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Review

Climate Change, Carbon Peaks, and Carbon Neutralization: A Bibliometric Study from 2006 to 2023

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Abstract: Climate change poses a threat to the survival of the human race. Increased interest in climate change, carbon peaks, and carbon neutralization and rising recognition of the challenges inherent to highlighting this issue provides the opportunity to carry out a bibliometric study to identify what research can generate ideas regarding climate change, carbon peaks, and carbon neutralization. As expected, it may align with the dual goals of the Chinese government agenda in terms of a carbon peak and carbon neutralization in 2030 and 2060, respectively. The recent argument has induced calls for improved transparency and standardization in the approaches adopted to synthesize climate change, carbon peak, and carbon neutralization research. Nevertheless, key questions are still unanswered, namely, what are the key contributions that the research community has produced in relation to climate change, carbon peaks, and carbon neutralization? Have their contributions been inclined toward specific geographical areas, directions, and themes? As such, software tools for bibliometric analysis, VOSviewer, and Python were used to conduct a systematic quantitative analysis of the relevant literature on climate change, carbon peaks, and carbon neutralization. The results show that carbon peaks and carbon neutralization have received wide attention from academic scholars. In the meantime, China faces the unfolding challenges of economic, technological, and political factors that need to be addressed to achieve carbon peak and carbon neutralization. This study provides policy implications for achieving China's emission reduction targets.

Keywords: climate change; bibliometric analysis; carbon peak; carbon neutralization; emission

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1. Introduction

1.1. Adaptation to Global Climate Change

Climate implies long-term average weather situations. A steady climate gives animals, plants, and people reliable living environments [1]. Climate change has emerged as a global issue for both people's ways of life and the research community [2]. The effects of climate change are found in different disciplines concerning natural resources and biodiversity [3]. Starting in the 21st century, rising global carbon dioxide emissions and the frequent occurrence of various extreme climate incidents (e.g., spreading wildfires, extra-tropical cyclones, and melting glaciers) led to an urgent demand for the adoption of mitigation strategies (e.g., a low-carbon or green economy, renewable energy, sustainable uses of forests and land, and electric vehicles) to foster sustainable development (Sustainable Development Goal 13) [4,5]. In response, the United Nations Framework Convention on Climate Change (UNFCC) was launched in 1992. The UNFCC contributes a framework toward global cooperation that address climate change by limiting average global temperature rises and the adverse impact of climate change [6]. In 1998, the introduction of the Intergovernmental Panel on Climate

Change (IPCC) aimed to provide governments at any level analytical information for the creation of climate policies, indicating a global consensus on the extreme adverse effect of climate change. After that, the Paris Agreement was signed at the Paris Climate Conference on 12 December 2015. It aims to set the goal of limiting the rise in average global temperatures to less than 2 degrees Celsius above pre-industrial levels and attempting to limit it to 1.5 degrees [7,8].United Nations Secretary-General Antonio Guterres invited every global leader to claim a state of climate emergency up to the time carbon neutralization is achieved. In addition, the Sustainable Development Goals of Agenda 2030 and the Sendai Framework for Disaster Risk Reduction (2015–2030) indicated the global commitment to addressing climate change and adjusting to its influences [9]. In addition, the Kyoto Protocol mechanism is going to bring about the transfer and circulation of climate change technologies associated with clean energy [6]. In response, Birkmann et al. [10] addressed that "climate change impacts include multi-hazard phenomena, such as the simultaneous occurrence of sudden-onset hazards and creeping changes". In other words, the effects of climate change can be multi-dimensional [2]. The effect of climate change has been recognized for a long time [9]. Climate change not only poses a serious threat to global economic security but also affects areas such as resources, marine environments, energy, freshwater, ecology, and food security, posing catastrophic risks to animals and humans [5,11]. As such, climate change is identified as the greatest risk of the next few decades [9]. Nowadays, there is an increasing trend in countries suggesting carbon neutralization strategies as their long-lasting emission diminishment goals for the middle of the 21st century during the execution of the Paris Agreement. Zhang et al. [6] pointed out that reductions in carbon emission levels may be achieved by reducing total carbon dioxide emissions from numerous production activities and using advanced climate change mitigation technologies. Nevertheless, the objectives of carbon neutralization are critical [4], with over 160 countries striving to achieve the global peak of greenhouse gas emission targets [12]. The European Union (EU) introduced the Fit for 55 plan, suggesting 12 initiatives to minimize carbon emissions (relating to buildings, energy, transport, and industry) and a commitment to a 55% decrease in greenhouse gas emissions before 2030 compared to 1990. Furthermore, the International Maritime Organization (IMO) has proposed a target of reducing CO_2 emissions from transport by at least 40% by 2023 and by at least 40% by 2050 [13] in order to address the severe problem of climate change.

