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Original Research

Knowledge Mapping of Research on the Impact of Industrialization on Carbon Emissions in China: a Bibliometric Analysis Using CiteSpace and VOSviewer

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Abstract

The relationship between industrialization and carbon emissions is incredibly complicated. Numerous academics have studied this subject in-depth and produced a wealth of research findings, but there has not been a comprehensive evaluation and analysis. As a result, the Web of Science Core Collection is used as the study's data source, and China is chosen as the research object. Visualization software CiteSpace and VOSviewer are utilized to conduct cooperation network analysis, co-citation analysis and cluster analysis to analyze the research progress and frontier of the impact of industrialization on carbon emissions in China (IICEC). The results indicate that: (1) Since 2007, the research enthusiasm for IICEC has grown and gone through three stages; (2) Most research institutions and authors are from China, and significant transnational research teams have not yet been established; (3) The most popular journal for this research is Journal of Cleaner Production, whereas Energy Policy has the most citations; (4) The overall research hotspots can be divided into five clusters. Based on these findings, possible future research frontiers were identified, including carbon emission decoupling analysis and carbon transfer, life cycle analysis and life cycle cost analysis of the industry, and embodied carbon measure.

Keywords: industrialization, carbon emissions, bibliometrics, CiteSpace, VOSviewer

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Introduction

Since the 21st century, under the background of global warming, it has gradually become a global consensus to develop a low-carbon economy and limit greenhouse gas emissions. In 2003, the UK put forward the concept of a low-carbon economy for the first time in the energy white paper, and the Copenhagen climate conference, which concluded at the end of 2009, pushed the development of a low-carbon economy to a climax [1]. Greenhouse gas emissions are the main driving force of global warming, among which carbon dioxide is the most important greenhouse gas, accounting for about 66% of the warming effect [2]. According to the sixth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC), the CO_2 concentrations in the atmosphere have been at the highest level in nearly two million years. Since 1970, the global surface temperature is also the highest in nearly 2000 years, indicating that human activities have exerted a very profound impact on the Earth's climate system since industrialization [3]. However, to cope with the global climate problem, countries worldwide need to cooperate to reduce CO_2 emissions. In 2015, nearly 200 contracting parties reached an agreement on the Paris Agreement at the Paris Climate Conference, explicitly proposing to maintain the global average temperature rise within 2ºC relative to the pre-industrial level by the end of this century, and make efforts to control the global average temperature rise within 1.5ºC [4]. Under the above context, it is essential to have a better understanding of the relationship between industrialization and carbon emissions [5-7].

China is the world's largest industrial country and the largest carbon emitter. Since the reform and opening up, the pace of industrialization has been accelerating. In 2021, the GDP of China accounted for 18% of the global economy [8], while carbon emissions accounted for 33% of the total global carbon emissions [9]. Economic growth is difficult to avoid the growth of carbon emissions, which brings a series of climate and environmental problems. In recent years, the Chinese government has also attached great importance to environmental issues. In 2020, Chinese leader Xi announced at the general debate of the 75th United Nations General Assembly (UNGA) that China would increase its nationally determined contributions, adopt more effective policies and measures, strive to reach the peak of carbon dioxide emissions by 2030, and endeavour to achieve carbon neutrality by 2060 [10]. The industry is the most dominant sector of China's energy consumption and carbon dioxide emissions, accounting for 70% of total emissions in 2021. It can be said that whether industry can take the lead in carbon peaking is the key to achieving the peaking target in 2030 [11]. Therefore, a systematic study on the impact of industrialization on carbon emissions is very necessary, which is also crucial for the effective implementation of carbon reduction policies in China.

The relationship between industrialization and carbon emission is an interdisciplinary subject of energy economics, environmental economics and ecological economics, involving many fields. In recent years, many scholars have carried out much research on the impact of industrialization on carbon emissions in China (IICEC), mainly focusing on the "carbon emission calculation method", "analysis of influencing factors", and "exploration of carbon emission reduction path" [12-14]. However, there are few literature reviews and frontier trend studies on IICEC, and there is also a lack of systematic review and analysis of the research results. Therefore, to enrich the research system, this study takes China as the research object, with the WOSCC as the data source. Retrieve the research literature of IICEC from 2007 to 2021. Based on the bibliometric theory, with the help of literature data visualization analysis software CiteSpace (version 6.1.R2) and VOSviewer (version 1.6.18), visual analysis was conducted on foreign literature basis, research hotspots and future frontier trends from the perspectives of keywords, burst words and co-cited literatures, so as to provide relevant references for academic scholars in the research of IICEC.

Material and Methods

Data Sources

It is very significant to find out the relevant literature for the systematic analysis. WOSCC selected as the literature source (https://www.webofscience.com/wos/woscc/advanced-search, accessed on 8 September 2022). The search criteria are as follows: TS = ("carbon emission" OR "CO_2 emission" OR "carbon dioxide emission") AND TS = ("industry") AND TS = ("China"). Since there were few relevant studies before 2007, the time span was set from 2007 to 2021. Document type: Article or Review. The export format is plain text, and the record content is selected as "full record and cited references", named "download_XXX.txt" (Fig. 1). Finally, a total of 3447 English and 3261 unique literatures were obtained through the CiteSpace deduplication function.

Research Methods

At present, there are dozens of knowledge mapping software developed at home and abroad, among which CiteSpace [15], VOSviewer [16], Bibexcel [17], HistCite [18], SciMAT [19], Gephi [20], CRExplorer [21] are more popular. Among them, CiteSpace and VOSviewer are two powerful and complementary bibliometric analysis tools. CiteSpace is a visual network analysis software proposed by Professor Chen of Drexel University in the United States in 2004. By drawing the knowledge graph of a related field, it can display the information panorama of the knowledge

