participation and behavior, and climate governance and global cooperation. Overall, its overall study can include four core scientific questions, which are basic scientific research on carbon peaking and carbon neutral targets (greenhouse gas emissions, carbon footprint, energy efficiency, carbon sinks, etc.), carbon neutral technology innovation and application (new energy technologies, energy conservation and emission reduction technologies, negative emission technologies, energy restructuring, etc.), carbon peaking and carbon neutral policies and policy tools (policies,carbon pricing, carbon financial system, green innovation system, etc.), as well as climate change and global governance (collaborative governance, international cooperation, etc.).

In general, the existing studies still have the following shortcomings: First, the existing studies on the theory and practice of carbon neutrality are still in a fragmented state, lacking a systematic construction of the goals and practices of carbon neutrality and a comprehensive interpretation of the specific steps. Secondly, the cooperation of existing research authors and research institutions is fragmented and lacks cross-organizational and cross-regional cooperation. Thirdly, the existing research focuses more on technical aspects. This fails to explain the overall research status in the field of carbon peak and carbon neutralization. And there are few studies on how to introduce climate policies and technical specifications for the national to promote the achievement of the goal of carbon neutrality.

5.2 Recommendations and prospects

(1) To construct an integrative research framework for carbon peaking and carbon neutrality research. In future research, an integrated and systematic research framework should be established from the scientific basis and data support, carbon peak neutrality and path selection, strategic objectives and management mechanisms, energy structure remodeling, industrial structure upgrading, and ecological environment optimization, to provide theoretical reference for subsequent research. Moreover, future research should combine theoretical research with the actual needs of countries, explore how to achieve climate governance goals for different countries and countries at different stages of development, so as to provide basic, prospective, and leading guidance for relevant countries.

(2) Further, the research perspective requires to be expanded and the research cooperation deepened. The realization of carbon neutrality urgently needs the comprehensive support of professionals and industries in natural science, technology, humanities, and social sciences. Therefore, follow-up research should more actively promote the integration of multidisciplinary perspectives. Furthermore, sustainable development and environmental issues are global problems, which require the active participation of governments, institutions, organizations, and citizens to form a stable global scientific research cooperation force. Relevant countries and government departments should actively establish cross-national and cross-departmental coordination and cooperation mechanisms, cooperate with government organizations, international institutions, universities, research institutes, and industries, and consider multidisciplinary integration schemes under the carbon neutrality goal to develop good governance policies with both theoretical and practical value.

(3) A comprehensive and coherent environmental policy framework must be established,which forms policy “combinations". At the macro level, the state and government should incorporate low carbon development into the overall framework of national development, formulate and update the overall strategy and roadmap for national carbon peaking and carbon neutral, determine different development goals and specific tasks according to the characteristics of different industry sectors, and strengthen the policy synergy in science and technology innovation, finance and taxation, energy and ecological environment. Simultaneously, a policy consultation and evaluation system of the government, enterprises, and scientific research institutions should also be established to evaluate and supervise policy formulation, policy implementation, and governance performance. In the middle level, a policy toolbox must be formed, which actively issues supporting laws and regulations and other mandatory policies, improves the innovation of climate change investment and financing systems, carbon emissions trading system, provides financial subsidies, such as economic policy, and energy efficiency identification, energy audit, carbon emission information publicity policy, give full play to the regulation policy tools, economic policy tools, and information policy tools to promote the combination of enterprise green transformation. At the micro level, the concept of low-carbon life must be popularized among the public, and the individual initiative of energy conservation and emission reduction must be encouraged. Specifically, citizens can be guided to form a green, low-carbon, and economical lifestyle by building low-carbon communities, zero-carbon buildings, zero-carbon travel, household carbon classification and subsidizing low-carbon products, and forming a new situation of carbon peak and carbon-neutral governance in which everyone participates and contributes.

(4) Carbon peak and carbon neutralization technology should be innovated and popularized. High-quality technological innovation is central to achieving the carbon peak and carbon-neutral target. In the future, research, enterprises, scientific research institutions, universities, and other innovation subjects should further research and innovate on green and low-carbon technologies such as energy conservation and emission reduction, new energy, negative emission, and carbon capture and storage. At the national top-level design level, an atmosphere should also be formed to ensure technological innovation and lead technological innovation, and encourage and promote breakthroughs in cutting-edge technologies, disruptive technologies, and original, innovative technologies of

the new generation of renewable energy, green hydrogen, energy storage, and smart energy through resource-oriented and scientific research projects. We should also support the transformation and application of scientific and technological achievements of green innovation technologies, guide the establishment of socialized, professional, and market-oriented technology trading service systems, and promote the "of scientific and technological innovation achievements from the laboratory" to the real carbon peak and carbon-neutral practice.