1.2. Overview of Carbon Neutrality in China

Indeed, China proclaimed the 'Dual Carbon Target' in 2020, striving toward a peak in net carbon emissions by 2030 and the attainment of carbon neutralization by 2060. This has come behind the Chinese government's proposed 1 + N policy system and the Action Plan for Carbon Dioxide Peaking Before 2030. It is expected that China will discharge around 12 billion tons of carbon in 2030 and then progressively decrease carbon emissions to 3 billion tons annually by 2060 [14]. In September 2020, China set a clear goal of a 'carbon peak' by 2030 and 'carbon neutralization' by 2060. In other words, China aims to achieve a historical peak in CO_2 emissions by 2030 through a comprehensive transformation of economic and social development toward green development. A steady decline in CO_2 emissions would be even better. Additionally, by 2060, China will strive to achieve carbon neutralization in order to reduce the harmful effects of greenhouse gases on the environment [15]. The implementation of China's carbon peak and carbon neutralization has promoted academic development in this field. Since 2020, the field of climate change, carbon peaks, and carbon neutrality has seen a surge in publications, and the field is gaining momentum.

1.3. Objectives and Contributions

In general, there was a rising tendency toward CO_2 emissions from 1960 to 2020. Such an increasing trend was remarkably boosted between 1990 and 2020. In particular, high-income and OECD economies are more responsible for intensifying environmental pollution than low-income and upper-middle-income countries [6]. Fostering an environment where carbon emissions decrease in terrestrial ecosystems is a vital approach for attaining the goal of carbon neutralization and mitigating the continuing rise in the concentration of climatic CO_2 [4]. To the best of the authors' knowledge, there is a shortage of systematic explorations of research addressing climate change, carbon peaks, and carbon neutralization through bibliometric analysis. Decreasing the systematic, complicated, and cascading risks generated by climate change is supposed to be of high importance in the coming future, which needs to be reinforced by carbon peak and carbon neutralization research. Zhao et al. [12] mainly focused on a bibliometric analysis of carbon labeling schemes in the period of 2007–2019. Liu et al. [7] conducted a bibliometric analysis to construct an information modeling-driven carbon emission reduction research study. Zhang et al. [4] carried out a bibliometric analysis of forest management in the environment of carbon neutralization. To better understand the relationship between climate change, carbon peaks, and carbon neutralization, this paper analyzes the current research trends and investigates the process of carbon peaks and carbon neutralization in China through a systematic bibliometric analysis.

2. Materials and Aims of the Study

Bibliometrics is a multidisciplinary science, as well as a new body of knowledge that combines statistics, linguistics, and mathematics. Bibliometric analysis aims to recognize related trends and quantify research development in different disciplines. This approach is usually adopted to identify existing research hotspots, investigate the evolution of academic research areas, and forecast forthcoming research directions. Bibliometric analysis has gained wide attention from researchers in the past decade [4]. As such, the main aims of this paper are as follows: (1) to enrich researchers by improving their understanding of the range and landscape of research concentrated on climate change, carbon peaks, and carbon neutralization based on bibliometric analysis of published research papers in the Web of Science Core Collection database, notably understudied and emerging research themes, and (2) to generate a groundwork for policy recommendations and future research directions for professionals in the discipline of climate change, carbon peaks, and carbon neutralization in China.

To comprehensively sort out the relationship among climate change, carbon peaks, and carbon neutralization, data analysis tools such as VOSviewer and Python were used to analyze the authoritative literature in the Web of Science in detail. The experiments were conducted on a PC (14-core CPU, 2.5 GHz, 64 GB of memory, VOSviewer version 1.6.16, Python version 3.7.0).

