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Does the COVID-19 pandemic derail US-China collaboration on carbon neutrality research? A survey

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A B S T R A C T

The COVID-19 pandemic has seriously impacted scientific research activities, especially international cooperation in scientific research. Using bibliometric methods and scientific knowledge graph software, and by calculating collaboration indicators such as international collaboration rates, this work conducts a comprehensive review of carbon neutrality publications in the Web of Science database before and during the COVID-19 pandemic, aiming to explore whether the COVID-19 pandemic derail China-U.S. collaboration on carbon neutrality research. The results show that (i) During the COVID-19 pandemic, more extensive research on carbon neutrality was carried out around the world, with China and the United States leading the way in carbon neutrality scientific output. (ii) Following the outbreak of the COVID-19, the global center of global carbon neutrality shifted from the United States to China. (iii) During the COVID-19 pandemic, research ties between China and the United States strengthened. The number of joint publications on carbon neutrality between China and the United States has greatly increased during the COVID-19 pandemic compared to those before. (iv) The proportion of China-U.S. cooperation in China’s international cooperation has decreased, while it is the opposite for the United States. At the end of the article, we put forward relevant suggestions for realizing the sustainable development goals of climate change in the post-epidemic era for policymakers’ reference. This paper provides important insights into the theoretical research of scholars in the carbon neutrality field.

1. Introduction

The concentration of CO₂ in the atmosphere has reached its highest level in nearly a million years as a result of industrialization. The ongoing rise in global temperatures poses a number of threats to the development of the Earth’s ecosystem and human society [1]. In the face of the climate change crisis, carbon neutrality goal calls for ambitious climate efforts globally. Promoting carbon neutrality can not only reduce carbon emissions to mitigate the effects of climate change, but also reduce air pollutant concentrations to improve air quality [2]. Carbon neutrality, according to the Intergovernmental Panel on Climate Change (IPCC) report “Global Warming of 1.5 °C”, refers to the global offsetting of anthropogenic CO₂ emissions in order to achieve net-zero CO₂ emissions over a specified time period [3]. The 2015 ‘Paris Agreement’ proposed limiting global average temperature rise above the pre-industrial revolution level to less than 2 °C, with a goal of 1.5 °C. However, according to the United Nations Environment Programme’s (UNEP) 2019 Emissions Gap Report, there is a significant gap between current national emission reduction and the 1.5 °C target [4]. To this end, many countries have set carbon neutrality targets. For example, in its 2019 climate change resolution, the European Parliament proposed that the EU aim for net-zero greenhouse gas emissions by 2050. In the newly revised Climate Change Act, published in June 2019, the United Kingdom stated unequivocally that it will be carbon neutral by 2050 [5]. More than 100 countries have pledged to become carbon neutral by 2050 [6].

Global carbon dioxide emissions are as high as 32,318.6 million tonnes in 2020, according to data from the BP Bureau of Energy Statistics. China and the United States are the two largest contributors to global CO₂ emissions. China’s and the United States’ carbon emissions in

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The COVID-19 pandemic has thrown the world into disarray, and climate change is also gaining global attention [12]. Pandemics directly endanger individuals and health-care systems, whereas climate change disrupts larger natural and human systems. The climate and COVID-19 crises are global and unprecedented in scale, necessitating a coordinated response from policymakers, business, and society as a whole [13].

Fundamental research is a critical driving force in achieving carbon neutrality. However, the emergence of the COVID-19 pandemic may result in a halt in the sharing of scientific research data and findings, limiting the extent to which data is shared and the scope of future international collaboration. As we all know, international collaboration is the key to scientific research. The United States and China are the world’s leading producers of scientific knowledge and the world’s leading forces in global frontier science [14]. Furthermore, according to research, China and the United States lead in COVID-19 scientific output [16]. Therefore, international cooperation between China and the United States is crucial. Close cooperation between the two countries will greatly benefit both domestic and global scientific systems. However, the COVID-19 pandemic has severely disrupted exchanges and cooperation between the two countries in many fields. Moreover, due to the huge carbon emissions of China and the United States, the carbon emission reduction potential of the two countries significantly affects the future progress of global carbon peaking and carbon neutralization. Amid heightened geopolitical tensions caused by the COVID-19 pandemic, China-U.S. scientific cooperation on carbon-neutral basic research can be a valuable tool for both countries’ capabilities to address climate change. Therefore, whether or not the carbon neutrality scientific cooperation between China and the United States is jeopardized warrants a more in-depth discussion. On the one hand, it is possible to better understand the current status and future trends of cooperative research between China and the United States, provide inspiration for other countries to achieve carbon neutrality and jointly address climate change in the future, and provide valuable reference for subsequent research. On the other hand, understanding the impact of the COVID-19 pandemic on China-U.S. carbon neutrality research cooperation can help companies make scientific judgments, so that they can adjust policies in a timely manner to promote their own future development.