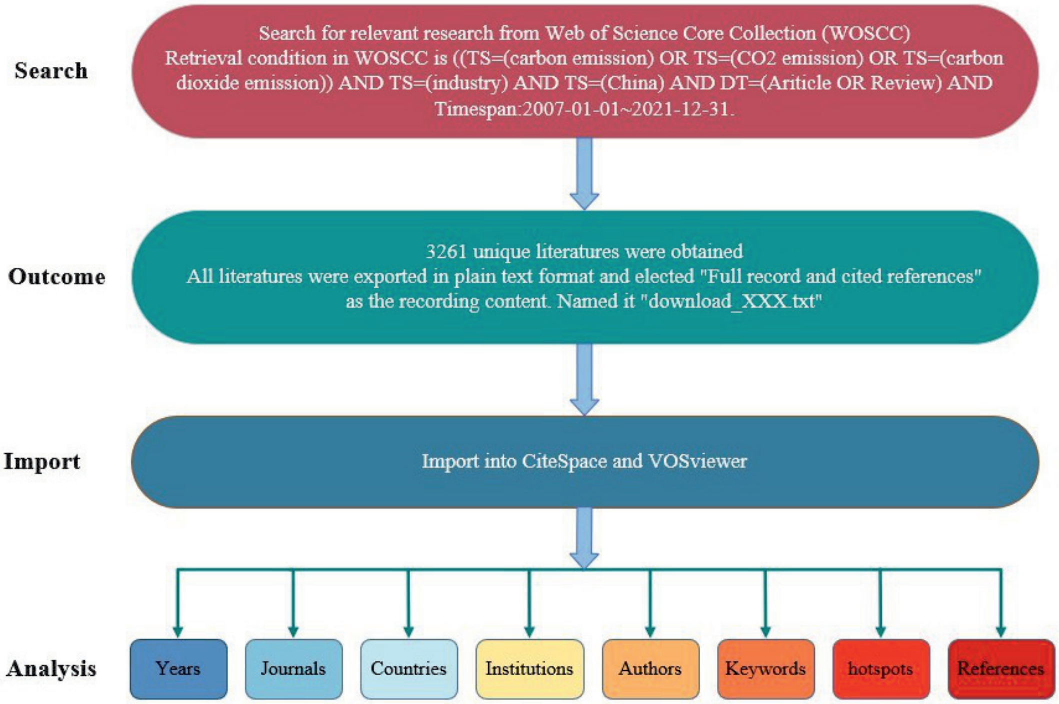

Fig. 1. Flow chart of retrieving and exporting literatures from Web of Science Core Collection and importing it into CiteSpace and VOSviewer for analysis.

field and the frontier direction of a scientific field. In addition, CiteSpace can also provide the function of co-occurrence analysis among different knowledge units, including authors, institutions, countries, etc., which can be conducted from the perspective of a cooperation network [22]. VOSviewer is a literature analysis and knowledge visualization software developed in 2009 by Van Eck and Waltman of the Centre for Science and Technology at Leiden University in the Netherlands [23]. Compared with other visualization software, VOSviewer has more advantages in processing big data and drawing images, which can draw national cooperative networks, institutional cooperative networks and author cooperative networks, understand the different levels of cooperation in this field and identify the core countries, institutions and individuals in this field. It also has unique advantages in keywords analysis and cluster analysis. So, this study combined CiteSpace and VOSviewer to conduct a comprehensive visual analysis of relevant literature.

Results and Discussion

Bibliometric Analysis of Literature Publications

The number of articles published in international academic journals on a particular topic is somewhat representative of the level of interest in that research topic. The annual publication of papers can reflect the research level and popularity of a particular knowledge field. Fig. 2 shows the annual number of publications for IICEC research in recent years. On the whole, the overall annual publication volume of research on IICEC showed an upward trend from 2007 to 2021, indicating that IICEC research has attracted more and more scholars' attention. Specifically, before 2010, there were few publications, which was defined as the initial exploration period. From 2011 to 2015, it was in a stable growth stage, and the number of papers issued in 2014 exceeded 100 for the first time. The period from 2016 to 2021 was the outbreak stage, with an average growth rate of 131.86%. This is mainly due to the introduction of the 13th Five-Year Plan for greenhouse gas emissions, the addition of ecological civilization to the modernization of socialism with Chinese characteristics at the 19th National Congress of the Communist Party of China (CPC), and the subsequent introduction of carbon peaking and carbon neutrality targets, which has led to an increasing interest in research on IICEC and a rising research heat.

Bibliometric Analysis of Journals and Cited Journals

Understanding the journal distribution of citation literature is conducive to helping researchers grasp the research hotspots and frontiers in this field *via* appropriate journals [24]. Figs 3(a, b) show the top 10 journals with the most papers published and the top 10 journals with the most citations in WOSCC of IICEC research, respectively. Related research has been published in journals in the fields of management science, engineering technology, environmental science

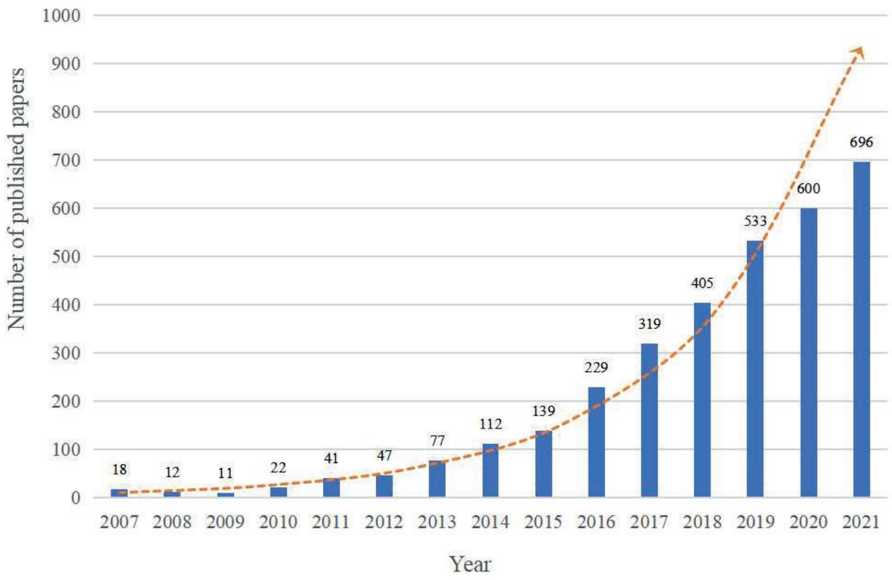

Fig. 2. Trend in the annual records of publication on the theme of IICEC from 2007 to 2021.