This part takes the Web of Science as the data source and selects the Core Collection in the Web of Science database as the retrieval object. The search conditions are set as follows. The themes are 'climate change' ('carbon neutrality' OR 'climate change') and 'emission peak', and the period is from 2006 to 2023. By 20 March 2023, 674 valid kinds of literature were included in the study after the retrieval results were de-duplicated and sorted.

A co-citation network provides a useful reference for evaluating academic influence and increases the amount of attention given to certain scholars. The size of the network nodes reflects the number of authors' publications, while the links indicate the internal relationship between them. Through analyzing the structural characteristics of authors and their cooperative networks, the core author group and its cooperative relationship in this field can be identified [16]. Based on the retrieved literature, this paper uses VOSviewer software to draw a graph of the connections between the authors of the literature through the constraint condition of the node connection.

3. Bibliometric Analysis

3.1. Analysis of the Number of Literature Articles

Through the number of article publications in different years, we can identify the evolution of research into climate change, carbon peaks, and carbon neutralization over a period of 17 years. As can be seen from Figure 1, the number of research papers in this area can be observed through three main periods. The first period is from 2006 to 2015. A total of 29 papers were published, an average of less than 3 per year, accounting for only 4.30 % of the total number of papers. The second period is from 2016 to 2020. A total of 79 papers were published, with an average of about 15 papers per year, accounting for 11.72 % of the total number of papers. The third period is 2021 to now, in which the number of published papers increases significantly. A total of 566 papers were published, with an average of about 188 papers per year, accounting for 83.98 % of the total number of papers.

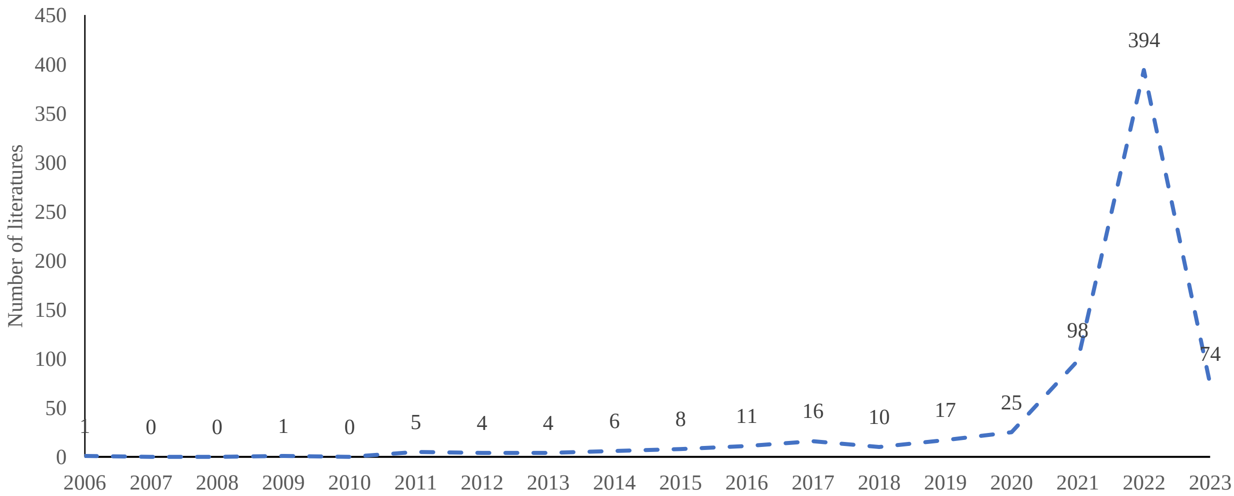

Figure 1. Number of published research articles.

In recent years, the negative impact of economic development on the environment has received more attention from people all over the world. China attaches great importance to environmental protection. Climate change and carbon emissions have gradually become a research hotspot. More and more scholars have focused on this field and produced excellent research results.