The rest of the paper is presented as follows: Section 2 reviews the relevant literature; Section 3 describes the study’s methodological framework and data sources; Section 4 presents the main findings; Section 5 concludes the paper.

2. Literature review

Climate change has a profound impact on the earth’s environment and has emerged as a major global challenge for humanity. Because of the complexities of COVID-19, scholars have focused on research on the intersection of COVID-19 and climate change with a large number of related studies. For example, Zang, et al. reviewed the literature on the intersection of the COVID-19 and climate change to better understand the complexities of emergency epidemics associated with the climate crisis [18]. Ruiu et al. summarized the similarities and differences between two global threats, climate change and COVID-19 [19,20]. Schwartz emphasized the importance of increasing climate change and COVID-19 preparedness and awareness, as well as understanding the impact of climate change migration on current and future pandemics [21]. Ray et al. explored the impact of COVID-19 on global environmental pollution and carbon emissions, and sustainable development strategies in the COVID-19 era [22-24]. Meanwhile, the relationship between COVID-19 and climate change [25,26], the impact of COVID-19 on climate change progress [27-29] have also been extensively explored.

Countries around the world are taking actions to jointly address climate change issue. Wang et al. discussed the current state, opportunities, challenges, and prospects of carbon-neutral technologies [30]. Wu et al. summarized the progress of carbon neutrality, the path to carbon neutrality, and carbon neutrality research in typical fields [5]. Wang et al. explored the impact of the COVID-19 pandemic on carbon emissions [31]. Zhao et al. summarized China’s carbon neutrality challenges, strategies, and countermeasures [32-34]. The research of Zuo et al. focused on carbon reduction in commercial development, identifying factors that enable or impede the development of carbon-neutral commercial buildings [35]. Wang and Han explored the decoupling of carbon emissions embodied in U.S.-China trade and its drivers [36]. Su et al. examined the impact of political risk on CO₂ emissions in Brazil [37]. Yang et al. analyzed the adjustment of energy consumption structure and carbon neutrality in the post-COVID-19 era [38-41]. Da Zhu analyzed the dynamics of carbon neutrality in China, the European Union and the United States by building a game model [42]. In addition, some scholars have used bibliometrics to conduct related research on carbon neutrality literature. Sun et al. summarized the research status of energy consumption and carbon emissions in the construction industry, identified research hotspots and knowledge gaps, and proposed suggestions on potential future research directions [12, 43]. Wang et al. used bibliometrics and knowledge graph methods to identify research hotspots, development context and future trends in the field of carbon neutrality, which provided implications for future related research and practice [44].

Through literature review, we noticed three gaps in existing research: (1) Most of the existing studies focus on single-dimensional studies of carbon neutrality, and few literatures explore the impact of COVID-19 on research cooperation on carbon neutrality. (2) Some of the existing studies are conducted in a global context, and there are fewer studies focusing on the COVID-19 and carbon-neutral scientific research between China and the United States. (3) Many previous studies carried out macro-analysis through traditional bibliometric methods with the help of maps or literature reviews, and few studies quantified cooperation from multiple perspectives to discuss the basic research cooperation between countries. Therefore, this study adopts the bibliometric method and visual analysis to innovatively conduct a comparative analysis of the cooperation trends and cooperation models of China-U.S. carbon neutrality research before and during the COVID-19 pandemic to fill the research gap. This study therefore primarily aims to answer three questions: Has the COVID-19 outbreak affected (1) the China-U.S. cooperation on carbon neutrality research? (2) the cooperation mode of carbon neutrality research in China? (3) the cooperation mode of carbon neutrality research in the United States?
3. Methodology and data