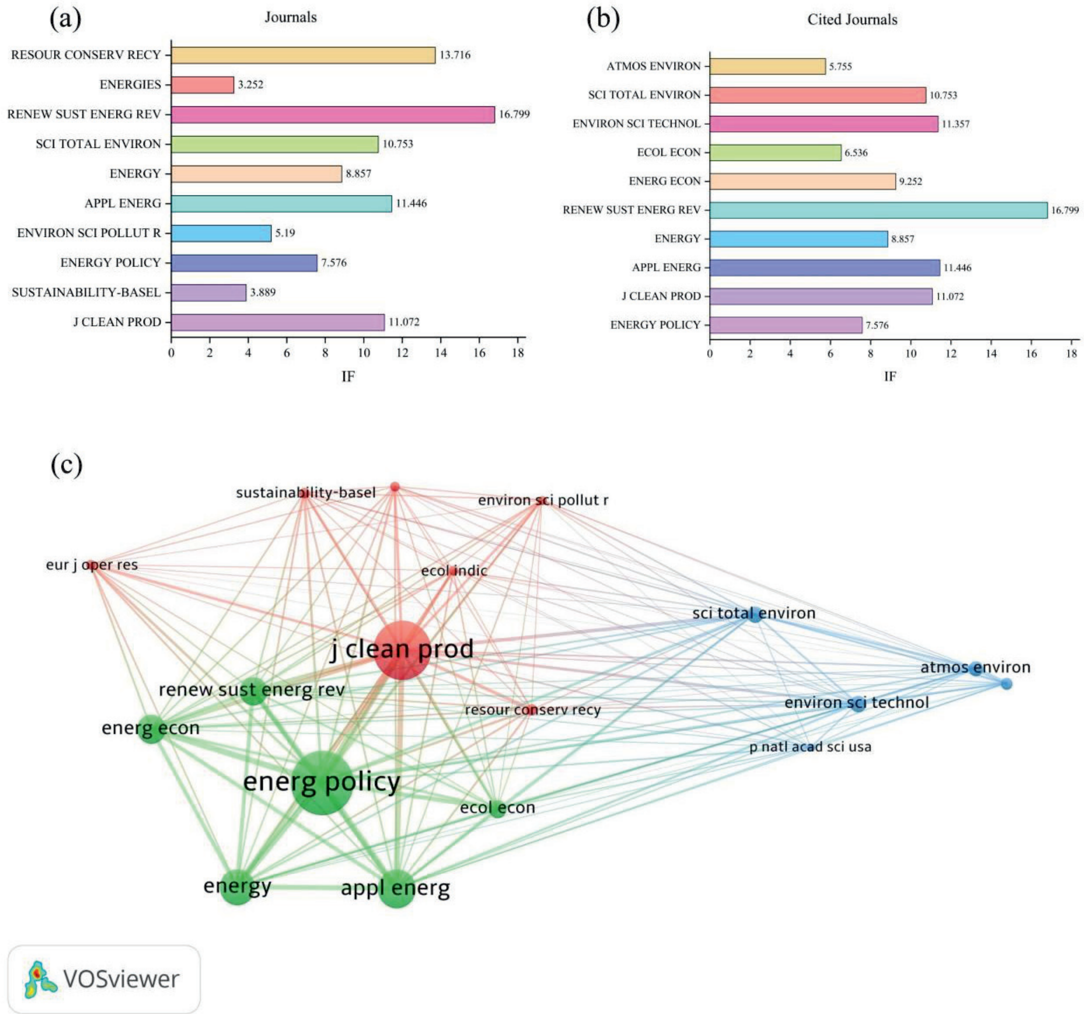

Fig. 3. Analysis of cited-journals. a) Bar chart of journals and its IF. b) Bar chart of cited journals and its IF. The IFs were obtained from Clarivate Analytics' Journal Citation Reports. c) Network visualization of cited journals. The larger the node, the more times it is referenced.

and ecology. Journal of Cleaner Production ranks first in terms of the number of articles published, followed by Sustainability, Energy Policy, Environmental Science and Pollution Research and Applied Energy. Impact factor (IF), as a relative statistic, is an important index to measure the academic level of journals. The IFs of the top ten journals are all >3, and the average IF is 9.255, indicating that many authoritative journals in academic circles are interested in IICEC research.

It is not difficult to find that the IF of co-cited journals tends to be higher than those of published journals. In order to more intuitively grasp the relationship between co-citation journals, we used VOSviewer to draw the distribution map of co-citation journals (Fig. 3c). The node size represents the frequency of the reference. It can be found that Energy Policy has the largest node on the visual map, followed by the Journal of Cleaner Production. Furthermore, they are also ranked third in the number of articles published. Thus, in a comprehensive way, they are the core journals of relevant papers, and their influence exceeds that of other journals in IICEC research.

Bibliometric Analysis of Countries and Institutions

More than 69 countries worldwide have participated in the IICEC study. The top 10 countries with the highest number of publications are shown in Fig. 4a). It is not hard to discover that the highest total number of articles was published in China (2862 articles), followed by the United States (354 articles), England (184 articles), Australia (111 articles). The publications studied in this study came from 2,044 institutions. Fig. 4b) demonstrates the top 10 institutions in terms of total publications on IICEC research from 2007 to 2021. It is noteworthy that the Chinese Academy of Sciences (CAS) has issued the most significant number of articles and the earliest time of their appearance, indicating that CAS has paid attention to the research on climate and environmental change earlier and attached great importance to it.

As shown in Fig. 4c), the research institutions are in a global aggregation state, indicating that the distribution of research institutions is relatively