3.2. Analysis of Authors and Countries

The minimum number of author appearances is one, and there is at least one collaboration between authors. A total of 3033 authors satisfied the condition. In Figure 2, the size of the hotspot represents the number of occurrences. The stronger the brightness of the hotspot, the more occurrences the author has, and vice versa. As can be seen in Figure 2, Wang Peng, Li Jiashuo, Geng Yong, Yang Yang, and Wang Jing have conducted more research in this field. In addition, there is a lot of cooperation among scholars. Scholars have formed strong collaborative teams among themselves to carry out interdisciplinary research for a specific area. However, the connection between the research teams is weak, and there are few academic exchanges. In terms of the countries of the authors (see Figure 3), Chinese scholars published the most articles, followed by American scholars and English scholars. As can be seen from Figure 3, cooperation between international scholars is relatively frequent.

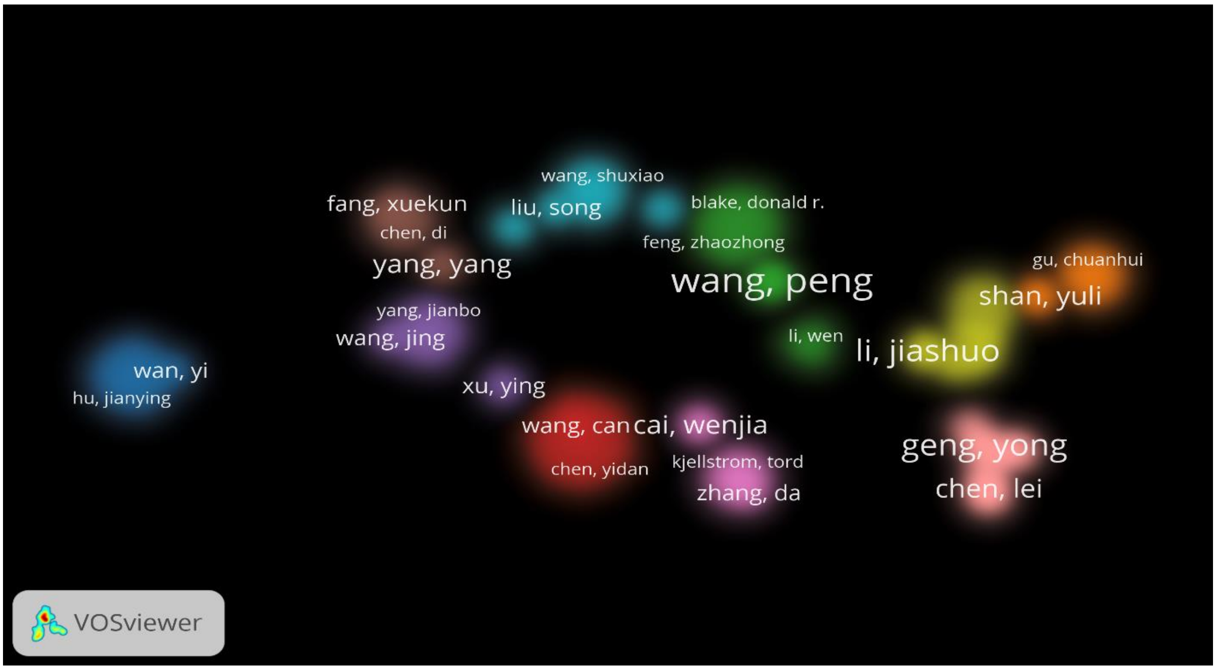

Figure 2. Map of authors.

