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Review article

Scientometric investigations on dual carbon research: Revealing advancements, key areas, and future outlook

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ABSTRACT

The dual carbon goal is a systematic project involving the entire society and has a leading and systematic role in the green and low-carbon development of China. In this study, we used the CiteSpace software to visualize and analyze 5809 documents from the core database of Web of Science from 1995 to 2023, covering four aspects: descriptive statistics, network collaboration, research hotspots, and thematic evolution analysis. The number of studies in the field of dual carbon is in an explosive growth stage and China and the Chinese Academy of Sciences have become the core country and institution for research, respectively, in this field. Major high-impact journals include Cleaner Production, Energy, Renewable and Sustainable Energy Review, Applied Energy, and Energy Policy. Relevant research has mainly focused on carbon neutralization, CO_2 emissions, impact factors, energy, and emission reduction performance. Research hotspots primarily include carbon dioxide electrocatalytic reduction technology, sustainable energy transition strategies, and green financial policy tools. The government should further support for the research and development of carbon-neutral technologies, particularly for the industrialization and application of CO_2 electrocatalytic reduction technology. Meanwhile, investment in renewable energy should be increased to optimize the energy structure and promote energy transition. In addition, green financial policy tools must be improved to promote the healthy development of the green financial market. The transparency and efficiency of the carbon trading market can be improved using digital technology and big data analysis, thus promoting the deep integration of the digital economy, with the goal of carbon neutrality.

1. Introduction

Climate warming has become indisputable and has far-reaching ecological, social, and corporate governance implications. First, in terms of ecology, warmer temperatures cause increased storms, melting glaciers, and rising sea levels, which has led to vulnerability to storm surges in the low-lying coastal areas of the Arctic [1]. Twardochleb et al. reported that warming temperatures affect the life cycle of metazoans, which may lead to the delayed extinction of populations [2]. Warmer temperatures also inhibit the efficiency of biological control and accelerate plant and animal invasions that encroach on and displace original species, resulting in severe economic and health consequences [3–5]. On the social front, the warming-induced melting of glaciers and permafrost has a direct impact on the initial decline of streams on the Tibetan Plateau, which further contributes to the problem of available water resources, which, in turn, triggers social unrest and volatility [6]. Regarding corporate governance, the challenges posed by warming climate are particularly

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evident, especially in the energy sector. Zhang et al. observed that environmental factors may inhibit economic performance in the short term [7].

Carbon emission reduction has become the "common denominator" for countries in the fulfillment of their ESG responsibilities. To deal with climate change caused by excessive CO_2 emissions, countries have implemented a series of measures, including promoting the use of renewable energy, setting stricter carbon emission standards, and establishing carbon emission-trading systems. Based on the data from 244 prefectural-level cities in China, Qu et al. found that the use of renewable energy within cities could notably reduce carbon emissions [8]. Similarly, the study of 33 OECD countries, based on the PSTR model by Nan et al. showed that renewable energy consumption can effectively reduce CO_2 emissions [9]. Other scholars have also demonstrated that renewable energy use helps reduce CO_2 emissions per unit of GDP, based on panel data from 30 provinces in China [10]. Strict carbon emission standards can notably accelerate carbon emission reduction, and the formulation of carbon emission right allocation standards is important for curbing CO_2 emissions in Shanghai [11]. In addition, a study showed that carbon emissions from the U.S. construction industry can be effectively reduced by implementing strict renewable energy and green building standards [12]. Carbon trading policies are also a key tool for curbing carbon emissions. Taking China as an example, studies have shown that carbon trading policies can guide high-energy-consuming industries to make industrial structural adjustments, thus promoting low-carbon transformation and realizing carbon emission reduction targets [13]. Zhao et al. found that carbon trading policies could effectively reduce carbon dioxide emissions by influencing the green innovation technologies of resource-based enterprises. These policy instruments include increasing revenues, reducing financial constraints, issuing subsidies, and providing R&D incentives [14].

Extensive research has been conducted on dual carbon fields at both the national and international levels. For instance, Qin et al. explored the impact of blockchain [15], sustainable finance and renewable energy [16], and the blockchain market alongside green finance [17] on carbon neutrality. Su et al. investigated the role of technological innovation in achieving carbon neutrality [18]. Additionally, some researchers have used bibliometric software in their studies. For example, Liu et al. employed CiteSpace to conduct a bibliometric analysis of data from the transportation sector [19], Li et al. performed a visualization analysis of literature on the "electricity market" and "carbon market" [20], and Zhu et al. examined the global impacts of urbanization on carbon emissions [21]. Despite the abundance of research, systematic analyses and comprehensive summaries of the development and research trajectories in this field remain scarce. Moreover, studies often exhibited limitations, such as having insufficient temporal coverage, having limited sample sizes, and lacking systematic and comprehensive content.

This study aimed to address these gaps by systematically analyzing the literature on the dual carbon field for the past 30 years, revealing research hotspots, frontier topics, and their evolutionary trends. Using CiteSpace 6.2 R2 to conduct a bibliometric analysis of the relevant literature from the WOS core dataset for specific year intervals and to present the findings visually, this study aimed to provide the academic community with a more systematic and comprehensive reference. This will lead to further research development in the dual carbon field. Additionally, this study sought to offer crucial data support to policymakers and research institutions, aiding in the optimization of resource allocation and the formulation of precise scientific collaboration strategies. This, in turn, may promote technological innovation and industrial applications. Thus, this study holds not only academic value but also considerable practical implications, providing robust support for achieving carbon neutrality.

2. Research methods

2.1. Methodology

An econometric analysis was conducted using the CiteSpace software for data mining. This study aimed to reveal research status, hotspots, and evolutionary trends by employing mapping techniques. The content includes author examination, institutional analysis, country co-occurrence network analysis, keyword co-occurrence mapping analysis, journal bitmap overlay analysis, keyword clustering analysis, journal co-citation analysis, and theme evolution analysis. These effectively highlights the contemporary research hotspots and evolutionary trends in dual carbon studies.

2.2. Data sources

This study focused on "dual carbon" to ensure that the data collected is comprehensive and accurate. The WOS core collection was used as the primary data source to search for literature associated with "dual carbon," "carbon peak," or "carbon neutral" from January 1, 1995 to August 8, 2023. The validity of the literature search was improved by limiting the search to these keywords. Only articles written in English were considered in this study to enhance the effectiveness of the bibliometrics. Following careful manual screening, irrelevant literature, meeting notices, and other nonessential information were excluded from the analysis. The remaining literature was transmitted in unformatted text form, named "download_XXX.txt," and input in the CiteSpace 6.2 R2 software for document filtering and de-weighting. Finally, 5809 valid documents were obtained.

3. Analysis of the present state of research on dual carbon

3.1. Descriptive statistical analysis

3.1.1. Volume of journal publications

Figs. 1 and 2 indicate that articles on "dual carbon" have grown exponentially over the past 28 years, with three distinct growth phases: slow, rapid, and explosive. The first phase, from 1995 to 2014, witnessed a slow increase in the number of articles on carbon neutrality and carbon peaking, as scholars had a limited understanding of carbon emission reduction and required further research in the dual carbon field. Thus, fewer related studies were present. Lasting from 2015 to 2020, the second phase witnessed a rapid growth in the total number of articles on dual carbon, with an average of approximately 65 articles. This growth was sparked by the first proposal of China in 2014, to achieve peak carbon emissions by 2030. As a result of this plan, numerous investigations have been conducted on methods to decrease carbon emissions and rapidly achieve peak carbon emissions, which have helped slowing down the rate of carbon dioxide emissions while effectively mitigating their scale. The third phase, from 2021 to 2023, was expected to witness explosive growth in the number of articles on dual carbon. The cumulative publication graph reveals that the cumulative percentage of publications within the last three years reached 87.5 %, representing more than four-fifths of the total publication count. This indicated that dual carbon has gained considerable attention as a focal point of scholarly investigation in recent years. According to the well-known bibliometrician Price, the development trend does not reach saturation when the number of papers in a research field demonstrates an exponential growth pattern. Instead, it remains at a stage of rapid progress. This implies that new hypotheses, methods, and technologies will continue appearing. Consequently, research within the field of dual carbon remains largely immature. The field still experiences rapid growth, leaving ample scope for further research and development.