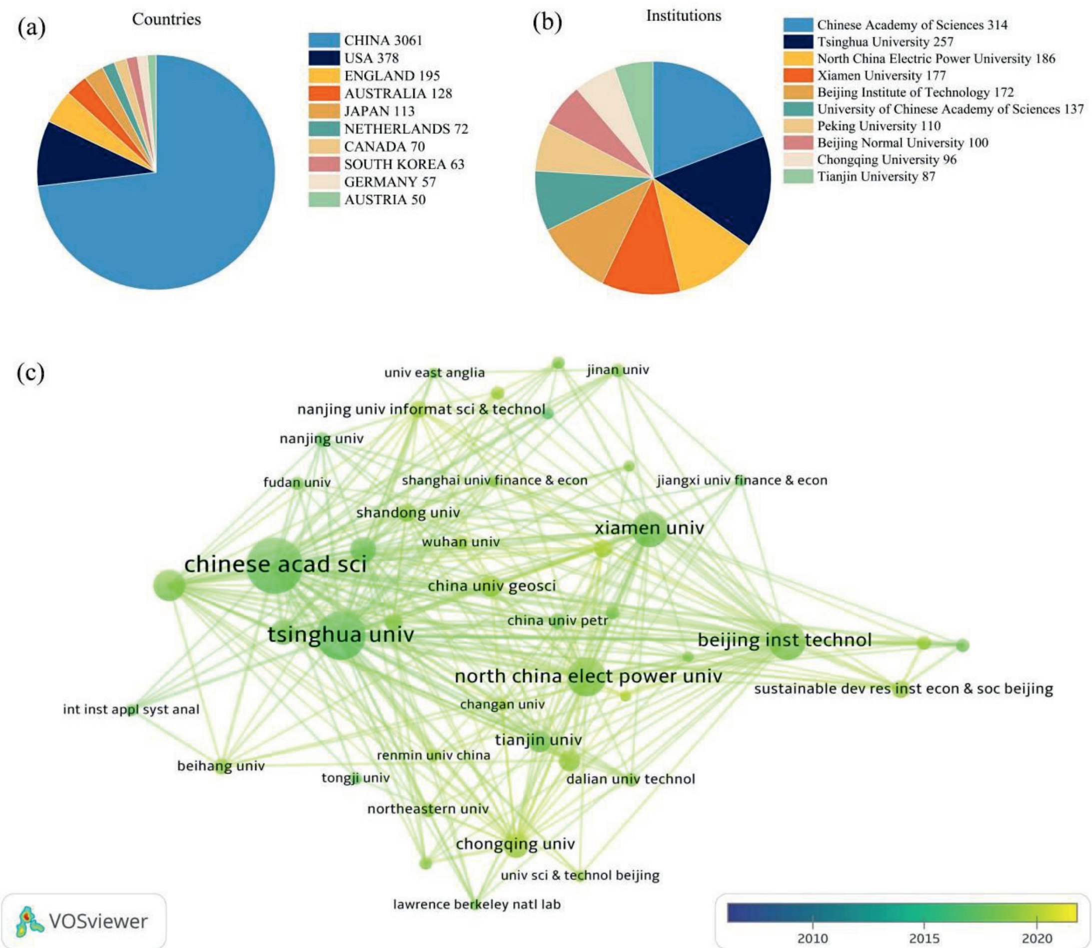

Fig. 4. Analysis of countries and institutions. a) Pie chart of top 10 published countries. b) Pie chart of top 10 published institutions. c) Visualization analysis of institutions. The larger the node, the more articles are published. The node connection lines represent the strength of the relationship between institutions. The colour of the node indicates the change in the number of published articles over time.

concentrated, forming a large aggregation cluster; that is, there is close cooperation among institutions. However, the research on IICEC is mainly conducted by Chinese research institutions, and there are few foreign research institutions, which indicates the lack of cross-country cooperative research on IICEC.

Bibliometric Analysis of Co-Authors

By analysing of the author's cooperation network, we can identify the representative scholars in the research field [25]. Table 1 shows the top 10 authors of IICEC studies from 2007 to 2021. It can be found that most of the top ten authors are from North China.

The author cooperation network diagram shows the close degree of cooperation between authors, and the node size in the network diagram indicates the importance of authors. In Fig. 5, the largest node is Lin, whose primary research directions are energy economy, energy policy and technology economy. From 2015 to 2021, dozens of articles on IICEC were published with Xu et al., with topics including research on heavy industry CO_2 drivers and spatial variability, and the role of new energy industry and high-tech industry in carbon emission reduction [26-30]. The author with the highest average number of citations per paper is Zhang, whose research interests include environmental policy and health impact assessment, carbon neutrality and clean air synergy. The relationship between fossil energy combustion and greenhouse gas emissions such as CO_2 and CH_4, as well as the resulting air quality problems and impacts on human health were discussed in his papers [31-33]. Other influential authors include Guan [34-35], Wei [36-37] and Geng [38-39]. The authors cooperated closely with each other.

Bibliometric Analysis of Hot Research Topics

Keywords can reflect the core content of the article. Through the understanding of high-frequency keywords

Table 1. Top 10 published authors of IICEC studies.

Rank	Author	ANCPP	Rank	Author	ANCPP
1	Boqiang Lin	42.08	6	Yuli Shan	43.14
2	Dabo Guan	61.75	7	Qiang Wang	20.08
3	Yiming Wei	62.06	8	Yalin Lei	39.83
4	Yong Geng	56.52	9	Jing Meng	45.81
5	Li Li	31.32	10	Qiang Zhang	151.30

Note: ANCPP stands for the average number of citations per publication of the author during the 2007-2021 period.

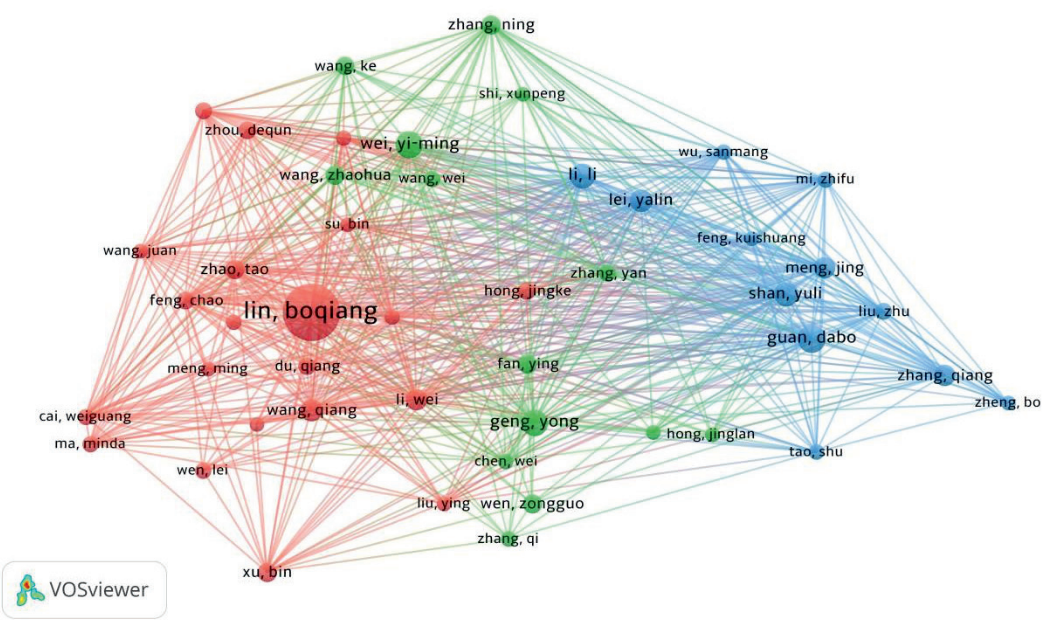

Fig. 5. Network visualization of collaboration between authors. The larger the node, the more publications. The node connection lines represent the strength of the relationship between authors.