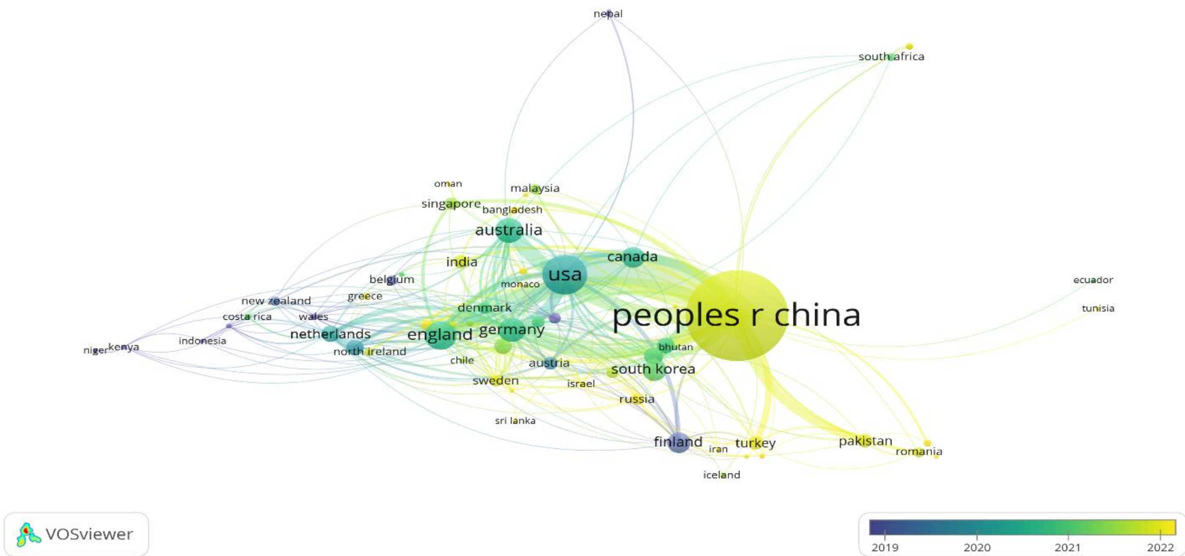

Figure 3. Map of the countries of authors.

3.3. Analysis of Research Institutions

According to the search results, Python was used to analyze the research institutions found in the literature. Table 1 shows the top 10 institutions that contributed to research output in terms of climate change, carbon peaks, and carbon neutralization. It can be found that the Chinese Academy of Sciences (*Chinese Acad. Sci.*) has published the most research papers (92). It is followed by institutions such as Tsinghua University (*Tsinghua Univ.*), the University of the Chinese Academy of Sciences (*Univ. Chinese Acad. Sci.*), Shanghai Jiao Tong University (*Shanghai Jiao Tong Univ.*), and Peking University (*Peking Univ.*). The common characteristic of these research institutions is a strong academic atmosphere, with scholars at the forefront of academic research. Researchers are ambitious. They focus on global issues and related policies, identify key problems that need to be solved, and devote considerable time and energy to the research process.

Table 1. Top 10 institutions that have published research papers related to climate change, carbon peaks, and carbon neutralization.

Institution Name	Number of Journals
Chinese Acad. Sci.	92
Tsinghua Univ.	60
Univ. Chinese Acad. Sci.	38
Shanghai Jiao Tong Univ.	32
Peking Univ.	26
Wuhan Univ.	23
Xiamen Univ.	19
China Univ. Geosci.	19
Beijing Forestry Univ.	16
Nanjing Univ.	14

The distribution and evolution of keywords can directly reflect the main changes in research hotspots, analysis perspectives, and research methods in different periods. Through the analysis of keywords, we can understand the current research trends in this field.

Figure 4 shows a co-occurrence map of keywords. The size of the keyword corresponds to the frequency of keyword occurrence. The more times the keyword appears, the larger the font. The keywords with high frequency are carbon neutrality, China, climate change, neutrality, sustainable development, emissions, sustainability, renewable energy, carbon emission, and policy.

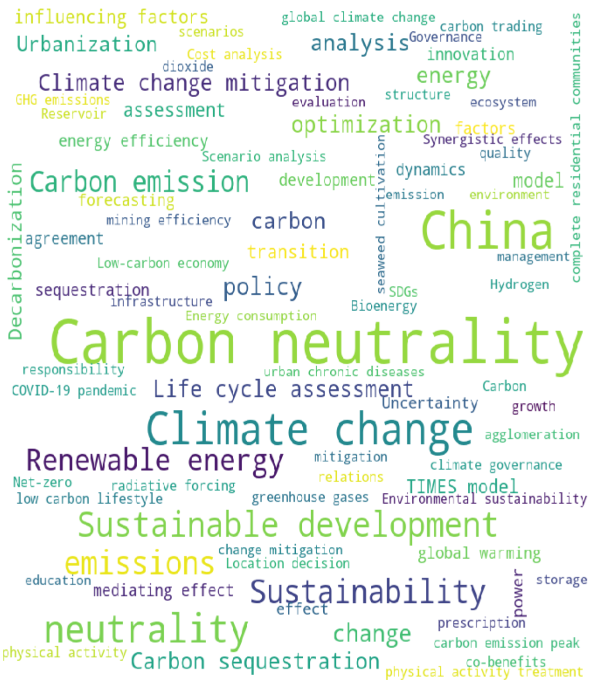

Figure 4. Co-occurrence map of keywords in the literature.