3.1. Data source

The data for this article was derived from the Web of Science (WOS) Core Collection database, which is a world-renowned citation index database. Scopus and WOS are commonly used databases for bibliometrics analysis. Some scholars conducted a comparative analysis of the data retrieved from the Scopus and WOS databases and discovered that the articles and references retrieved from the two databases were extremely similar [45]. Because of its groundbreaking content, high-quality data, and longer history than Scopus, the WOS Core Collection database is widely used in scientific research [46]. Therefore, this study uses the WOS Core Collection database as the initial data source [47]. Besides, “carbon neutrality” and “carbon neutral” are used as search terms, meanwhile, the Boolean operator “OR” is applied to ensure comprehensiveness of the document. Because journal articles typically provide more in-depth research and higher quality information than other types of publications [48], articles with document types “Article” and “Review” are selected. In addition, in order to obtain the maximum number of relevant documents and improve search accuracy, we use the search field “TS”, which means that the search term appears in the title, abstract, author keywords and keywords plus. Data retrieval time is March 21, 2022.

To better illustrate the collaboration trends between the China and the United States before and during COVID-19. Datasets for each country during two time periods are created: carbon neutrality publications (a) from 1 January 2015 to 31 December 2019 (b) from 1 January 2020 to December 31, 2021. The 2015–2019 dataset is generated to explore the state of carbon neutrality research in the five years prior to the COVID-19 outbreak. Also, it should note that January 1, 2020 is set as the start date for COVID-19 as the COVID-19 emerged in December 2019, so publications from 2020 to 2021 are considered to be publications during COVID-19.

Finally, the publication information of China and the United States obtained according to the aforementioned data retrieval process is shown in Table 1. All data are exported with full records for analysis.

3.2. Methodology

3.2.1. Bibliometrics

Bibliometrics covers structural, dynamic, evaluation, and predictive scientometrics [49], and it has been widely used to analyze the state of scientific research and evaluate research outcomes [50,51]. Numerous studies have demonstrated the benefits of bibliometrics. Bibliometrics provides quantitative indicators to ensure academic output objectivity and is an effective technique to avoid subjectivity and possible biases in expert-based reviews [52]. Furthermore, bibliometric analysis allows us to track and summarize research content and trends in specific topics, thereby providing directions for future research [53]. Currently, bibliometric research is playing an increasingly important role in responding to international public health emergencies. It helps to inform policy making in response to the crisis.

Numerous knowledge graph software packages (CiteSpace, VOSviewer, HistCite, and BibExcel, for example) are used for bibliometric analysis, each with different capabilities and limitations [54]. This paper mainly uses VOSviewer software for visualization. VOSviewer has numerous advantages when performing quantitative visualization analysis. First of all, VOSviewer can convey information through different colors, sizes and angles, and the drawn knowledge graph is very readable. Second, it has a strong ability to present knowledge graphs and can clearly present the relationships among research topics [55]. Third, the software has been repeatedly verified by many researchers, and the map results are highly reliable [56]. Importantly, compared with software such as CiteSpace, VOSviewer can receive tens of thousands of data sources and can provide researchers with more comprehensive visual information. VOSviewer software currently has a very wide range of applications and has basically been recognized by users. This paper selects VOSviewer to map the global, Chinese, and American knowledge collaboration networks. Each node in the collaborative network graph represents a country, and its size represents the number of co-authored publications. The degree of cooperation is represented by links between nodes, and the wider link width indicates closer collaboration between countries. Different colors denote different groups of countries that are cooperating.

3.2.2. Calculation of international cooperation indicators

To compute cooperation indicators to compare the China-U.S. patterns and trends of cooperation during the COVID-19 pandemic (2020–2021) with the 2015–2019 dataset, this paper adopts the following steps.

Firstly, we calculate the annual average number of publications on carbon neutrality research. To compute cooperation indicators to compare the China-U.S. patterns and trends of cooperation during the COVID-19 pandemic, we first calculate the annual average number of international cooperation publications, and the international cooperation rates of China and the United States, so as to compare and determine whether the international cooperation of China and the United States has increased or decreased since the outbreak of the COVID-19. It is noteworthy to mention that international cooperation is measured by the total number of publications with which a country/region collaborates with other countries/regions, and it is calculated by subtracting the total number of publications belonging only to that country/region from the total number of publications in that country/region. By excluding all other countries/regions from the WOS search results, the total number of publications belonging only to that country can be obtained. Furthermore, a country’s international cooperation rate is the ratio of international cooperation publications to total publications.