5.3 Theoretical contributions and research limitations

This paper analyzes the international carbon peaking and carbon neutral literature and presents the current status, hot keywords and topic distribution of international carbon neutral research in the field of carbon mitigation, revealing the knowledge base and research frontier of international carbon mitigation research, and identifying the theoretical basis for subsequent research. This paper also illustrate the development direction of carbon neutral technologies and policies, which can help enterprises to make strategic decisions, determine the direction of technology R&D and investment, stimulate innovation, and promote the deepening of research in carbon neutral technologies, as well as provide useful references for relevant countries to formulate carbon neutral strategic goals and action plans. However, there are some limitations in this study: First, the sample data of this study are mainly from the WOS core collection database, and the review article, books and conferences are excluded, so some literature on the topic of carbon neutral research may be neglected. Future research can use multiple databases for analysis, so as to enhance the credibility of research conclusions. Second, due to the limitation of current research tools, it is not possible to effectively handle the econometric analysis of cross-lingual literature. Future research on literature on carbon neutral related topics may have better research tools or research methods that can handle multilingual and large sample data, thus further enhancing the reliability and accuracy of research conclusions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YZ and ZL: Writing-original draft preparation. JC: Editing data curation, Supervision.

Funding

This work was supported by the Foundation for soft science research program of Shaanxi Province, China (grant number 2022KRM183), and the Foundation of Science and Technology Program–Industry-University-Research Cooperation Project of Yulin, Shaanxi Province, China (grant number CXY-2022-164).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Asif, M., Suleman, M., Haq, I., and Jamal, S. A. (2018). Post-combustion CO2 capture with chemical absorption and hybrid system: Current status and challenges. *Greenh. Gases Sci. Technol.* 8 (6), 998–1031. doi:10.1002/ghg.1823

Biermann, F. (2007). 'Earth system governance'as a crosscutting theme of global change research. *Glob. Environ. change* 17 (3-4), 326–337. doi:10.1016/j.gloenvcha.2006.11.010

Boujjat, H., Rodat, S., Chuayboon, S., and Abanades, S. (2020). Experimental and CFD investigation of inert bed materials effects in a high-temperature conical cavity-type reactor for continuous solar-driven steam gasification of biomass. *Chem. Eng. Sci.* 228, 115970. doi:10.1016/j.ces.2020.115970

Bristow, A. L., Wardman, M., Zanni, A. M., and Chintakayala, P. K. (2010). Public acceptability of personal carbon trading and carbon tax. *Ecol. Econ.* 69 (9), 1824–1837. doi:10.1016/j.ecolecon.2010.04.021

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., et al. (2018). Carbon capture and storage (CCS): The way forward. *Energy & Environ. Sci.* 11 (5), 1062–1176. doi:10.1039/c7ee02342a

Carmona, R., Fehr, M., Hinz, J., and Porchet, A. (2010). Market design for emission trading schemes. *Siam Rev.* 52 (3), 403–452. doi:10.1137/080722813

Change, P. C. (2018). *Global warming of 1.5° C.* Geneva, Switzerland: World Meteorological Organization.

Chen, S., Liu, J., Zhang, Q., Teng, F., and McLellan, B. C. (2022). A critical review on deployment planning and risk analysis of carbon capture, utilization, and storage (CCUS) toward carbon neutrality. *Renew. Sustain. Energy Rev.* 167, 112537. doi:10.1016/j.rser.2022.112537

Chen, X., and Lin, B. (2021). Towards carbon neutrality by implementing carbon emissions trading scheme: Policy evaluation in China. *Energy Policy* 157, 112510. doi:10.1016/j.enpol.2021.112510

Cheng, A. W., and Lee, H. F. (2022). Energy transition towards sustainable development: Perspective of individuals' engagement amid transition process. *Sustainability* 14 (16), 10381. doi:10.3390/su141610381

Cherubini, F., Peters, G. P., Berntsen, T., Strømman, A. H., and Hertwich, E. (2011). CO2 emissions from biomass combustion for bioenergy: Atmospheric decay and contribution to global warming. *Gcb Bioenergy* 3 (5), 413–426. doi:10.1111/j.1757-1707.2011.01102.x

Cherubini, F. (2010). The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Convers. Manag.* 51 (7), 1412–1421. doi:10.1016/j.enconman.2010.01.015

Da Zhu, J. (2022). Cooperative equilibrium of the China-US-EU climate game. *Energy Strategy Rev.* 39, 100797. doi:10.1016/j.esr.2021.100797

Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science* 360 (6396), eaas9793. doi:10.1126/science.aas9793

De Luna, P., Hahn, C., Higgins, D., Jaffer, S. A., Jaramillo, T. F., and Sargent, E. H. (2019). What would it take for renewably powered electrosynthesis to displace

petrochemical processes? *Science* 364 (6438), eaav3506. doi:10.1126/science.aav3506