As can be seen in Figure 4, China ranks high in the number of occurrences of keywords. This indicates that scholars pay high attention to China's carbon emissions and research enthusiasm is high. This is closely related to the importance the Chinese government attaches to climate change. The carbon policy proposed by China is also a major hot spot for scholarly research.

Quantitative analysis of the literature shows that the study of climate change, carbon peaks, and carbon neutralization has been emerging in recent years, especially in 2022. Currently, the country with the most research output on this aspect is China, with numerous domestic institutions researching this area, such as Tsinghua University and the University of the Chinese Academy of Sciences. This is consistent with China's commitment to reaching a carbon peak and carbon neutrality by 2030 and 2060, respectively. In the future, China's carbon neutrality, emissions, and climate change will be the main focus of research.

4. Overview of Climate Change, Carbon Peaks, and Carbon Neutralization Research

4.1. Carbon Peak

The term carbon peak refers to the historical peak in annual carbon dioxide emissions for a region or industry. After a plateau, carbon emissions began to decline, which is a historical inflection point that marks the decoupling of carbon emissions from economic development [17]. China will reach its carbon peak by 2030. Additionally, how China will achieve this carbon peak by 2030 has been studied by many scholars from different aspects.

To a large extent, many scholars have addressed how China can achieve a carbon peak by 2030. Wu et al. [18] used the enterprise innovation-driven agent model to predict China's energy consumption and carbon emissions. The results show that there are certain differences in the key trends of peak energy consumption and peak carbon emissions at different levels. Carbon emissions and energy consumption will peak in 2027 and 2028, respectively. Li et al. [19] constructed the STIRPAT model and GA-BP (BP neural network based on a genetic algorithm) model, combined with the historical data of Hebei Province from 1990 to 2015, to predict the peak carbon emissions of Hebei Province for 2016 to 2030. The results show that peak carbon emissions can be achieved in 2030. Qi et al. [20] developed a Kaya inequality to evaluate when the peak will occur and the emission reduction rate of energy-related CO_2 emissions in China. The results highlighted that China would reach its peak carbon emissions around 2030. Chen et al. [21] employed the minimum complexity earth simulator and semi-empirical statistical model to create emission paths covering each carbon peak year and carbon neutralization year in China. The results suggested that peak carbon year and peak carbon emission year have a significant contribution to mitigating climate change in the short term. Carbon neutralization has a considerable impact in the long run.

Other researchers have studied China's carbon peak by estimating emission reductions in the power sector. For example, Meng et al. [22] employed a logarithmic linear equation and hybrid model combined with emission-related data from 2001 to 2013 to conduct a scenario analysis of CO_2 emissions in China's power industry. The results demonstrated that the Chinese electric power industry will struggle to reach a peak in carbon dioxide emissions before 2030, putting considerable pressure on the Chinese government to meet its emission reduction targets. Tao et al. [23] used the bottom-up CO_2 emission reduction model to evaluate potential emission reductions that may be realize by 2030 with various technologies in the thermal power industry. The results pointed out that CO_2 emissions in the power industry will peak in 2030 under the medium-term policy control scenario of slow macroeconomic growth.

Several scholars have examined whether the carbon peak has generated an impact on the Chinese economy. Some of them have investigated it through carbon trading mechanisms and carbon pricing. Li and Jia [24] developed ten key scenarios with numerous free quota ratios of emission rights and combined them with a dynamic recursive computable general equilibrium model to simulate the carbon trading market. They explored the relationship between the free quota ratio and carbon trading price and the impact of the carbon trading system on the Chinese economy and environment. The results show that the free quota ratio has no direct impact on economic and environmental indicators, such as gross domestic product (GDP), but does have a direct impact on carbon trading price. Duan et al. [25] produced a stochastic integrated energy–economy–environment model to assess Chinese energy and climate goals for 2030 in terms of peak carbon emissions and non-fossil energy development. The results provided further evidence that the probability of achieving the peak carbon emissions target and the non-fossil energy target is low under the current circumstances. Nevertheless, additional policy support may be required.