3.1.2. Dual map overlay

A superimposed map labeling key points in the dual carbon field is shown in Fig. 3. The map is partitioned into two sections, with the left side displaying the sizing map and the right side exhibiting the cited map. Each point on the map corresponds to a journal, signifying the distribution of journals within their respective partitions. In the left-hand panel, the ellipses represent the number of publications corresponding to a journal and show the ratio of authors to the number of publications. The vertical axis of the ellipse represents a more significant number of publications. In comparison, a larger number of authors is indicated by the horizontal axis length of the ellipse [22]. The trajectory of links between maps provides an understanding of the interdisciplinary relationships in the field. The z-score function highlights the more robust and seamless trajectories, with thicker lines denoting higher scores. Publications in the fields of Physics, Materials Science, and Chemistry were influenced by publications in the fields of Natural Environment, Toxicology, and Nutrition ($z = 2.87$, $f = 2230$), as well as Economics, Economics, and Policy ($z = 2.75$, $f = 1840$). Furthermore, publications in the veterinary, animal, and science domains were influenced by publications in the fields of environmental science, toxicology, nutrition ($z = 2.99$, $f = 2316$), chemistry, materials, and physics ($z = 2.13$, $f = 1732$), as well as and economics, economics, and policy ($z = 2.09$, $f = 1704$). A crucial reason for the intersection of disciplines is that, during the transition to cleaner fossil energy sources, to realize the transformation of coal from "black" to "white" and complete low-carbon utilization, coal will not only be used as a raw material but also as a material for demonstrating the vision of human beings. Comprehensive research in various disciplines is required to explore frontiers of high-end technology related to coal, such as coal-to-oil conversion; coalbed methane development for natural gas production; underground gasification for direct syngas and hydrogen production; the utilization of biodegradable polyglycolic acid for materials, packaging, and components; and the production of high-end jet engine fuel. Therefore, at the frontier of high-end technology, coal requires comprehensive research from various disciplines.

The uppermost bar in Fig. 3 illustrates the sequential movement of the trajectories, compiled based on the citation behaviors of the 5809 documents. The leftmost bar of the histogram represents the displacement in 2000, using the discipline distribution center of 1995 as a benchmark. The diagram shows a substantial increase in the displacement magnitude between 1997 and 1998. This was, in large, because 1997 witnessed the signing of the first international treaty to concretize carbon market mechanisms, the Kyoto Protocol, and new perspectives in dual carbon research that could lead to new content being published in different journals.

3.1.3. Co-citations

To examine the journal distribution, the top 15 journals, according to the number of published articles, are listed in Table 1. The literature database used in this study contains 1619 journal types, as reflected in WOS statistics. The field of carbon neutrality has not yet established a cohesive group of journals, resulting in a fragmented publication landscape that is still in the developmental stage.

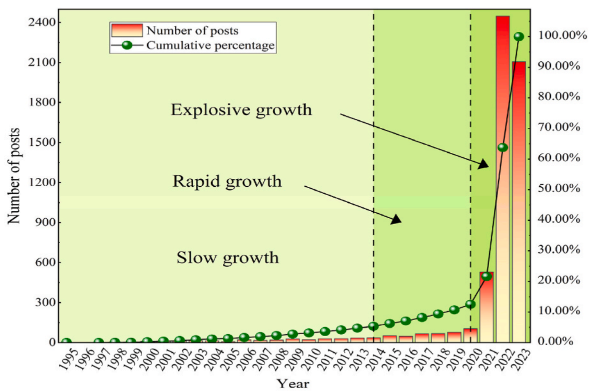

Fig. 1. Annual graph of journal publications dual carbon field.

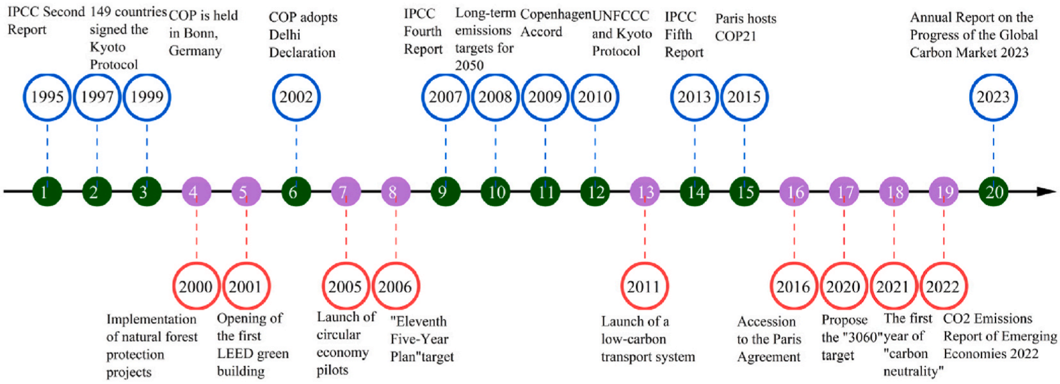

Fig. 2. Axis of historical events in dual carbon field.
Note: COP21 refers to the twenty-first meeting of the Conference of the Parties of the United Nations Framework Convention on Climate Change.

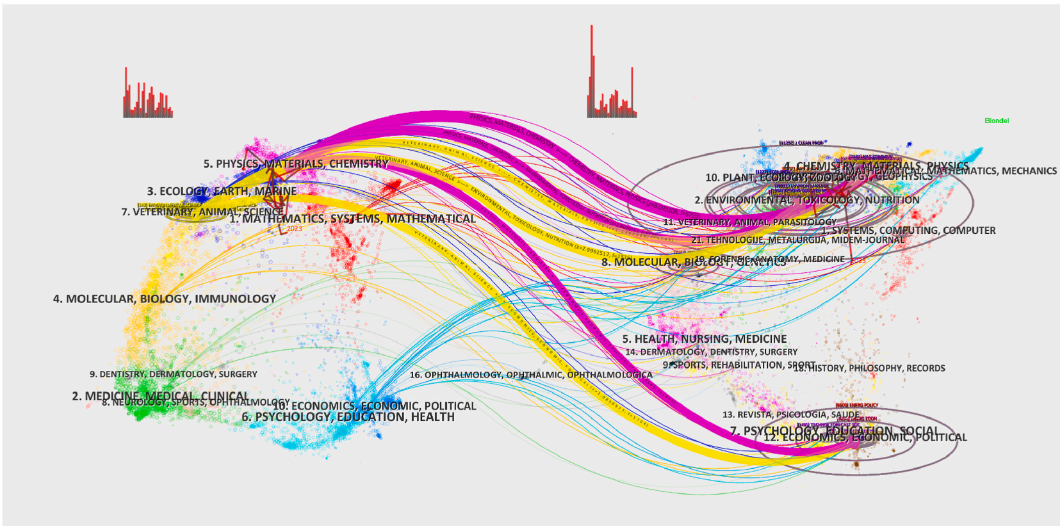

Fig. 3. Dual graph overlay analysis of citing and cited journals.

Table 1
Distribution of periodicals.

Number	Journal	TP	Centrality	IF
1	Journal of Cleaner Production	2795	0.12	11.1
2	Energy	2130	0.07	9
3	Renewable & Sustainable Energy Reviews	2117	0.02	15.9
4	Applied Energy	2102	0.07	11.2
5	Energy Policy	2037	0.09	9
6	Science of The Total Environment	1726	0.03	9.8
7	Sustainability	1469	0.01	3.9
8	Journal of Environmental Management	1421	0.06	8.7
9	Energy Economics	1349	0.05	12.8
10	Environmental Science And Pollution Research	1294	0.01	5.8
11	Nature	1190	0.19	64.8
12	Science	1163	0.09	56.9
13	Nature Communications	1091	0.04	16.6
14	Renewable Energy	1073	0.01	8.7
15	Resources Conservation And Recycling	1049	0.01	13.2
16	Energies	982	0	3.2

Note: TP = the number of publications, IF = impact factor.

The number of core regions can be determined using the formula r0 = 2ln (eE × Y), where r0 represents the core regions, E denotes the Euler coefficient (E = 0.5772), and Y denotes the upper limit of the number of journal articles. After calculation, the value of r0 was determined to be 16.70. Remarkably, the core region encompasses 16 leading journals on carbon neutrality.