in a field, we can quickly grasp the hot topics and cutting-edge trends in this field [40]. In this study, CiteSpace was used to calculate the centrality of each keyword. However, since CiteSpace software could not accurately identify synonymous rewriting and acronyms of keywords, other team members integrated similar keywords in this study. For example, "carbon dioxide emission" and "carbon emission" have been incorporated into "CO_2 emission". After processing, the top ten high-frequency keywords are shown in Table 2.

VOSviewer can combine keywords with similar research topics into a cluster and display them in the same colour. The larger the node, the higher the frequency of keywords in the knowledge graph, and the line between nodes represents the co-occurrence of keywords. Through the keyword co-occurrence network map (Fig. 6), we can find that the keyword network map of research on IICEC focuses on "CO_2 emission", "industry", "China" and "energy consumption", which can be roughly divided into five clusters. Additionally, combining Table 2 and Fig. 6, it can be found that high-frequency keywords such as "emission", "energy consumption" and "model" constitute a representative theme of IICEC research. At the same time, these keywords are also the central points in the keyword co-occurrence network map.

VOSviewer also features the ability to draw density views. In order to more clearly subdivide the research in this field, we used VOSviewer to generate keyword co-occurrence clustering density maps (Fig. 7). Combined with network map and density visualization map, we can extract the five major clusters of IICEC research (Table 3).

Carbon Footprint

The research and practice of carbon footprint make up for the lack of attention to the source, complete cycle and process of carbon emissions. It is of great practical significance in the context of China's strategy of basing itself on the new development stage, building a new development pattern, and achieving the dual carbon goal. At present, the research on carbon footprint mainly focuses on the research perspective and calculation method. Specifically, carbon footprint has been studied from the perspective of overall national macro [41], supply chain management [42], and regional level [43]. For calculation methods, carbon footprint calculation

Table 2. Top 10 keywords with cooccurrence.

Rank	Keywords	Centrality	Year	Rank	Keywords	Centrality	Year
1	CO_2 emission	0.06	2007	6	Economic growth	0.02	2011
2	Energy consumption	0.02	2011	7	Energy	0.02	2007
3	China	0.04	2007	8	Efficiency	0.02	2007
4	Industry	0.03	2007	9	Reduction	0.01	2013
5	Impact	0.02	2009	10	Model	0.02	2008

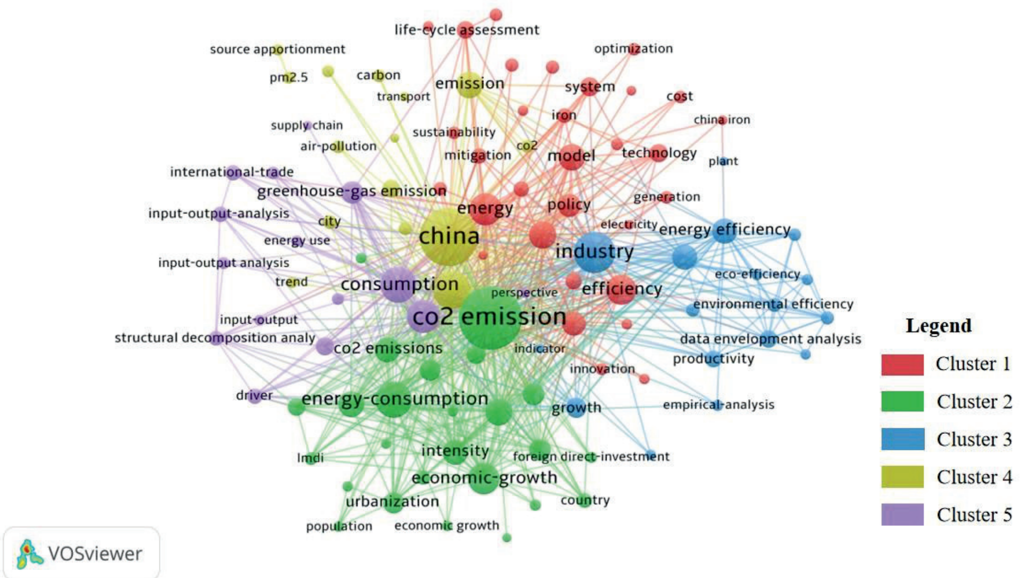

Fig. 6. Keywords cooccurrence network map. Different colours indicate different clusters.