Some scholars have used carbon emission trajectories to assess socioeconomic costs. For example, Matsumoto et al. [26] adopted a general equilibrium model to analyze the impact of 30 to 50 pathways with different emission reduction starting years and different subsequent emission pathways on major global socioeconomic indicators. The results demonstrated that the earlier and slower the emission reduction, the smaller the GDP loss. Yu et al. [27] created a new economic–carbon emission–employment multi-objective optimization model. They generated different analyses of China's carbon emissions trajectory. The results summarized that China's energy-related CO_2 emissions are likely to peak between 2022 and 2025, with the most likely occurrence in 2023.

Some researchers have discussed the relationship between China's economic structure and carbon peak. For example, Ding et al. [28] analyzed the impact of modernization on CO_2 emissions in China by using a comprehensive index system and combining panel data. The results addressed that industrialization, agricultural modernization, informatization, and urbanization had a positive impact on CO_2 emissions during the study period. However, there is a negative correlation between ecological modernization and CO_2 emissions. Meng et al. [29] adopted a segmented quadratic equation to fit the relationship between economic level and CO_2 emissions. A hybrid trend extrapolation model was used to predict emission-related indicators. The results recognized that 2018 is the peak of CO_2 emissions in China. Su et al. [30] developed an input–output optimization model to evaluate the impact of economic structure changes on carbon emissions. The results suggest that the inhibition effect of structural change on carbon emissions presents a progressively increasing marginal trend and that accelerating the pace of China's economic transformation is very conducive to realizing the peak of CO_2 emissions in advance.

4.2. Carbon Neutralization

Achieving carbon neutrality means that the amount of carbon emitted by social activities is equal to the amount of carbon absorbed by a series of social activities. To achieve carbon neutralization within a certain period, enterprises, social groups, and individuals can measure their CO_2 emissions and offset them by planting trees, saving energy, and using clean energy [17]. China's goal of achieving carbon neutralization by 2060 has been studied by numerous scholars.

There are various ways to achieve carbon neutralization, including nationally determined contributions (NDCs), carbon pricing, carbon dioxide removal (CDR) technology, CO_2 negative emission technology, renewable energy sources, carbon capture and storage, and carbon productivity. NDCs are a central component of the post-2020 global climate agreement. Pan and Teng [31] evaluated China's CO_2 emission reduction targets in NDCs using the fair ranges calculated by the effort-sharing framework of six equity principles. The results explained that equity in China's NDCs relies heavily on specific equity principles, as well as China's energy system needs, to achieve carbon neutralization by 2030 at the latest. Other ways to achieve carbon neutralization concern CDR technology. Strefler et al. [32] assessed a comprehensive combination of CDR options. The results pointed out that CDR helps to slow down net carbon dioxide emissions and achieve carbon neutrality earlier. Strefler et al. [33] proposed other carbon price pathways that may be easier to implement while limiting CDR technologies to prevent warming. Carbon capture, use, and storage is an emerging technology that can reduce carbon emissions. Hu et al. [34] investigated the impact of energy consumption, technological innovation, and capital on economic output and CO_2 emissions in India from 1990 to 2018. As such, the results pointed out that carbon capture and storage would dramatically reduce CO_2 emissions. Liu et al. [35] constructed a complex decision model for risk assessment and evaluated carbon capture technology based on the comprehensive decision model.

The realization of carbon neutralization is closely related to the economy, which a low-carbon economy fails to fulfill without financial support. Iqbal et al. [36] suggested that export diversification, fiscal decentralization, and GDP growth generated a positive impact on CO_2 emissions. Liu and Liu [37] investigated the impact of financial development on carbon emission intensity and its mechanism theoretically and empirically. To this end, the results explained that financial development significantly decreases China's overall carbon emission intensity. Carbon neutralization is the main goal of climate change mitigation. Renewable energy policies play an important role in achieving carbon neutralization. Tudor and Sova [38] conducted an empirical analysis of 94 countries to study the impact of relevant economic and environmental drivers emerging from the current policy objectives on the heterogeneity of renewable energy consumption (REC). The results indicated that CO_2 intensity has a significant mitigation impact on REC worldwide. Other scholars have studied China's carbon neutralization in other ways. Zhou et al. [39] employed the entropy model to allocate China's renewable energy quotas from the perspective of provinces. They introduced the environmental Gini coefficient to evaluate the rationality of the allocation results.