After that, we compare total collaborations and percent of China’ and United States’ international collaborations with the top 10 research producing countries to gain a thorough understanding of the international cooperation patterns of the United States and China.

To sum up, in order to analyze the changes in international cooperation between China and the United States during and before the epidemic, a variety of indicators related to international cooperation are calculated. Fig. 1 depicts the research framework for this paper.

4. Results and analysis

4.1. Global collaboration

Fig. 2 depicts the regional distribution of carbon neutrality research publications prior to and during the COVID-19 pandemic. Shades of color on the map represent the number of carbon neutrality publications published by each country. The darker the color, the higher the number of publications in that country. Conversely, lighter colors represent fewer publications in that country. The majority of the countries in Asia, Europe, the Americas, and Oceania play important roles in carbon neutrality research.

Countries such as the United States, China, India, the United Kingdom, Germany, South Korea, Canada, and Australia perform well in terms of scientific productivity of carbon neutral research. Both before

| Time period | Global total | China | United States |
|-------------|--------------|-------|---------------|
| 2015–2019   | 894          | 149   | 234           |
| 2020–2021   | 1590         | 719   | 223           |
and during the outbreak, China and the United States are the most productive countries. The United States has the most publications (234 publications) and total citations (10,147 citations) from 2015 to 2019, while China is slightly lower (149 publications, 9841 citations). China (719 publications, 3,151 citations) surpasses the United States (222 publications, 1,340 citations) in the number of publications and citations from 2020 to 2021, making it the most influential country.

Consistent with the findings of the study by Chahrour et al., China and the United States lead in scientific output in many fields [16].

Fig. 3 depicts the national knowledge collaboration networks for 2015–2019 and 2020–2021. It is clear that cooperation during 2020–2021 is more complicated than that during 2015–2019, with closer ties among various countries. The COVID-19 pandemic has accelerated the cross-regional trend of carbon-neutral collaborative research, which is more conducive to knowledge production. Prior to the COVID-19 pandemic, 80 countries have published at least one article on carbon neutrality, 95% of which have at least one international collaboration, with a total number of 1,320 links among countries. The number of countries involved in carbon-neutral research has risen to 85 until December 31, 2021, and the proportion of countries with at least one international collaboration has also risen slightly (95.4%). The total number of links among countries is 3,214, which is 2.4 times the sum of the five years preceding the COVID-19 pandemic.

Table 2 shows the status of cooperation among the top ten countries in terms of the number of cooperative publications published before and during the COVID-19 pandemic. Fig. 3 and Table 2 indicate that China and the United States have a high level of mutual cooperation in carbon neutrality research. Prior to and during the outbreak, China’s cooperation with the US surpassed that of any other country. Furthermore, China and the United States are at the forefront of international collaboration on carbon neutrality research, with authors based in the United States or China collaborating the most extensively with authors from other countries in the network. It is worth noting that the focus of

![Fig. 1. Workflow of the system analysis.](image1)

![Fig. 2. Geographical distribution of carbon neutrality publications during 2015–2019 (left) and 2020–2021 (right).](image2)

![Fig. 3. Network Map for countries with at least 1 carbon neutrality article during 2015–2019 (left) and 2020–2021 (right).](image3)
international cooperation has shifted. Before the COVID-19 pandemic, the cooperation mainly revolved around the United States and China. Among them, the number of contacts in the United States is the highest, with 169 contacts. The cooperation between the United States and China ranks first (33 publications), followed by the United States and Germany (14 publications), the United States and Canada (13 publications), and the United States and the United Kingdom (11 publications). During the COVID-19 pandemic, China dominated state cooperation, with 410 contacts. China and other countries are involved in nine of the top ten collaborations in terms of the number of collaborative publications. The United States (71 publications), United Kingdom (37 publications), Australia (32 publications), Pakistan (29 publications), South Korea (20 publications), Canada (17 publications), France (17 publications), Turkey (17 publications), and Germany (16 publication) are Chinese partner countries.