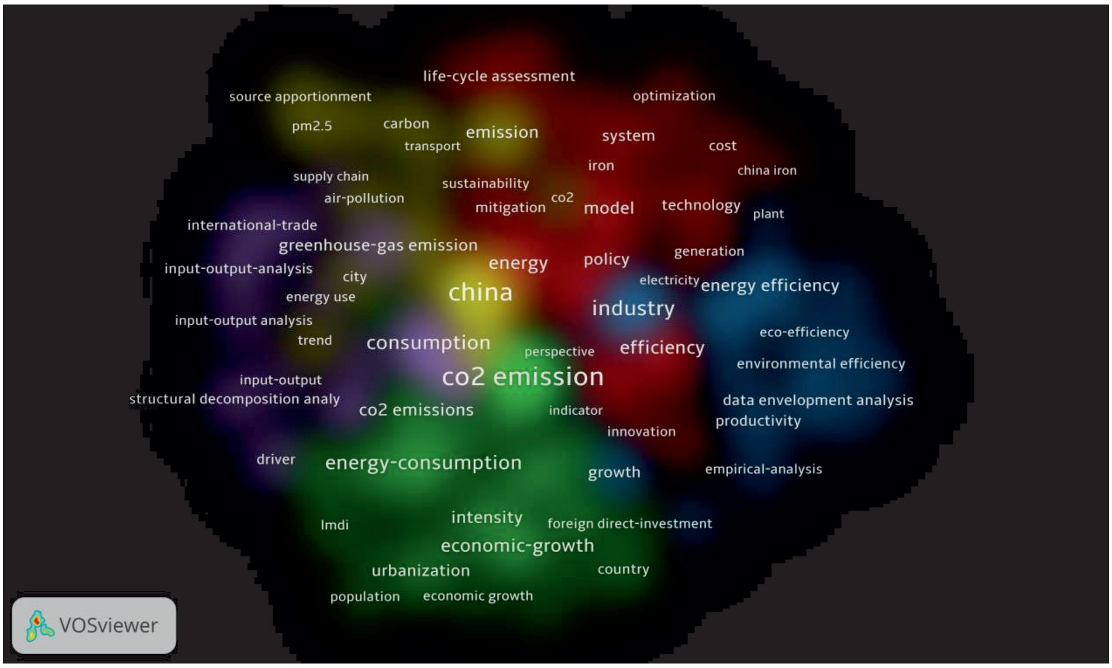

Fig. 7. Keywords cooccurrence clustering density visualization map.

Table 3. Keywords cooccurrence clustering induction.

Cluster-ID	Research topics	Main keywords included
1	Carbon footprint	CO_2 capture, life cycle assessment, climate change, air pollution, adsorbent particle, black carbon, combustion, source apportionment
2	Economic growth and carbon emission	CO_2 emissions, financial development, carbon intensity, foreign direct-investment, determinants, empirical evidence, sustainable development, urbanization
3	Efficiency assessment	Energy efficiency, productivity, empirical analysis, technical efficiency, environmental efficiency, CO_2 emission performance, index, data envelopment analysis
4	Sustainable industrial development policy	Industrialization, climate policy, carbon reduction, supply chain, strategies, carbon tax, emission trading scheme, innovation
5	Energy consumption	Industry sector, embodied energy, driving forces, carbon intensity, input-output analysis, structural decomposition analysis, LMDI model, decoupling analysis

mainly includes three methods: input-output analysis (IOA) [44], process analysis [45] and mixed life cycle assessment [46]. However, although the current relevant research is helpful for analysis, there are still some aspects to be optimized. On the one hand, the impact degree of carbon footprint on ecological environment, high or low energy consumption and emission standard of carbon footprint level have not been recognized, and there is a lack of threshold and standard setting. On the other hand, the current calculation, assessment and analysis do not consider the impact of technological progress and innovation on sustainable development and carbon emissions. These are worthy of further exploration by scholars.

Economic Growth and Carbon Emission

Since the reform and opening up, China's economy has developed rapidly with the continuous acceleration of industrialization and urbanization. However, due to the massive combustion of fossil energy, carbon emissions are also increasing, which has brought enormous pressure on resources and environment. Therefore, it is essential to coordinate the relationship between economic development and carbon emissions. Wang et al. [47] used the quadratic directional output distance function to derive the shadow price of China's provincial total carbon emissions. They found that China's weighted average shadow price presented an "N-shaped" curve, and the cost of carbon emission reduction would increase significantly with the economic growth. Du et al. [48] adopted system dynamics to analyse the effects of different economic growth rates and different carbon emission reduction technology policy factors on carbon emissions and GDP carbon intensity. In addition, Jin et al. [49] found that the decoupling between carbon emission and economic development was mainly dominated by the decoupling between energy consumption and industrial added value. In recent years, China's economy has also shifted from a high-speed development model to a high-quality one, but further research is needed on how to achieve better high-quality development.

Efficiency Assessment

Energy efficiency assessment not only helps to understand energy performance and environmental performance, but also provides an essential reference for improving energy efficiency and environmental efficiency [50]. Wang et al. [51] used data envelopment analysis (DEA) and the Malmquist-Luenberger productivity index to analyse the efficiency and performance of industrial total factor CO_2 emissions. The findings suggest that to achieve carbon emission reduction in China's heavy industrial provinces, it is necessary to focus on accelerating technological change. Wang et al. [52] introduced the RAM-DEA model to evaluate the energy and carbon dioxide emission efficiency of Chinese tobacco companies. The results indicated that the energy saving and emission reduction based on the improvement of scale efficiency had great potential. Zhang et al. [53] established a three-stage empirical system to assess the CO_2 efficiency of China's construction industry, so as to determine the CO_2 emission allocation scheme of China's construction industry at the provincial level. The results of these studies provide unique insights and guidance on the assessment of regional allocations of industry CO_2 emissions, and are of significant reference value.

Sustainable Industrial Development Policy

Sustainable industrial development policies are conducive to mitigating climate change and seeking the highest quality development at the lowest cost. Its core is to emphasize the flexibility of management methods, that is, to seek the maximum synergy through the combination of industrial development management policies [54]. There are many scholars have put forward relevant policy suggestions. First, promote the construction and innovation of the carbon trading market, formulate more flexible and efficient policies, and attract more enterprises to participate in the carbon trading market [55]. Second, increase investment in carbon capture and storage (CCS) technology research and development, and improve public awareness of CCS by formulating relevant laws and regulations [56]. Third, implement a carbon tax recycling system based on the principle of tax neutrality to reduce the carbon dioxide emissions of enterprises and promote the development of more energy-saving and emission reduction technologies [57]. Fourth, facilitate an industrial structure optimization and upgrading strategy that suits the reality of the region. Build a deep industrial system covering the whole industrial chain and promote long-term sustainable economic development [58]. Last but not least, properly optimize the energy structure, appropriately reduce energy use with high carbon emission factors, and raise the proportion of clean energy. Share energy use pressures with energy sources that exhibit low carbon emission factors wherever possible without compromising economic development [59]. Nevertheless, due to the significant differences in the actual situation in different regions, the selection of research regions is not yet comprehensive. Thus, in future research, scholars need to build industrial sustainable development policies suitable for each region according to local conditions, to achieve orderly promotion of emission reduction and sustainable economic growth.