In this study, 24,988 articles from various journals were analyzed, of which 22.98 % were from core regional journals. These journals had an average impact factor of 16.29 and cover the environmental, energy, and economic fields. These studies are known for their interdisciplinary approaches and crossover topics. The top journals in this domain are "Journal of Cleaner Production," "Energy," "Renewable & Sustainable Energy Reviews," "Applied Energy," and "Energy Policy." These journals play a vital role in disseminating knowledge and information on carbon research. Additionally, two comprehensive top journals in Nature and Science were included in the analysis.

3.2. Network analysis

3.2.1. National cooperation networks

Fig. 4 (national cooperation network diagram) shows 105 nodes and 837 connecting lines with a network density of 0.1533. China (4023), the United States (455), the United Kingdom (209), South Korea (186), and Japan (176) were the leading countries in terms of publication numbers. Fig. 5 shows that Asia, with China as the representative and North America, including the U.S. and Canada were at the forefront in article count and made remarkable contributions to the field of carbon research. Cooperative relationships are represented by lines connecting nodes. Thicker lines indicate greater cooperation, and closer nodes indicate closer collaboration. The countries in this paper generally have cooperative relationships with each other, which have been downplayed owing to the overly dense connectivity. Node's annual ring color shows publication time. Brighter colors indicate recent in-depth studies on a research field. Thicker rings signify a higher number of published articles. Over 90 % of the countries in the figure show red color in the outer ring, indicating the dual carbon field is globally important. China, the United States, South Korea, and Japan have more red colored areas, which denotes considerable literature in related fields. Higher centrality means more substantial influence and outstanding contribution in the specialized field.

The pink circles mark nodes with a centrality greater than 0.1, which are called vital nodes. The United States (0.11), Germany (0.11), the UK (0.10), and Saudi Arabia (0.10) have high centrality, indicating extensive communication and a notable global influence on dual carbon emissions. By contrast, China, South Korea, and Japan have relatively low intermediary centrality despite the high number of articles, indicating that these countries are relatively independent in their research, have insufficient cooperation with other countries, have low international influence, and lack innovation in their research content.

3.2.2. Institutional cooperation networks

Core institutions are influential organizations in a field with highly cited research results. A statistical table of their article outputs helps understand their research output. Fig. 6 shows a dense institutional cooperation network with 543 nodes and 635 connecting lines at a network density of 0.0043. The CAS published the highest number of research articles on dual carbon (a total of 594). Tsinghua University, North China Electric Power University, and China University of Mining and Technology followed with 194, 166, and 143 articles, respectively. Other institutions that have made considerable progress in this field include Xi'an Jiaotong University, Chongqing University, Tianjin University, and the Institute of Geographic Sciences and Natural Resources. In terms of institutional cooperation, a great deal of collaboration existed between the CAS, the University of London, and other research institutions. Regarding collaboration time, CNR-France, Columbia University, USDA, the US Department of Energy, and the Argonne National Laboratory collaborated previously. Regarding centrality, UDICE-France Research University, CAS, Helmholtz Association, and National Council (CNR) had the highest centrality, at 0.62, 0.43, 0.31, and 0.31, respectively, which indicates that these research institutions have extensive international influence in the field of dual carbon. Scholars within the country play a pivotal role in dual carbon research, as demonstrated by the Chinese Academy of Sciences (CAS) having the highest publication count and centrality.

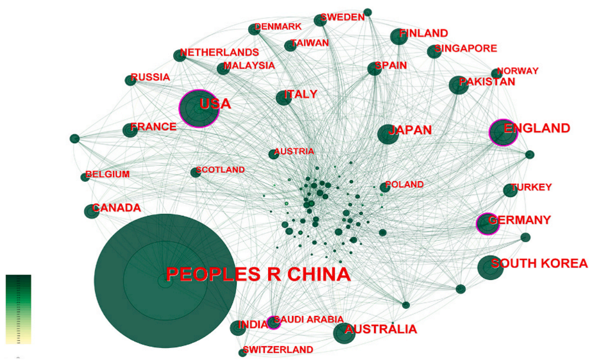

Fig. 4. National cooperation network.

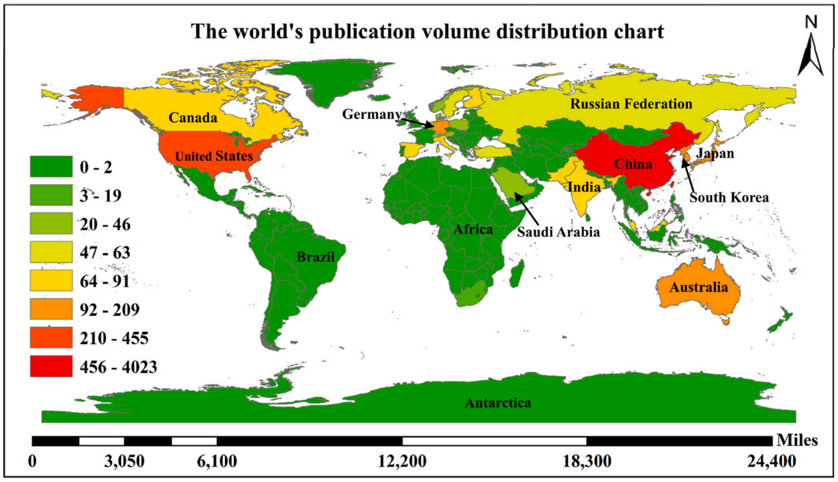

Fig. 5. Global publications sorted by region.

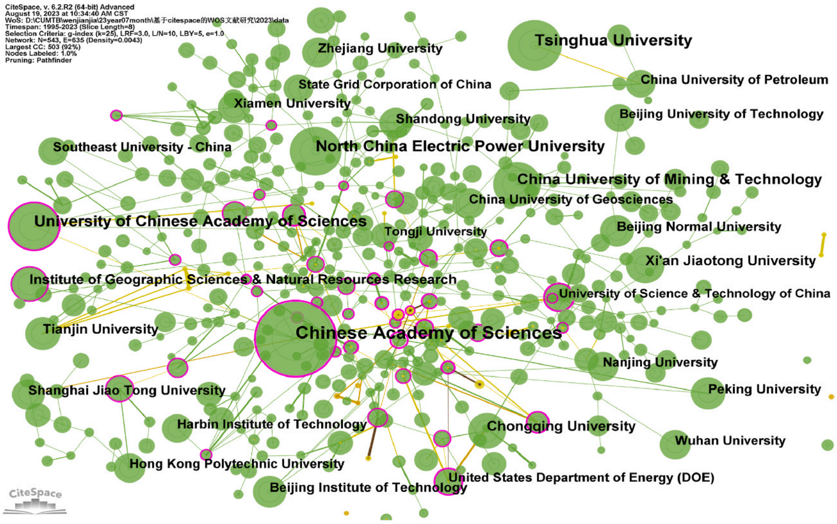

Fig. 6. Institutional cooperation network.

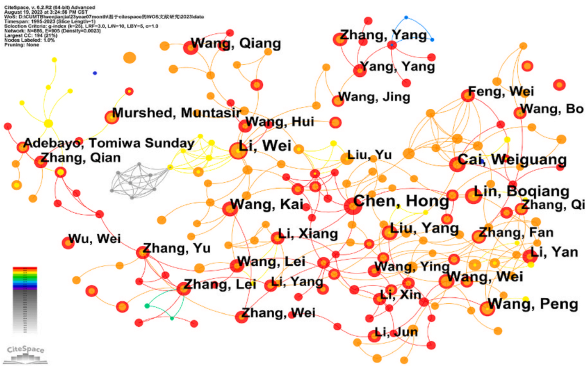

Fig. 7. Co-authorship network.

3.2.3. Co-authorship networks

In the field of dual carbon, a network relationship graph with 886 nodes, 905 connecting lines, and a density of 0.0023 was formed. Fig. 7 shows that a relatively dense network of author partnerships has been formed in the field of dual carbon, and the most extensive network is the group of authors centered on Chen Hong from Jiangnan University. Chen Hong (25 articles), Li Wei (23 articles), and Lin Boqiang (20 articles) had the largest publication volumes. Regarding collaboration time of the study authors, the lighter color of the network nodes represents earlier collaboration between authors. The research group centered on Boucher, Olivier had carried out research cooperation since 2007. It is a pioneering and outstanding contribution to carbon emission reduction and peaking research.