4.2. Collaboration of China and the US

Table 3 summarizes the status of the two countries’ carbon neutrality research collaboration during 2015–2019 and 2020–2021. Table 3 shows that the carbon neutrality cooperative research conducted by China and the United States during the COVID-19 pandemic has vastly improved over that conducted prior to the COVID-19 pandemic. The annual average number of publications in the period 2020–2021 is 35.5, which is 5.4 times the number in the five years preceding the COVID-19 pandemic. The findings demonstrate that, despite the significant challenges posed by COVID-19 and international tensions, international cooperation on carbon neutrality research between China and the United States has increased in the midst of the global crisis.

Table 4 shows the number of domestic publications, the number and the average annual number of international cooperation publications, and the international cooperation rates on carbon neutrality research in China and the United States. The amount of international cooperation has risen after the outbreak of COVID-19 pandemic significantly. The numbers of United States’ annual international cooperation increased from 18.6 to 63.5, and China has increased from 15.8 to 127. This indicates that the connection between the two countries and other countries has increased. Moreover, the United States’ average annual international cooperation is slightly higher than China’s before the COVID-19 pandemic. During the COVID-19 pandemic, however, the number of China’s annual international cooperation reach 127, more than doubling that of the United States.

In terms of the international cooperation rate, the United States during the COVID-19 pandemic is 57.0%, higher than that before the COVID-19 pandemic (39.7%). However, China’s international cooperation rate (35.3%) is lower than that of five years ago before the COVID-19 pandemic (53.0%). The reason could be that China’s scientific research has not been hampered since the COVID-19 pandemic, and China has published a large number of publications on carbon neutrality as a result of first-mover advantage. Furthermore, it can be seen that the number of publications published in China has increased significantly, resulting in a decrease in the rate of international cooperation. To summarize, COVID-19 has not had a significant negative impact on bilateral cooperation, and has even promoted bilateral cooperation to some extent. The results of previous studies by some scholars also showed that despite the threat of COVID-19 and the rising tension between China and the United States, the number of co-authored articles on COVID-19 between the two countries is the largest internationally. Also, the overall proportion of the United States and Chinese papers on COVID-19 is higher than pre-pandemic [57,58].

4.3. Collaboration with China

First, we examine China’s patterns of collaboration in carbon neutrality research during COVID-19. Fig. 4 demonstrates that China has 410 links in carbon neutrality studies with 44 countries/regions. And the United States, the United Kingdom, Australia, Pakistan, and South Korea are China’s primary partners. Chinese researchers collaborate with researchers from these five countries, each of which has published more than 20 papers. As previously stated, despite the impact of COVID-19, China’s cooperation with the United States is far greater than that of any other country. For example, Chinese researchers collaborated with American scholars 1.9 times more than British researchers (the second highest collaborator).

Table 5 lists the proportion of China’s international cooperation with the top ten carbon neutral research producing countries and demonstrates that China as a whole has maintained or increased the proportion of international cooperation with each country. In the past five years, 41.8% of articles in China are co-authored with the United States, and by 2020–2021, this proportion dropped to 28.0%. This decline indicates that China-U.S. cooperation has shrunk as a proportion of China’s international cooperation. The proportion of cooperation with Canada, Germany, and Japan has also decreased. However, the proportion of cooperation between other countries and China in China’s international cooperation has increased, with Pakistan (8.9% increase) and Turkey (6.7% increase) being the most visible examples.

4.4. Collaboration with US

The United States’ cooperation patterns on carbon neutrality research during 2020–2021 (Fig. 5) demonstrates that the United States collaborated with 43 countries and established 236 linkages. China (71 publications), Germany (15 publications), the United Kingdom (13 publications), South Korea (13 publications), Australia (12 publications), Spain (11 publications), Canada (8 publications), France (8 publications), the Netherlands (8 publications), and Sweden (6 publications) are the countries with the most cooperation with the United States. As with China’s cooperation, the United States and China have a much higher level of cooperation than any other country.