Energy Consumption

Academics have carried out a series of studies on the relationship between fossil energy consumption and carbon emissions, and the development of new energy. Wang et al. [60] compared the carbon emission performance and decoupling performance of China and the U.S. The results show that the energy strength and energy structure effect promoted the decoupling process of the two countries. Zhang et al. [61] used the LMDI method to decompose the changes in carbon emission and carbon emission intensity in China. They concluded that the reduction of energy intensity and the final energy consumption structure had a significant inhibiting effect on carbon emission. Xie et al. [62] applied the direct carbon emission index calculation model and impact factor decomposition model to study the dynamic changes and impact factors of direct carbon emissions, confirming that energy prices are the main negative factor. Yang et al. [63] found that natural gas, coalbed methane, coke oven gas and other energy gases may become potential substitutes for coal, because they have abundant reserves and critical advantages of carbon reduction environment. In conclusion, As a developing country, China is currently in a rapid development stage. The energy consumption structure is "more coal, less oil and less gas", and it is hard to change its dependence on fossil energy, especially coal resources, for a period of time. The optimization and adjustment of energy consumption structure is not only an important task for China's energy development, but also one of the necessary measures to achieve carbon peaking and carbon neutrality, which is an essential issue today and even in the future period.

Table 4. Top 25 keywords with the strongest citation bursts.

Keywords	Year	Strength	Begin	End	2007-2021
Black carbon	2007	7.16	2007	2016	
Climate change	2007	5.4	2007	2013	
Asia	2007	5.18	2007	2013	
Carbon	2007	4.95	2008	2014	
Cement industry	2007	8.23	2009	2018	
Inventory	2007	8.13	2010	2015	
Particulate matter	2007	5.84	2010	2014	
Energy use	2007	5	2011	2016	
Input-output analysis	2007	4.34	2012	2014	
Scenario analysis	2007	7.59	2013	2016	
LMDI method	2007	5.05	2013	2018	
Demand	2007	5	2013	2014	
Time series	2007	4.61	2013	2015	
Intensity	2007	4.54	2014	2015	
Empirical analysis	2007	8.73	2015	2017	
CO_2 emissions reduction	2007	4.91	2015	2017	
Region	2007	4.68	2015	2016	
Undesirable output	2007	4.34	2015	2018	
Paper industry	2007	4.16	2017	2018	
Panel data analysis	2007	4.53	2018	2019	
Residential building	2007	4.4	2018	2019	
Technological progress	2007	4.07	2019	2019	
Empirical evidence	2007	5.64	2020	2021	
Total factor productivity	2007	4.86	2020	2021	
Embodied carbon emission	2007	4.09	2020	2021	

Although the keywords co-occurrence cluster density map generated by the VOSviewer can intuitively display the hot research clusters in this field, it does not take time into account, so we cannot see the frontier hotspots in this field from the map. Therefore, we combine with the keyword burstiness function of CiteSpace to explore the research frontier trend in this field by studying the intensity and duration of keyword bursts [64]. Table 4 summarizes the top 25 keywords with the strongest citation bursts of the research on IICEC. Where the blue line indicates the time interval, and the red line indicates the time period of the keyword burst. The greater the intensity of the burst, the higher the intensity of attention in the field, and the longer the duration, the longer the keyword has been followed in the field. We can see that the strongest citation explosion in studies on China is for the keyword "cement industry", which lasted from 2009 to 2018. In 2020, the burst keywords of citation were "empirical evidence", "total factor productivity" and "embodied carbon emission", which lasted until 2021. It can be seen that the current research hotspots are the empirical analysis of carbon decoupling, total factor productivity evaluation and embodied carbon measurement [65-67].

Bibliometric Analysis of Co-Cited References

By analyzing the co-cited references, researchers can obtain more abundant data sources without being limited by the research direction [25]. Therefore, in order to have a deeper understanding of IICEC related research fields, we conducted a co-citation reference analysis. The top ten co-cited references were summarized in Table 5. Among them, the first three co-cited references are Ang (2004), Ang (2005) and Charnes et al. (1978). It is worth noting that the most

Table 5. Top 10 Co-Cited References of research on IICEC.

Rank	Co-Cited References	Rank	Co-Cited References
1	Ang, BW [68], 2004, energ policy, v32, p1131, doi 10.1016/s0301-4215(03)00076-4	6	Su, B [73], 2012, energ econ, v34, p177, doi 10.1016/j.eneco.2011.10.009
2	Ang, BW [69], 2005, energ policy, v33, p867, doi 10.1016/j.enpol.2003.10.010	7	Ang, BW [74], 2000, energy, v25, p1149, doi 10.1016/s0360-5442(00)00039-6
3	Charnes, A [70], 1978, eur j oper res, v2, p429, doi 10.1016/0377-2217(78)90138-8	8	Tapio, P [75], 2005, transp policy, v12, p137, doi 10.1016/j.tranpol.2005.01.001
4	Chung, Y [71], 1997, j environ manage, v51, p229, doi 10.1006/jema.1997.0146	9	Zhou, P [76], 2012, eur j oper res, v221, p625, doi 10.1016/j.ejor.2012.04.022
5	Liu, Z [72], 2015, nature, v524, p335, doi 10.1038/nature14677	10	Tone, K [77], 2001, eur j oper res, v130, p498, doi 10.1016/s0377-2217(99)00407-5

frequently cited is Ang. Three articles by Ang et al. [68-69, 74] focus on industrial energy decomposition analysis methods and compare a large number of existing energy decomposition analysis methods to explore which method is the best, concluding that the LMDI method is the preferred method. In recent years, four structural decomposition analysis (SDA) methods have been analyzed and empirically compared through the decomposition of CO_2 emission changes in China. The similarities and differences between SDA and index decomposition analysis (IDA) have also been discussed. Furthermore, among the top ten co-cited references, four of them involve decomposition analysis [68-69, 73-74], which is consistent with the analysis conclusion of the above research hotspots.

Discussion

In this study, we used CiteSpace and VOSviewer to conduct a bibliometric analysis of articles on IICEC research. The annual number of papers, countries, institutions, authors, journals, keywords and research frontiers were analyzed to understand the current status, research hotspots and development trends of IICEC research. We found that the annual publications showed an overall upward trend from 2007 to 2021. Journal of Cleaner Production is the most published journal on the research of IICEC. In addition, Energy Policy is the most frequently cited journal. Most of the research institutions and authors of the two countries come from their own countries, indicating that the research has regional limitations. In future research, countries, institutions and authors should strengthen cooperation to promote further development of research.