Demirbas, A. (2005). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. *Prog. energy Combust. Sci.* 31 (2), 171–192. doi:10.1016/j.pecs.2005.02.002

Dhyani, V., and Bhaskar, T. (2018). A comprehensive review on the pyrolysis of lignocellulosic biomass. *Renew. energy* 129, 695–716. doi:10.1016/j.renene.2017.04.035

Du, M., Feng, R., and Chen, Z. (2022). Blue sky defense in low-carbon pilot cities: A spatial spillover perspective of carbon emission efficiency. *Sci. Total Environ.* 846, 157509. doi:10.1016/j.scitotenv.2022.157509

Duan, H., Mo, J., Fan, Y., and Wang, S. (2018). Achieving China's energy and climate policy targets in 2030 under multiple uncertainties. *Energy Econ.* 70, 45–60. doi:10.1016/j.eneco.2017.12.022

Dutta, S., Bhaumik, A., and Wu, K. C. W. (2014). Hierarchically porous carbon derived from polymers and biomass: Effect of interconnected pores on energy applications. *Energy & Environ. Sci.* 7 (11), 3574–3592. doi:10.1039/c4ee01075b

Fajardy, M., and Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environ. Sci.* 10 (6), 1389–1426. doi:10.1039/c7ee00465f

Fan, Z., and Friedmann, S. J. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule* 5 (4), 829–862. doi:10.1016/j.joule.2021.02.018

Fawcett, T. (2010). Personal carbon trading: A policy ahead of its time? *Energy policy* 38 (11), 6868–6876. doi:10.1016/j.enpol.2010.07.001

Fleming, D. (2005). *Energy and the common purpose: Descending the energy staircase with tradable energy quotas (TEQs). Lean economy connection*.

He, R., Luo, L., Shamsuddin, A., and Tang, Q. (2021). The value relevance of corporate investment in carbon abatement: The influence of national climate policy. *Eur. Account. Rev.* 31, 1233–1261. doi:10.1080/09638180.2021.1916979

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., et al. (2019). The technological and economic prospects for CO2 utilization and removal. *Nature* 575 (7781), 87–97. doi:10.1038/s41586-019-1681-6

Itaoka, K., Chapman, A., and Farabi-Asl, H. (2022). Underpinnings of consumer preferences and participation in Japan's liberalized energy market. *Util. Policy* 76, 101379. doi:10.1016/j.jup.2022.101379

Kwon, E. E., Cho, S. H., and Kim, S. (2015). Synergetic sustainability enhancement via utilization of carbon dioxide as carbon neutral chemical feedstock in the thermo-chemical processing of biomass. *Environ. Sci. Technol.* 49 (8), 5028–5034. doi:10.1021/es505744n

Liu, C., Liu, G., Casazza, M., Yan, N., Xu, L., Hao, Y., et al. (2022). Current status and potential assessment of China's ocean carbon sinks. *Environ. Sci. Technol.* 56, 6584–6595. doi:10.1021/acs.est.1c08106

Liu, Q., Liang, W., Chan, C., Cao, Y., and Lu, M. (2022). The impact of low-carbon policy on green manufacturing development. *Indoor Built Environ.*, 1420326X221121061. doi:10.1177/1420326X221121061

Ma, Z., Liu, X., Li, G., Qiu, X., Yao, D., Zhu, Z., et al. (2021). Energy consumption, environmental performance, and techno-economic feasibility analysis of the biomass-to-hydrogen process with and without carbon capture and storage. *J. Environ. Chem. Eng.* 9 (6), 106752. doi:10.1016/j.jece.2021.106752

Majava, A., Vaden, T., Toivanen, T., Järvensivu, P., Lähde, V., and Eronen, J. T. (2022). Sectoral low-carbon roadmaps and the role of forest biomass in Finland's carbon neutrality 2035 target. *Energy Strategy Rev.* 41, 100836. doi:10.1016/j.esr.2022.100836

Mäkipää, R., Linkosalo, T., Komarov, A., and Mäkelä, A. (2015). Mitigation of climate change with biomass harvesting in Norway spruce stands: Are harvesting practices carbon neutral? *Can. J. For. Res.* 45 (2), 217–225. doi:10.1139/cjfr-2014-0120

Mallapaty, S. (2020). How China could be carbon neutral by mid-century. *Nature* 586 (7830), 482–483. doi:10.1038/d41586-020-02927-9

Man, Z., Che, S., Xie, C., Jiang, R., Liang, A., and Wu, H. (2021). Effect of climate change on CO2 flux in temperate grassland, subtropical artificial coniferous forest and tropical rain forest ecosystems. *Int. J. Environ. Res. Public Health* 18 (24), 13056. doi:10.3390/ijerph182413056