3.3. Research hotspots

3.3.1. Keyword co-occurrence network analysis

Fig. 8 (keyword co-occurrence mapping) exhibits 1074 nodes and 5135 connecting lines, resulting in a network density of 0.0089. The leading five carbon neutrality field keywords were “carbon neutrality,” “CO_2 emissions,” “impact,” “energy,” and “performance.” Analyzing the frequency of relevant keywords showed that the extensive use of fossil fuels leads to notable greenhouse gas emissions, including that of carbon dioxide, with notable environmental repercussions. To address climate change, the construction industry is researching new building materials that prioritize enhanced performance, cost-effectiveness, and the reduction of carbon emissions. From the time evolution of Fig. 9, the keywords of 1995–2014 are centered on “carbon neutrality” and “climate change,” the keywords of 2015–2020 are centered on “nanoparticles” and “carbon neutrality,” and the keywords of 2021–2023 are centered on “carbon neutrality” and “carbon dioxide emissions,” which reveal that the term “carbon neutrality” has always been a hotspot of research.

To analyze the specific content of keywords, we tabulated the 30 most frequent keywords (Table 2). The table demonstrates that these often-used words encompass diverse subjects, including climate change, carbon storage, optimization paths, modeling methods, and other areas. Greenhouse gases are widely acknowledged as the primary driver of global warming, posing a pressing and major threat to sustainable development, comparable to a “gray rhino.” To tackle climate change resulting from high carbon emissions, China declared at the 75th UN General Assembly its commitment to peak carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060. To achieve this, high-emission enterprises must expedite a shift to low-carbon energy, optimize energy structures, and actively promote the development of green and renewable energy sources, while safeguarding energy security through coordinated efforts.

Liu et al. used the Tapio decoupling model to determine the carbon emissions produced by six provinces in central China [23]. Wang et al. optimized the hyperparameters of the LSSVR model using the AABC algorithm. They developed a hybrid intelligent model that accurately predicts CO_2 emissions within a range of$\pm$5% [24]. Two recent studies provided valuable insights into the carbon peak period in China. Gao and Pan predicted the timing and intensity of the carbon peak in Shanghai using a system dynamics model, whereas Huo et al. simulated two carbon peak scenarios in the commercial building sector [25,26]. Studies have found that the low-carbon scheme is expected to peak in 2029, while the baseline scenario is predicted to peak in 2037. These findings can help policymakers develop targeted measures to reduce carbon emissions and their spatial progression. Several studies have assessed the carbon emission performance in China. For instance, Chen et al. used data envelopment analysis to examine energy efficiency and its determinants. Their study covered 31 industrial categories in Beijing based on data from 2002 to 2018 [27]. Similarly, Niu et al. evaluated carbon emission efficiency using a three-stage SBM flawed model and data from 2006 to 2019. They found significant disparities in carbon emission efficiency among regions [28]. Lu et al. used the PSO algorithm to identify Pareto solutions and employed the TOPSIS algorithm to select an optimal compromise solution. They aimed to develop a dual-objective optimization model that reduced operating costs within the shipping cycle and minimized carbon emissions to enhance the overall carbon emission

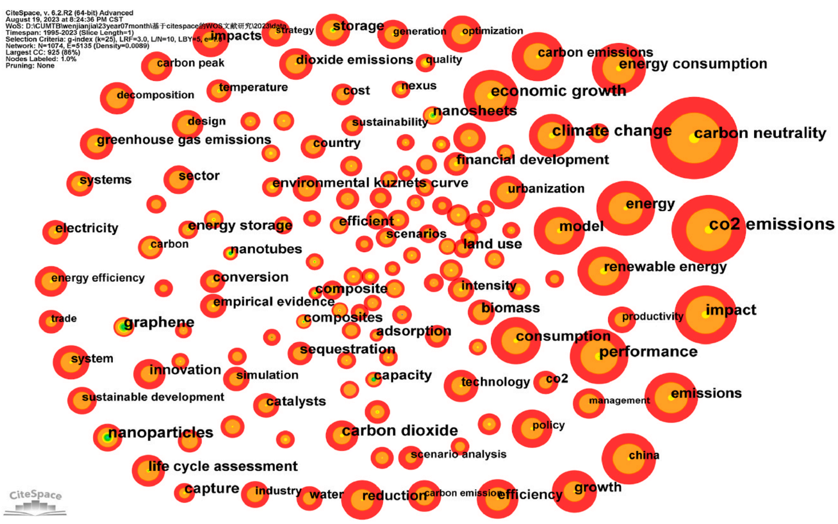

Fig. 8. Keyword co-occurrence network.

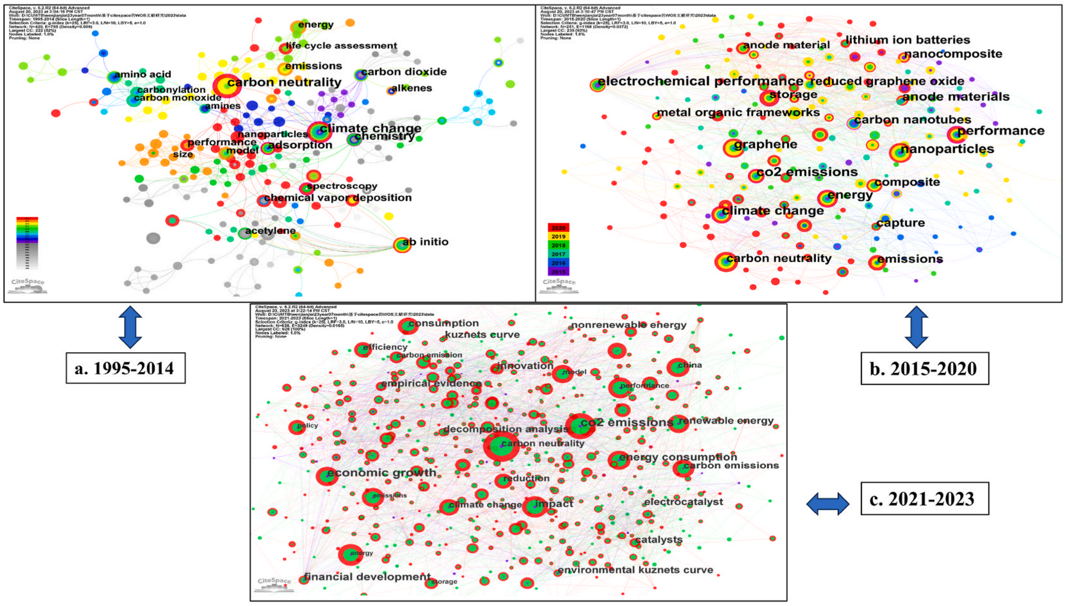

Fig. 9. Phased keyword co-occurrence map.

Table 2
Top 30 high-frequency keywords.

Number	Frequency	Centrality	Keyword	Number	Frequency	Centrality	Keyword
1	896	0.06	Carbon neutrality	16	211	0.03	efficiency
2	608	0.09	CO_2 emissions	17	204	0.03	reduction
3	436	0.03	impact	18	203	0	policy
4	434	0.02	energy	19	170	0.01	system
5	404	0.06	performance	20	169	0	optimization
6	336	0.01	emissions	21	165	0.01	impacts
7	334	0.02	energy consumption	22	149	0.03	storage
8	326	0.02	economic growth	23	142	0.02	life cycle assessment
9	325	0	china	24	140	0.01	urbanization
10	310	0.05	model	25	139	0	decomposition
11	301	0.01	renewable energy	26	138	0.02	technology
12	296	0	carbon emissions	27	137	0.02	greenhouse gas emissions
13	285	0.08	climate change	28	133	0.07	carbon dioxide
14	277	0.01	consumption	29	129	0	dioxide emissions
15	230	0.02	growth	30	127	0	management

efficiency [29]. Chun et al. proposed a novel integrated assessment framework based on the BWM-entropy TOPSIS to address low efficiency [30]. In addition to quantifying carbon emission efficiency, scholars have researched the factors contributing to the major gaps observed across provinces. Multiple investigations have been conducted on the drivers of carbon footprint reduction, revealing that the energy structure and clean energy play pivotal roles in mitigating carbon emissions [31–36]. Wang et al. used cointegration and Markov chain models and found that optimizing the energy structure in low- and medium-high growth scenarios leads to an earlier carbon peak year in China and notably suppresses carbon peaks [37]. In their study, utilizing the extended STIRPAT model, Sun et al. found that residents, real GDP, energy use per unit, industrial composition, and investment in fixed assets contributed to increasing the carbon footprint. Alternatively, the level of urbanization has a suppressive effect on greenhouse gas emissions [38]. Using a spatial econometric panel model, Yu et al. found that implementing clean energy policies in a particular region facilitates increased carbon dioxide emissions. However, it also promoted a reduction of carbon dioxide emissions in adjacent areas. Moreover, they uncovered a distinctive association between the advancement of renewable energy and greenhouse gas emissions, exemplified by a reversed "U" shaped correlation [36].