Through a comprehensive keyword co-occurrence analysis, burst words, and co-cited references analysis, we summarized the frontier hotspots of IICEC research. They are divided into three main aspects: the analysis of decoupling carbon emissions from economic development, life cycle analysis (LCA) and life cycle cost analysis (LCCA) of the industry, and embodied carbon measure.

Decoupling Analysis

Carbon emission decoupling refers to an idealized process in which the relationship between economic growth and CO_2 emissions gradually weakens until it disappears. China is in a critical period of transition from high-speed development to high-quality development, and the dilemma of coordinating economic development and carbon emission reduction is particularly crucial for achieving energy conservation and emission reduction targets [78]. At present, China's economic growth has been decoupled from carbon emissions, but carbon emissions still rank first in the world, and the task of carbon emission reduction remains onerous. Nevertheless, there are already many countries that have achieved economic growth compatible with carbon reduction, and there have been relatively successful experiences in this area, such as the transition to cleaner energy consumption, the reduction of fossil fuel consumption, and the development of new energy vehicles and other advantageous industries [79]. In recent years, several scholars have studied the relationship between industrial carbon emissions and economic development from the perspective of industries [80], the overall macro level of China [81], and the provincial level [82], and the research fervour has been increasing. However, the study is not yet comprehensive and needs to be explored in depth in the future. To sum up, in future research on decoupling industrial carbon emissions and economic development in China, we should not only strengthen the scope and depth of research, but also learn from the successful experience of other countries. The idea of separating carbon emissions from economic growth should be presented in accordance with the unique national circumstances of China.

LCA and LCCA

With the development of industrialization, more and more waste and pollutants are being produced, which have exceeded the digestion and absorption capacity of nature. Meanwhile, the consumption of natural resources by industrialization has exceeded its recovery capacity and destroyed the balance of the ecosystem [83]. In order to have a comprehensive understanding of the resource consumption and environmental impact of industrial development, researchers have introduced life cycle assessment as a powerful tool for environmental management to promote sustainable development. Carbon life cycle analysis (CLCA) plays a vital role in greenhouse gas (GHG) management analysis [84]. By combining LCA and LCCA in research, more information can be provided for developers and decision-makers [85]. In a techno-economic and LCA of biofuels, it was found that the use of biofuels may be a cost-effective means of reducing GHG and that the use of biomass in conjunction with natural gas is a more practical approach [86]. Additionally, if carbon dioxide can be used as raw material through carbon capture and conversion technology, the output can be increased [87]. In conclusion, CLCA is a key development direction for future carbon reduction analysis.

Embodied Carbon and Carbon Transfer

Most previous studies only considered direct carbon emissions, without considering the embodied carbon related to the production and consumption of intermediate products. This may lead to possible deviation in the carbon emission prediction results [67]. Embodied carbon refers to the amount of carbon emitted directly and indirectly from the whole production process of raw material acquisition and final product output, which can be used as an environmental indicator. It is very important to make clear the transfer path of carbon footprint and actual carbon emissions for formulating carbon reduction strategy [66]. In recent years, scholars have paid more attention to the carbon embodied in trade. Commonly used measurement methods include IOA and LCA. Some of the important implications have been provided for policymakers from the perspective of reducing trade emissions [88]. This will be a crucial frontier for future carbon reduction research in all countries.

On the whole, as the largest developing country, China has been paying more and more attention to the relationship between economic development and the environment in recent years, and the research enthusiasm has been increasing, expecting breakthroughs in the future IICEC research. However, with the increasingly severe situation of emission reduction and environmental protection, driven by technological advances such as new energy and intelligence and rapidly declining costs, the energy transition along the direction of diversification, decarbonization, decentralization and digitalization is accelerating, which may become a key direction for future research by scholars worldwide.

Conclusions

It is of great significance to research IICEC for mitigating global warming. In this study, we used CiteSpace and VOSviewer, two scientometric analysis software, to conduct bibliometric analysis, visualization analysis, and comparative analysis of 3261 articles in the WOSCC, including the annual number of papers, journals, countries, institutions, research authors, keywords, research hotspots and frontier analysis. According to the results of the bibliometric analysis, the following conclusions are drawn. Based on the number of annual publications, IICEC research has gone through three phases. Since 2007, the annual number of papers has shown an overall upward trend. Research institutions and authors are concentrated in China. Moreover, the distribution of institutions is concentrated and there are close cooperative relationships among authors. However, sizeable multinational research institutions have not yet been formed. Meanwhile, the keywords "CO_2 emission", "energy consumption" and "energy efficiency" are used as the core issues and the field can be divided into five research clusters. Finally, according to the keyword burst analysis, it is found that the research frontiers are the analysis of decoupling carbon emissions from economic development, LCA and LCCA of the industry, and embodied carbon measure.

In addition, since the industrialization development model involves multidisciplinary cross-cutting issues, along with climate change, carbon emission reduction and other factors, the exploration and application of the new industrial development model are full of opportunities and challenges. Research on IICEC could be enhanced in the following aspects. Firstly, theoretical innovation still requires to be enhanced. Currently, the study in this area is mostly through technical and mathematical models, lacking theoretical construction and innovation. If ecological science, environmental science, energy science and material science are comprehensively taken into consideration, higher environmental benefits and cost-effectiveness may be generated. Secondly, the research area needs to be subdivided. Most current research perspectives are based on the national macro level or regions. Due to the large differences in the development levels of individual cities, further research can be extended to specific cities to construct sustainable industrial development policies in each city. Finally, the research objectives can be more specific. The successful realization of carbon emission reduction cannot be achieved without the joint efforts of each enterprise. Further research objectives can be diffused to the impact of industrial enterprises on carbon emissions, and carbon emission reduction targets can be set for each enterprise according to local conditions.

This study also has some limitations, which can be further improved in future research. Firstly, since our data only came from WOSCC databases, some relevant information in other databases could be lost, resulting in our analysis may not be comprehensive enough. Secondly, we only searched the "Article OR Review" published in English, which may make our analysis results incomplete. Finally, although we used the professional bibliometric analysis software CiteSpace and VOSviewer for objective analysis, it may have some subjective bias because different researchers may have different views and interpretations of the same research content.

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Conflict of Interest

The authors declare no conflict of interest.

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