McKechnie, J., Colombo, S., Chen, J., Mabee, W., and MacLean, H. L. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environ. Sci. Technol.* 45 (2), 789–795. doi:10.1021/es1024004

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresour. Technol.* 83 (1), 37–46. doi:10.1016/s0960-8524(01)00118-3

McKendry, P. (2002). Energy production from biomass (part 2): Conversion technologies. *Bioresour. Technol.* 83 (1), 47–54. doi:10.1016/s0960-8524(01)00119-5

McKendry, P. (2002). Energy production from biomass (part 3): Gasification technologies. *Bioresour. Technol.* 83 (1), 55–63. doi:10.1016/s0960-8524(01)00120-1

Nitopi, S., Bertheussen, E., Scott, S. B., Liu, X., Engstfeld, A. K., Horch, S., et al. (2019). Progress and perspectives of electrochemical CO2 reduction on copper in aqueous electrolyte. *Chem. Rev.* 119 (12), 7610–7672. doi:10.1021/acs.chemrev.8b00705

Nordhaus, W. (2015). Climate clubs: Overcoming free-riding in international climate policy. *Am. Econ. Rev.* 105 (4), 1339–1370. doi:10.1257/aer.15000001

Pattanayak, S., Hauchhum, L., Loha, C., and Sailo, L. (2020). Selection criteria of appropriate bamboo based biomass for thermochemical conversion process. *Biomass Convers. Biorefinery* 10 (2), 401–407. doi:10.1007/s13399-019-00421-5

Qi, Z., Zhang, E., Wang, C., and Liu, W. (2022). The power of civilization: The role of civilized cities in corporate ESG performance. *Front. Environ. Sci.* 453. doi:10.3389/fenvs.2022.872592

Quimby, C. C., and Angelique, H. (2011). Identifying barriers and catalysts to fostering pro-environmental behavior: Opportunities and challenges for community psychology. *Am. J. community Psychol.* 47 (3), 388–396. doi:10.1007/s10464-010-9389-7

Ren, S., Li, X., Yuan, B., Li, D., and Chen, X. (2018). The effects of three types of environmental regulation on eco-efficiency: A cross-region analysis in China. *J. Clean. Prod.* 173, 245–255. doi:10.1016/j.jclepro.2016.08.113

Seh, Z. W., Kibsgaard, J., Dickens, C. F., Chorkendorff, I. B., Nørskov, J. K., and Jaramillo, T. F. (2017). Combining theory and experiment in electrocatalysis: Insights into materials design. *Science* 355 (6321), eaad4998. doi:10.1126/science.aad4998

Shan, Y., Huang, Q., Guan, D., and Hubacek, K. (2020). China CO2 emission accounts 2016–2017. *Sci. data* 7 (1), 54–59. doi:10.1038/s41597-020-0393-y

Shi, X., Lin, Y., and Chen, X. (2022). Development of sorbent materials for direct air capture of CO2. *MRS Bull.* 47, 405–415. doi:10.1557/s43577-022-00320-7

Srivastava, R. K., Shetti, N. P., Reddy, K. R., Kwon, E. E., Nadagouda, M. N., and Aminabhavi, T. M. (2021). Biomass utilization and production of biofuels from carbon neutral materials. *Environ. Pollut.* 276, 116731. doi:10.1016/j.envpol.2021.116731

Tan, X. C., Kong, L. S., Gu, B. H., Zeng, A., and Niu, M. M. (2022). Research on the carbon neutrality governance under a polycentric approach. *Adv. Clim. Change Res.* 13 (2), 159–168. doi:10.1016/j.accre.2022.01.005

Wang, J., Xiao, J., Shen, Y., Liang, X., Lv, T., and Xiao, W. (2021). A molten-salt electrochemical biorefinery for carbon-neutral utilization of biomass. *J. Mater. Chem. A* 9 (48), 27442–27447. doi:10.1039/d1ta09498j

Yang, C., Kwon, H., Bang, B., Jeong, S., and Lee, U. (2022). Role of biomass as low-carbon energy source in the era of net zero emissions. *Fuel* 328, 125206. doi:10.1016/j.fuel.2022.125206

Yang, Z., and Shi, D. (2022). Towards carbon neutrality: The impact of innovative city pilot policy on corporate carbon intensity in China. *Clim. Policy*, 1–14. doi:10.1080/14693062.2022.2124224

Yangka, D., Rauland, V., and Newman, P. (2019). Carbon neutral policy in action: The case of Bhutan. *Clim. Policy* 19 (6), 672–687. doi:10.1080/14693062.2018.1551187

Zhang, Y. H., and Feng, T. T. (2022). How does the design of personal carbon trading system affect willingness to participate under carbon neutrality goal?—Evidence from a choice experiment. *Environ. Sci. Pollut. Res.* 29, 81970–81992. doi:10.1007/s11356-022-21549-4