In studies on optimizing pathways for achieving carbon peaking and neutrality, the relevant literature primarily focuses on several categories. First, studies have explored implementation pathways based on the current state of energy development, such as Hao et al.'s exploration of achieving dual carbon goals through industrial technology reforms and energy structure adjustments [39]. Second, system dynamics analyses, such as those by Gao and Pan [40], highlight that improving industrial energy efficiency and increasing the proportion of clean electricity are key factors. Third, research on the selection of influencing factors and model applications, such as that of Li et al., indicates that energy intensity and industrial structure adjustments are crucial for curbing CO_2

emission growth and achieving carbon neutrality [41]. Additionally, Li et al. used the random forest model to reveal that energy structure and technological factors can significantly reduce CO_2 emissions, thus aiding in achieving carbon neutrality goals [42]. Finally, the application of digital technology to carbon reduction, as discussed by Wang et al., examines emission reduction pathways from the perspective of digital trade and finance [43,44].

Marine spatial planning (MSP) is a crucial tool for carbon reduction and enhancing carbon sequestration [45,46]. Covering 71 % of Earth's surface, oceans constitute the largest carbon sink of the planet. Systematic and rational spatial planning of these vast marine areas is essential to balance carbon reduction and sequestration. Studies have demonstrated that dividing marine spaces into ecological protection, control, and development zones (including renewable energy zones) can significantly enhance carbon sequestration and reduce carbon emissions. These zones can be further classified into carbon sequestration, carbon reduction, carbon sequestration, carbon replenishment, green low-carbon and high-carbon intensity zones to facilitate precise carbon management. Soil carbon storage is another crucial area of focus, with research primarily centered on land use changes and their impact on carbon reserves [47–50]. Specifically, the type of arable land conversion significantly affects carbon reserves. For example, converting unused or construction land into arable land can increase carbon sequestration, whereas converting arable land into construction land can lead to a substantial decrease in carbon storage [51,52]. Forests also play a pivotal role in carbon storage, with bamboo being particularly effective in carbon sequestration [53–56]. The rapid growth, short regeneration cycle, and strong carbon sequestration capacity of bamboo make it highly beneficial, particularly in the construction industry, owing to its biodegradable nature. Research has revealed that bamboo can absorb approximately 35 % of the atmospheric CO_2 while releasing a substantial amount of oxygen [57].

3.3.2. Keyword clustering

By employing keyword clustering, the crucial aspects in the field of dual carbon systems can be analyzed to gain further insights into the ongoing research progress and current hotspots. Utilizing the log-likelihood ratio algorithm of the CiteSpace software, the keyword network was subjected to clustering analysis using the K-means algorithm, with parameter K = 9. Consequently, nine class clusters were extracted, as shown in Fig. 10. The clusters were numbered based on their sizes, with smaller numbers indicating a more prominent inclusion of literature and vice versa. The three dominant themes observed in the clustering analysis were carbon dioxide emission reduction, carbon neutrality, and sustainable development.

According to the keyword clustering analysis, the keyword labels under each cluster were listed (Table 3). A thorough examination of the extensively referenced articles within each cluster allows for a comprehensive understanding. The secondary organization of the existing theme clusters and the classification and division of the clustering results reveal that the focal points of carbon-neutral research predominantly lie in the subsequent three areas.

(1) Electrocatalytic carbon dioxide reduction. Targeted conversion of CO_2 into valuable chemicals, energy, and materials can alleviate environmental problems to a certain extent and reduce the dependence of humanity on fossil fuels. Catalytic conversion technologies for carbon dioxide mainly include thermochemical, photocatalytic, electrocatalytic, and photoelectrocatalytic reduction [58–62]. CO_2 electrocatalytic reduction is a promising carbon-negative technology used to convert CO_2 into organic fuels and feedstocks, increase renewable energy consumption, and realize carbon recycling [63]. The CO_2 catalytic conversion technologies have different maturity levels. High-temperature solid oxide electrolysis has a high level of maturity and is already approaching commercial application, whereas low-temperature CO_2 electrolysis for the production of C2+ products is still in the initial development phase. Rapid growth is required to enhance the maturity of technologies for industrial applications [64]. CO_2 electrocatalytic reduction is a complex process that occurs at multiple scales, going sequentially through the catalytic active site, local concentration, gas-liquid transport, catalytic layer, gas diffusion electrode, and electrolytic system. Recent findings have demonstrated that CO_2 electrolysis performance correlates strongly with the localized concentration of reactants in the vicinity of the catalyst and the nature of gas-liquid transport, in addition to the activity of the catalyst itself. Numerous studies have investigated catalyst active sites and electrolyte

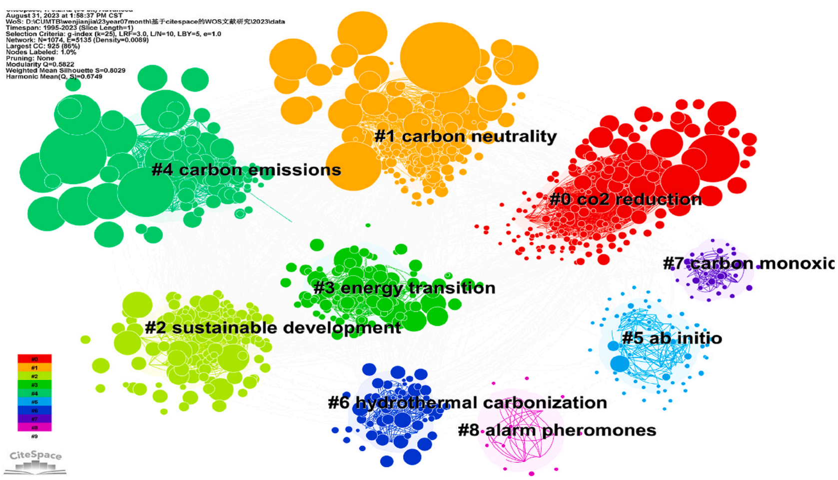

Fig. 10. Keyword clustering.

Table 3
Keyword clustering.

Number	Cluster Label	Keyword
0	CO_2 reduction	CO_2 reduction; carbon neutrality; catalysts; carbon dioxide; graphene
1	carbon neutrality	carbon neutrality; climate change; carbon sequestration; carbon footprint; carbon storage
2	sustainable development	sustainable development; digital economy; environmental regulation; evolutionary game; green finance
3	Energy transition	energy transition; multi-objective optimization; wind power; demand response; hydrogen
4	carbon emissions	carbon emissions; co_2 emissions; economic growth; financial development
5	ab initio	ab initio; carbon neutrality; chemistry; electronic structure
6	hydrothermal carbonization	hydrothermal carbonization; anaerobic digestion; hydrochar; circular economy; lignin
7	carbon monoxic	carbon monoxide; palladium; carbonylation; amino acid
8	alarm pheromones	alarm pheromones; ants; alkenes

solutions; the efficiency and electrolytic density of CO_2 electrocatalytic reduction can be notably improved by optimizing the catalyst composition and specific active site conditions, as well as the cations and anions of the liquid electrolyte [65]. In addition, optimizing CO adsorption activation, profound reduction, and C-C coupling can be achieved by introducing organic molecules or condensates on the catalyst surface to modulate the CO scope, adsorption configuration, and local pH of the catalyst surface. Nam et al. found that modifying pyridine molecules with different structures on Cu catalysts optimized the CO sorption configuration, promoting C-C coupling and ethylene generation [66]. Chen et al. found that the ethylene production efficiency decreased gradually. The efficiency of hydrogen precipitation gradually increased with an increase in the proportion of hydrogen substituted by the methyl groups on the amine, indicating that polyamine modification could significantly affect the CO_2 electro-reduction performance of Cu catalysts. In addition, polyamine P1 modification increased the CO coverage and local PH value on the Cu catalyst surface, promoting C-C coupling and effectively inhibiting the side reaction of hydrogen precipitation [67]. García De Arquer et al. introduced Nafion ionomers onto the surface of Cu catalysts and observed that a fast gas and K+ transport channel could be constructed, which, in turn, significantly reduced the depth of the gas-transport scattering layer and increased the current density of CO_2 electrolysis [68]. Kim et al. controlled the transport of CO_2 and OH- by enhancing the synergistic regulation of cationic and anionic bilayers of ionomers, thus achieving higher CO_2 concentration and higher local pH at the electrode surface, based on which, combined with pulse electrolysis, the catalyst concentration could be further enhanced. This in turn enhanced the current density of C2+ products [69]. Li et al. used QAPEEK ionomers to activate CO_2, which improved CO coverage on the surface of Cu catalysts and promoted ethylene production. Different ionomers have different promotional effects [70].