China is faced with challenges in the process of achieving carbon neutralization, such as a continuous increase in energy consumption, CO_2 emissions, the short transition time for emission reduction, low energy utilization rate, unbalanced economic development, immature low-carbon technology, etc. [17]. Achieving carbon neutralization will require rapid and far-reaching changes across the community. On the one hand, comprehensive emission reduction measures are required in all sectors, including energy decarbonization, electrification, an increasing share of renewable energy, improvements to energy efficiency, sustainable land management, transport decarbonization, reductions in food loss and waste, and behavioral and lifestyle changes. On the other hand, neutralization could be achieved by enriching the application of emission reduction technologies, such as CDR technologies, renewable energy, and carbon capture and storage [40].

5. Discussion and Conclusions

Climate change requires all of humanity to work together and take their share of the responsibility. China has set a target of achieving a carbon peak by 2030 and carbon neutralization by 2060 [14]. Nevertheless, there are still many challenges ahead. Through quantitative analysis and a systematic review of the literature on climate change, carbon peaks, and carbon neutralization, it can be identified that scholars are concerned about China's carbon peak and carbon neutralization.

This paper adopted data from the Web of Science as the research object and used VOSviewer and Python to quantitatively analyze the number of publications, authors and countries, research institutions, and keywords in the literature. The results are as follows: (1) Research papers in the field of climate change, carbon peaks, and carbon neutralization can be divided into three main periods. Additionally, the number of research papers published in the three key periods accounts for 4.30%, 11.72%, and 83.98% of the total, respectively. The third period shows a significant increase in the number of published papers, almost equal to the total number of papers published in previous years. In other words, climate change, carbon peak, and carbon neutralization research output increased dramatically and has continued to expand. As supported by Wang et al. (2023) [41], the number of published review studies has increased quickly. Key issues relevant to climate change, carbon peaks, and carbon neutralization have been the focus of mainstream journals. (2) Researchers' understanding of climate change, carbon peaks, and carbon neutralization keeps improving. The research direction not only focuses on macro research areas (e.g., sustainability, emissions, climate change) but also on micro research disciplines (e.g., renewable energy, hydrogen, carbon trading). Future research will be carried out from an interdisciplinary viewpoint. The results align with Zhang et al. (2022) [42]. (3) The five researchers with the most research achievements in this field are Wang Peng, Li Jiashuo, Geng Yong, Yang Yang and Wang Jing. Chinese scholars publish the most articles, followed by American and English scholars. Thus, they were the key exporting countries of climate change, carbon peak, and carbon neutralization research [41]. In addition, cooperation among international scholars is relatively frequent. In response, Zhang et al. (2022) [42] also pointed out that attention to climate change, carbon peaks, and carbon neutralization is associated with the financial strength and development background of a country. (4) In terms of research institutions, the Chinese Academy of Sciences, Tsinghua University, and the University of the Chinese Academy of Sciences are the three leading institutions that publish the most research papers. President Xi Jinping suggested the "30–60" carbon peaking and carbon neutralization goals on 15 March 2021, which intensified efforts [41]. (5) The country with the most research on climate change, carbon peaks, and carbon neutralization is China, which is closely related to the importance that the Chinese government attaches to climate change. Global carbon policy has become a hot topic for worldwide scholars to study.

To attain the carbon peak and carbon neutralization, we may need to balance environmental protection and economic development. Developing renewable energy through technological innovation, improving the carbon emission trading market, speeding up the process of climate change legislation, and developing extensive collaboration with the international community will further help China successfully achieve the dual goals of reaching its carbon peak and realizing carbon neutralization. All of this can encourage China to commit to achieving its carbon peak and carbon neutralization on schedule and provide a significant contribution to mitigating the impact of global warming.

It is worth noting that this paper only analyzes the current research trends of climate change, carbon peaks, and carbon neutralization based on bibliometric analysis. Specific measures on how to achieve the carbon peak and carbon neutralization have not been analyzed. In the future, specific ways to reach the carbon peak and carbon neutralization can be analyzed through scenario analysis or empirical analysis.

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