Table 6 depicts the proportion of international cooperation between the United States and the top ten carbon-neutral research producing countries before and during the outbreak. In general, the United States maintains a percentage of international collaborative articles with these top research producers. The United States’ collaboration with China,
Table 4
Total number and average annual number of international collaborations during 2015–2019 and 2020–2021.

| Country | Time period | Domestic publications | International collaborations | Average annual international collaborations | International cooperation rate |
|---------|-------------|-----------------------|----------------------------|-----------------------------------------------|-------------------------------|
| United States | 2015–2019 | 141                   | 93                         | 18.6                                         | 39.7%                         |
| United States | 2020–2021 | 96                    | 127                        | 63.5                                         | 57.0%                         |
| China    | 2015–2019  | 70                    | 79                         | 15.8                                         | 53.0%                         |
| China    | 2020–2021  | 46.5                  | 254                        | 127                                          | 35.3%                         |

Fig. 4. Network map for China’s collaborating countries on carbon neutrality publications during 2020–2021.

Table 5
Total collaborations and percent of China’s international collaborations for articles published between 2020 and 2021, 2015 and 2019 with the top 10 research producing countries.

| Country | Total collaborations with China (2020–2021) | Total collaborations with China (2015–2019) | % of China’s international collaborations (2020–2021) | % of China’s international collaborations (2015–2019) | % Difference (2020–2021)—(2015–2019) |
|---------|---------------------------------------------|---------------------------------------------|--------------------------------------------------|--------------------------------------------------|----------------------------------------|
| United States | 71                                          | 33                                         | 28.0%                                            | 41.8%                                            | −13.8%                                 |
| United Kingdom | 37                                          | 9                                          | 14.6%                                            | 11.4%                                            | 3.2%                                   |
| Australia | 32                                          | 7                                          | 12.6%                                            | 8.9%                                             | 3.7%                                   |
| Pakistan | 29                                          | 2                                          | 11.4%                                            | 2.5%                                             | 8.9%                                   |
| South Korea | 20                                          | 3                                          | 7.9%                                             | 3.8%                                             | 4.1%                                   |
| Canada    | 17                                          | 9                                          | 6.7%                                             | 11.4%                                            | −4.7%                                  |
| France    | 17                                          | 2                                          | 6.7%                                             | 2.5%                                             | 4.2%                                   |
| Turkey    | 17                                          | 0                                          | 6.7%                                             | 0.0%                                             | 6.7%                                   |
| Germany   | 16                                          | 7                                          | 6.3%                                             | 8.9%                                             | −2.6%                                  |
| Japan     | 13                                          | 6                                          | 5.1%                                             | 7.6%                                             | −2.5%                                  |

Fig. 5. Network Map for US’ collaborating countries on carbon neutrality publications during 2020–2021.
South Korea, Spain, the Netherlands, and Sweden has grown significantly. Cooperation with China increased the most, with Chinese authors authoring more than half of the carbon-neutral international articles published in the United States (55.9%), a 20.4% increase from pre-COVID-19. Table 6 also demonstrates that these countries play important roles in international cooperation of carbon neutrality research in the United States during the COVID-19 pandemic, with cooperation with China being especially important. Furthermore, cooperation between the United States and Canada accounted for 6.3% of the United States’ international cooperation on carbon neutrality research, which is significantly lower than the previous five years (7.7% decrease). The United States’ cooperation with other countries has dwindled slightly. Similar to previous studies, overall, countries increased their share of international collaborations and open access publications during the pandemic [59].

To sum up, this paper begins with a summary of global collaboration. Following that, the scientific collaboration between the United States and China on carbon neutrality is shown. In addition, the two countries’ collaboration patterns concerning carbon neutrality research during COVID-19 are investigated and compared to those prior to the COVID-19 pandemic.

5. Conclusions

The relationship between COVID-19 and climate change has drawn attention to carbon reductions. Carbon neutrality is a global strategic measure to deal with climate change, and the realization of carbon neutrality cannot be achieved without the support of scientific knowledge. China and the United States have huge carbon emissions and carbon emission reduction potential, so it is of great significance to explore the status of international cooperation in carbon neutrality scientific research between China and the United States to achieve carbon neutrality globally. Therefore, this study conducted a systematic review of carbon neutrality publications in the WOS database to examine the state of scientific research capacity and international cooperation in the carbon neutrality field between China and the United States during and before the COVID-19 pandemic. The following are the main findings of the study:

(i) A large number of studies have been conducted on carbon neutrality in various countries around the world. The United States, China, India, the United Kingdom, Germany, South Korea, Canada, Australia, and other countries performed well on carbon neutrality research. China and the United States were the most productive countries both before and during the outbreak.