In summary, CO_2 electrocatalytic reduction technology has several advantages. First, it can convert CO_2 into high-value-added chemicals, thus completely utilizing and recycling waste CO_2 resources. Second, combining it with alternative energy sources, such as solar and wind energy can achieve the dual goals of carbon reduction and energy transition. Third, CO_2 electrocatalytic reduction can substitute or improve traditional chemical production processes. Fourth, it promotes innovation in the development of catalysts, electrode materials, and related technologies, providing novel insights and opportunities for applying new energy materials and technologies.

(2) Sustainable energy transition strategy. Technologies play a crucial role in the shift toward sustainable energy, such as eco-friendly energy, energy reservoir, energy-from-waste, electric automobiles, and energy efficiency technologies, with renewable energy being the most popular representative [71]. The primary impact of clean energy is its ability to replace fossil fuels, resulting in reduced emissions. From the highest tier at the national to the regional and municipal levels, the consequences of renewable energy on emissions control are extensive. For instance, at the national level, Gu and Zhou compared the carbon emission levels from the existing electricity technology mix and electricity emission factors of the nation along the Belt and Road with those from investment of China in approximately 36 green energy projects and found that the energy transition helps host countries achieve at least 48.69 Mt of carbon emission reductions [72]. Mittal et al. found that China needs to enhance its renewable energy proportion more significantly than India to achieve its exact CO_2 reduction target [73]. Boosting the adoption of clean energy sources is another influential strategy for mitigating warming in New South Wales grid of Australia [74]. By comparing the carbon emissions of conventional internal combustion engine vehicles and electric vehicles in several countries, Xia et al. found that expanding the allocation of clean energy production and energy transition is a shortcut for the transportation sector to achieve the dual carbon goal [75]. Therefore, scholars have conducted research from the perspective of renewable energy layouts to examine the impact of the order of alternative energy advancement and utilization on carbon footprint-reduction targets. For example, Li et al. used the hierarchical analysis method and various MCDM methods and found that the order of green energy progress and utilization affected the fulfillment of green emission mitigation objectives in different regions of China for areas with severe greenhouse gas emissions; the second highest carbon footprint of regions III and IV offered the most favorable conditions for the advancement of hydropower generation [76].

At the provincial level, Wang et al. used panel quintiles to compare pollutant emissions from clean and fossil energy power generation in 30 provinces in China. After the cleaner electricity reform, they found that non-fossil fuel power generation favored dual carbon goals of China [77]. The established literature has also considered spatial dependence when studying the affinity between sustainable energy and CO_2 reduction effects. For example, research performed by Gu et al. examined the spatial interdependency of carbon intensity and the consequent spatial spillover impacts across 30 Chinese provinces by employing the spatial Durbin model. They found that the technological advancement of green energy could reduce carbon efficiency, though would boost the carbon intensity of adjacent regions [78]. Regarding the association between the utilization of clean energy and the extent of economic output measured per unit of greenhouse gas emissions, Meng et al. used longitudinal data of China for 30 years, from 2011 to 2020, and discovered that applying eco-friendly energy played a noteworthy role in driving the upward trajectory of carbon productivity, especially in the western region [79].

Although limited scholarly attention has been paid to renewable energy at the urban level, cities play a vital role in mitigating carbon emissions. By studying a city-scale wastewater treatment plant system consisting of 31 plants in Guangzhou, China, Ma et al. found that the overall adjustment and optimal management of a mix of renewable energy sources in wastewater remedy studies could achieve energy independence in the wastewater system and offset the carbon output generated by the wastewater cure process [80]. Lund et al. studied three cities, namely Delhi, Shanghai, and Helsinki and found that the sustainable power fraction in cities could be increased by increasing the application of clean power [81]. However, some studies have suggested that, as the scale of urbanization increases, the space constraints of coal-fired power plants lead to inadequacy of equipping urban coal-fired units with carbon capture and storage, which hinders renewable-energy expansion and the progress of the urban low-carbon transition to achieve the zero-carbon or even negative-carbon goal. To address this challenge, Xia et al. utilized rooftop photovoltaic-assisted power generation coupled with sludge co-combustion in a coal-fired power system to significantly reduce carbon dioxide emissions based on residual life cycle analysis [82].

(3) Green financial policy tools. Unlike traditional financial instruments, sustainable finance, a financial tool, combines market oversight and ecological and environmental interests and leads to the low-carbon development of society by investing limited financial assets in efficient, sustainable, low-carbon, green, and environmentally friendly industries. Three paths exist for green finance to reduce CO_2 emissions: the first promotes the innovative progress of green technology, the second objective involves fostering an ecological shift within the industrial framework, and the third is to promote the restructuring of the industry to align with ecological principles with eco-innovation [83–86]. Wang et al. studied a dataset comprising information from 30 provincial administrative areas in China from 2008 to 2019 using a fixed-effects model. They also find that green financial instruments could notably reduce CO_2 emissions by enhancing the efficiency of energy usage through structural optimization and upgrading the industrial structure [87]. Moreover, green financial instruments remarkably inhibit greenhouse gas emissions in immediate and extended timeframes [88]. Evidence suggests that in agriculture, eco-friendly finance policy measures can reduce agricultural carbon output and facilitate a reduction in fertilizer usage, thus significantly reducing agricultural carbon dioxide emissions [89]. In addition, green finance has spatial spillover effects. Lin et al. and Feng et al. found that the influence of eco-friendly finance on carbon emissions was not always inhibitory, based on state-level panel data from 2008 to 2019 applied using the spatial Durbin model, and in the national scope, green finance correlated positively with carbon emissions in bordering locales first and then became negative, indicating an inverted U-shaped relationship [90,91]. Regarding the connection between industrial clustering, green finance, and CO_2 emissions, Hou et al. proposed that vigorously developing green finance can inhibit the promotion of CO_2 emissions by energy-consuming industrial clusters [92]. However, is green finance really "green"? Scholars have studied the long-term impact of green finance and renewable energy on the ecological environment, confirming the major role played by eco-finance and eco-friendly energy in promoting carbon mitigation and realizing sustainable development in China [93–95].

3.4. Analysis of the evolution of research themes

The timeline graph of co-citation clustering aims to demonstrate the research history of a particular research topic by analyzing the relationships between clusters and literature citations in a particular cluster. CiteSpace enables the categorizing and clustering of scholarly articles with similar dual carbon research content to identify the central themes within the dual carbon domain. Each node in a clustered timeline graph represents a reference. The co-citation analysis of journals in the last ten years, that is, from 2013 to 2023, is

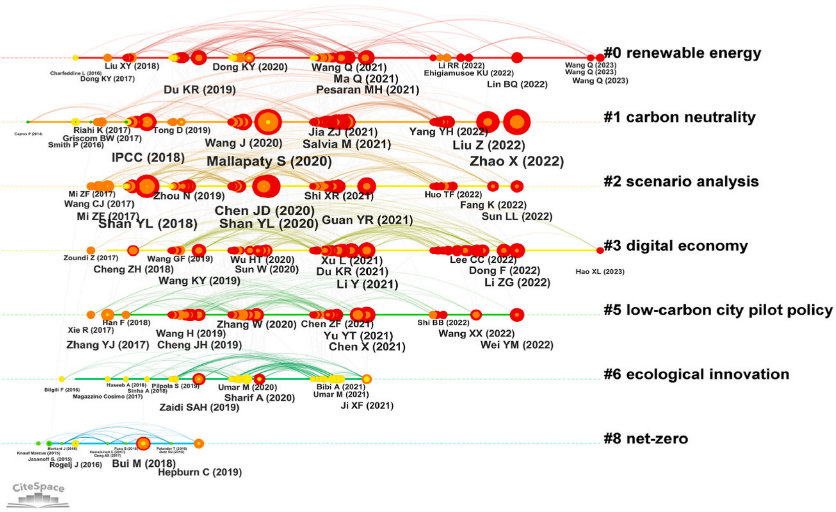

Fig. 11. Time line graph of co-citation analysis.

presented in Fig. 11. It contains 1295 nodes, 4107 connectors, and a network density of 0.0049.

As depicted in Fig. 11, the "# 8 Net Zero Emissions" study had the shortest duration, whereas the "#1 Carbon Neutral" study had the longest duration. "#0 Renewable Energy," "#1 Carbon Neutrality," "#2 Scenario Analysis," "#3 Digital Economy," and "#5 Low Carbon City Pilot Policies" were the newest research hotspots in the past two years, whereas "#6 Eco-Innovation" and "# 8 Net Zero Emissions" were less researched in the past two years, suggesting that the study conducted in this field has attained a considerable level of maturity. To achieve a more thorough examination of the transformation of research themes in the dual carbon field over the past decade, we categorized and summarized the results of the co-cited literature as follows: Renewable Energy contributes to a soft landing for Carbon Neutrality ("#0 Renewable Energy," "#1 Carbon Neutrality"); scenario analysis implements a hard landing for dual carbon goals ("#2 Scenario Analysis"); and the Digital Economy joins forces with a two-pronged approach for pilot policy ("#3 Digital Economy," "#5 Pilot Policy for Low-Carbon Cities").

The first level is renewable energy, which contributes to the soft landing of carbon neutrality targets. The seven most highly cited documents at the first level are listed in Table 4. The proportion of fossil fuels replaced by renewable energies largely determines the attainment of the temperature increase target of 1.5 °C of the Paris Agreement [96]. Zhao et al. proposed a "three-stage four-step" strategy for low-carbon development in China, indicating that renewable and clean energy should be actively pursued to contribute to carbon-neutral development [97]. Similarly, Khan et al. verified the adverse correlation between the integration of clean energy and consumption-based CO_2 emissions using a second-generation panel cointegration method for G7 countries [98]. To achieve the dual carbon goal, Mallapaty suggested the need to produce clean electricity from zero-emission sources and to increase renewable power generation by 16 times, 9 times, 6 times, and 1 time in the next 40 years from solar, wind, nuclear, and hydro energy, respectively. The inevitable production of CO_2 from fossil fuels and biomass must be offset by capture from the atmosphere and underground storage [99]. Liu et al. pointed out that China boasts the highest capacity installation globally for wind, solar, and hydroelectric power and is one of the most promising green technology frontrunners [100]. Jia and Lin [101] proposed renewable energy investment as the primary driver of long-term carbon reduction from a coal substitution perspective. However, with the determination of countries to mitigate warming, will they accomplish the dual carbon objective and reach the vision of 1.5 °C warming? Salvia et al. found that 78 % of the cities in the sample had a contingency plan, with an average emission reduction target of a 47 % reduction in CO_2 emissions, whereas 22 % had no plans [102]. Therefore, realizing the dual carbon goal and mitigating climate warming still has a long way to go and requires joint efforts from all cities.

The second level is a scenario analysis to implement a hard landing of the dual carbon target. Table 5 summarizes the eight journals with more than 30 citations under cluster 2. Accurate accounting of CO_2 emissions and reliable and transparent carbon inventories are the first tasks in implementing mitigation policies and are the blueprint for guiding the development of low-carbon transition policies. To provide an accurate database for studying carbon emission models, researchers have analyzed most recent CO_2 emission inventories of China, considering data from all 30 provinces according to the extent of administrative regions defined by the IPCC [103,104]. Chen et al. used the PSO-BP algorithm to unify the rankings of DMSP/OLS and NPP/VIIRS imagery, overcoming the limitations of traditional studies in terms of period and geographic coverage, to estimate the CO_2 emissions of 2, 735 counties in China over the last 20 years [105]. Quantifying carbon emission drivers is a notable asset for achieving this dual carbon goal. Ma et al. found that high economic growth and urbanization are essential factors inhibiting carbon emission reduction, whereas energy efficiency, industrial systems, and economic measure systems are essential engines driving the achievement of the dual carbon goal [106]. Chen et al. identified the drivers of the four pillar industries: industry, transportation, construction, and agriculture. Research has revealed that economic ripening is the predominant trigger for carbon emissions, whereas reducing energy assertiveness is an immediate impetus for carbon mitigation efforts [107]. Researchers have also conducted extensive research on whether and when China can achieve carbon peaking. Guan et al. [104] studied the endogenous motivating factors for implementing carbon emission reduction in 30 provinces in China and found that 2030 is the optimal year to reach carbon plateauing. Liu and Xiao found that China may attain maximum carbon emissions in 2023, obtaining value of 81.5, 85.83, and 83.2 million tons [108]. Numerous studies have shown that achieving carbon neutrality occurs over a prolonged timeframe and is a burdensome task that requires the participation of all sectors in deeper decarbonization and emission reduction [109], accelerated energy transition, accelerated R&D, and innovation of green technologies.

The third level is the synergistic advancement of an Internet-based economy combined with carbon trading policies. Table 6 lists the top five articles with the highest number of citations at the third level. Chen and Lin found that emissions trading can significantly improve the Total Factor Carbon Performance Index and the Energy Carbon Performance Index, confirming the vital role of the carbon trading mechanism in curbing CO_2 emissions [110]. Hu et al. found that the cap-and-trade policy could reduce the CO_2 emissions of the pilot region by 15.5 % at the macro-industry level relative to non-pilot regions [111]. Meanwhile, an unprecedented surge was observed in digital technology, accompanied by remarkable momentum bringing about disruptive changes in various industries. Globally, digital technology will become an essential engine for "zero carbon." Integrating digital technology with the carbon market, carbon trading systems, and carbon asset management will facilitate the conversion of various industries to eco-friendly and low-carbon development and provide novel ideas for the green development of the industry, as well as energy saving and carbon reduction. Multiple studies have indicated that an Internet-based economy is crucial for achieving high-quality economic growth and addressing climate change. To explore the relationship between the knowledge-based economy and carbon footprint, Li and Wang suggested that the information economy is proposed to catalyze carbon emissions initially and later as a restraint, exhibiting a "reverse U″ shape [112]. However, how does a data-driven economy affect greenhouse emissions? Li et al. found that digital economic technologies could help collect and monitor carbon emission data. Through intelligent sensors, the Internet of Things, and extensive data analysis, real-time carbon emissions information from companies and organizations could be obtained, providing an accurate data foundation for carbon trading [113]. Ren et al. proposed that digital economic technologies have realized the digitization and automation of carbon trading. Through technologies, such as blockchain and smart contracts, transaction security and efficiency can

Table 4
Major articles distributed in clusters (numbers 0, 1).

First Author	Year	Article	Journal	Co-Citation	Centrality	Cluster
Mallapaty S	2020	How China Could be Carbon Neutral by mid-century [99]	NATURE	106	0	1
Zhao X	2022	Challenges toward carbon neutrality in China: Strategies and countermeasures [97]	RESOUR CONSERV RECY	99	0	1
Liu Z	2022	Challenges and opportunities for carbon neutrality in China [100]	NATURE REVIEWS EARTH & ENVIRONMENT	70	0	1
Duan HB	2021	Assessing China's efforts to pursue the 1.5 degrees C warming limit [96]	SCIENCE	65	0.02	1
Salvia M	2021	Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU [102]	RENEW SUST ENERG REV	45	0	1
Jia ZJ	2021	How to achieve the first step of the carbon-neutrality 2060 target in China: The coal substitution perspective [101]	ENERGY	41	0.01	1
Khan Z	2020	Consumption-based carbon emissions and International trade in G7 countries: The role of Environmental innovation and Renewable energy [98]	SCI TOTAL ENVIRON	41	0.03	0

Table 5
Major articles distributed in clusters (numbers 2).

First Author	Year	Article	Journal	Co-Citation	Centrality	Cluster
Shan YL	2020	China CO_2 emission accounts 2016–2017 [103]	SCIENTIFIC DATA	81	0	2
Chen JD	2020	County-level CO_2 emissions and sequestration in China during 1997–2017 [105]	SCIENTIFIC DATA	73	0	2
Guan YR	2021	Assessment to China's Recent Emission Pattern Shifts [104]	EARTHS FUTURE	47	0	2
Ma XJ	2019	Carbon emissions from energy consumption in China: Its measurement and driving factors [106]	SCIENCE OF THE TOTAL ENVIRONMENT	36	0	2
Chen X	2020	Analysis on the carbon emission peaks of China's industrial, building, transport, and agricultural sectors [107]	SCIENCE OF THE TOTAL ENVIRONMENT	34	0.02	2
Liu DN	2018	Can China achieve its carbon emission peaking? A scenario analysis based on STIRPAT and system dynamics model [108]	ECOLOGICAL INDICATORS	34	0.01	2
Huang MT	2021	Achieving Paris Agreement temperature goals requires carbon neutrality by middle century with far-reaching transitions in the whole society [109]	ADVANCES IN CLIMATE CHANGE RESEARCH	31	0	2

Table 6
Major articles distributed in clusters (numbers 3,5).

First Author	Year	Article	Journal	Co-Citation	Centrality	Cluster
Li Y	2021	Energy structure, digital economy, and carbon emissions: evidence from China [113]	ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH	45	0	3
Chen X	2021	Towards carbon neutrality by implementing carbon emissions trading scheme: Policy evaluation in China [110]	ENERGY POLICY	41	0.03	5
Hu YC	2020	Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China [111]	ENERGY ECONOMICS	37	0.01	5
Li ZG	2022	The Dynamic Impact of Digital Economy on Carbon Emission Reduction: Evidence City-level Empirical Data in China [112]	JOURNAL OF CLEANER PRODUCTION	36	0.01	3
Ren SY	2021	Digitalization and energy: How does internet development affect China's energy consumption? [114]	ENERGY ECONOMICS	31	0	3

be improved and intermediaries and transaction costs can be reduced, promoting the development of carbon trading markets. In addition, the digital economy provides tools and systems for carbon emissions accounting and management. It creates carbon trading platforms and markets, enabling more convenient trading of carbon emission rights between companies and organizations. Furthermore, innovation and the synergistic effects of the digital economy provide novel opportunities for carbon-trading policies [114].

4. Conclusions and prospects

Using text mining techniques, we conducted a bibliometric analysis of emerging hotspots, knowledge evolution, and thematic trends in the dual carbon field for the past 30 years. The findings are presented as knowledge graphs. The results were clear and comprehensible. By analyzing keyword co-occurrence, we explored the theoretical foundations of the dual carbon field from the perspectives of energy, modeling methods, optimization pathways, and carbon storage. Through keyword clustering, we examined the development of carbon dioxide catalytic reduction technologies, sustainable energy transitions, and green financial instruments. Thematic evolution analysis shed light on the roles of renewable energy, scenario analysis, digital economy, and carbon trading policies in achieving the “3060″ targets, offering a dynamic mechanism for research in the dual carbon field. Our findings provide a valuable reference for future scholars to deepen their research. Based on our results, we propose the following development trends for future research, aiming to provide novel insights and help researchers identify key focus areas.

(1) Transforming Coal from “Black” to “White"

The emergence of interdisciplinary integration in the carbon-neutrality field underscores the pivotal shift in clean low-carbon development. Researchers are focusing increasingly on methods for reducing carbon dioxide emissions and enhancing the clean and efficient use of coal from a material science perspective. This transformation of coal from “black” to “white” is not only a key focus for scientists but also a crucial consideration for policymakers shaping emission reduction strategies. Future research should prioritize advancements in clean coal utilization technologies, exploration of novel catalytic materials and processes, and the minimization of environmental impacts.

(2) Regional Disparities in Global Low-Carbon Research

Although Asia and North America have conducted extensive research on low-carbon initiatives, a paucity of studies remains on Europe, Africa, and South America. Africa relies predominantly on traditional biomass fuels for energy consumption. Many South American countries depend heavily on the oil and gas industries. Despite attempts to promote renewable energy in some Central and Eastern European countries, primary energy consumption remains largely based on coal and natural gas. Thus, transitioning to a more sustainable and low-carbon energy structure is a long-term endeavor. Future research should expand the geographical scope of carbon reduction studies to analyze the diverse pathways of low-carbon transitions across regions. Case studies, such as Brazil’s biocarbon storage projects in the Amazon rainforest can offer valuable insights.

(3) Development of carbon storage and capture technologies

The frequent appearance of terms and term clusters related to carbon storage and capture indicates the global undertaking of multiple carbon storage projects (for example, geological carbon storage projects in the United States, Canada, Norway, and Australia; biological carbon storage projects in Amazon rainforest of Brazil) and carbon capture methods (for example, combustion-source carbon capture and direct air capture). This underscores the increasing importance and potential of carbon storage and capture technologies, despite their limited large-scale commercial applications. Future research should focus on the economic viability and policy support for these technologies, addressing challenges, such as high costs, technical feasibility, regulatory policies, and public acceptance. For example, geological carbon storage projects in the United States offer valuable insights into the practical applications of these technologies.

(4) Prospects for CO_2 Electrocatalytic Reduction

The emergence of CO_2 electrocatalytic reduction indicates a global commitment by scientific institutions, universities, and industries to this area of research. Although still in the research and development phase, facing challenges, such as low efficiency, limited product selectivity, and catalyst stability issues, this technology holds considerable promise. It is poised to make crucial contributions to reducing greenhouse gas emissions and advancing sustainable energy and chemical production. This trend has spurred extensive scientific research and technological innovation aimed at accelerating the maturity and practical application of CO_2 electrocatalytic reduction. Future research should prioritize enhancing the catalyst performance and stability, developing novel reactor designs, and conducting economic assessments for large-scale implementation. For instance, laboratory studies in China and Japan on CO_2 electrocatalytic reduction underscore the potential applications of this technology.

(5) Synergistic Development of the Digital Economy and Carbon Trading Policies

The synergistic development of the digital economy and carbon trading policies is gradually unfolding, supported by technological advancements and informatization. However, this integration faces several challenges, such as the uncertainty regarding credibility and accuracy of digital economy data. The findings in this paper offer recommendations for fostering synergy, such as investing in digital infrastructure and promoting technological innovation and R&D. These strategies present novel opportunities and solutions to achieve a low-carbon economy and sustainable development. Practical examples, such as the European Union Emissions Trading System and the application of digital yuan to carbon trading of China, illustrate the real-world importance and challenges of this synergistic development.

The findings of this study have several implications. First, it can assist policymakers in optimizing resource allocation, formulating more precise strategies for international scientific collaboration, and providing data support for research funding policies. Second, by uncovering the development trajectories and trends in CO_2 catalytic reduction technologies, sustainable energy transitions, and green financial instruments, this study offers valuable insights for enterprises and research institutions, in terms of technological development and industrial application. Additionally, by analyzing the regional differences in global low-carbon research, this study provides a reference for different regions to learn from experiences of one another in low-carbon transitions, thus promoting international cooperation and knowledge exchange. Finally, this study explores the synergetic development of the digital economy and carbon trading policies, highlighting the potential and challenges of the digital economy in carbon trading, and offering novel perspectives and approaches for future policy and technological innovation.

Ethics declarations

Review and approval by an ethics committee were not needed for this study because this study did not involve animal or human experiments.

Data availability statement

We agree that our study was deposited into a publicly available repository.

CRediT authorship contribution statement

Zhen Chen: Writing – original draft, Visualization, Investigation, Conceptualization. **Ying Shi:** Supervision, Software, Formal analysis. **Rijia Ding:** Visualization, Supervision, Software, Investigation, Conceptualization. **Jingye Liu:** Writing – original draft, Visualization, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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