(ii) Following the outbreak of the COVID-19 pandemic, global collaboration has become more intricate, as evidenced by the global network of scientific collaborations on carbon neutrality research. The number of countries participating in cooperation has increased, and countries are becoming more interconnected.

(iii) The momentum of China-U.S. carbon neutrality research cooperation has not diminished during the COVID-19 pandemic. The number of carbon neutrality publications jointly conducted by China and the United States after 2020 has greatly increased than that before the COVID-19 pandemic. Furthermore, the number of international cooperation of the two countries increased significantly during 2020–2021 than the prior period, demonstrating that the connection between the two countries and other countries has grown. The international cooperation rate in the United States during the COVID-19 pandemic was higher than that before, however, China’s international cooperation rate was lower than that of five years prior to the COVID-19 pandemic.

(iv) The COVID-19 pandemic has affected the international cooperation patterns of carbon neutrality research of China and the United States. Although the two countries have always been each other’s primary international collaborators, the trend of cooperation between the two countries and top research producers has shifted to varying degrees. China has maintained or increased the proportion of international cooperation with other countries during the COVID-19 pandemic. On the other hand, China-U.S. cooperation has shrunk as a proportion of China’s international cooperation, so is the cooperation with Canada, Germany, and Japan. Furthermore, compared to before the COVID-19 pandemic, the United States has generally maintained the proportion of international collaborative articles with top research producing countries. Specifically, there has been significant growth in the United States collaboration with China, South Korea, Spain, Netherlands and Sweden. Among them, cooperation with China has the largest increase. The U.S.-Canada collaboration accounted for a significantly lower proportion of the United States’ international collaborations on carbon neutrality research. The United States cooperation with other countries has decreased slightly.

Based on the above findings, in order to achieve the Sustainable Development Goals (SDGs) for climate action in the post-pandemic period and achieve carbon neutrality at an early date, efforts can be made in the following aspects: (i) China and the United States should give full play to the leading role of major powers in advancing global climate governance, and continue to increase research results related to

| Country   | Total collaborations with US (2020–2021) | Total collaborations with US (2015–2019) | % of US’ international collaborations (2020–2021) | % of US’ international collaborations (2015–2019) | % Difference (2020–2021)–(2015–2019) |
|-----------|----------------------------------------|----------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------|
| China     | 71                                     | 33                                     | 55.9%                                         | 35.5%                                         | 20.4%                                |
| Germany   | 15                                     | 14                                     | 11.8%                                         | 15.1%                                         | –3.2%                                |
| United    | 13                                     | 11                                     | 10.2%                                         | 11.8%                                         | –1.6%                                |
| Kingdom   |                                        |                                        |                                               |                                               |                                      |
| South Korea | 13                              | 5                                      | 10.2%                                         | 5.4%                                          | 4.9%                                 |
| Australia | 12                                     | 9                                      | 9.4%                                          | 9.7%                                          | –0.2%                                |
| Spain     | 11                                     | 4                                      | 8.7%                                          | 4.3%                                          | 4.4%                                 |
| Canada    | 8                                      | 13                                     | 6.3%                                          | 14.0%                                         | –7.7%                                |
| France    | 8                                      | 6                                      | 6.3%                                          | 6.5%                                          | –0.2%                                |
| Netherlands | 8                           | 3                                      | 6.3%                                          | 3.2%                                          | 3.1%                                 |
| Sweden    | 8                                      | 3                                      | 6.3%                                          | 3.2%                                          | 3.1%                                 |
COVID-19 and carbon neutrality. In addition, it is necessary to actively seek international cooperation to form a stable global scientific research cooperation force. (ii) Climate change is a common global challenge, so all countries in the world should work together to generate huge synergies to promote sustainable climate development. (iii) Effectively leverage the unique roles of sub-state and non-state actors, including cities, NGOs, and businesses, in global climate governance. (iv) Actively promote the reform and improvement of the global climate governance system. Promote technological innovation and achieve breakthroughs in green and low-carbon technologies.

However, there are some limitations to this study and may be the direction of future research. First, in terms of data selection, the search query may not be broad enough to capture all publications on carbon neutrality. Furthermore, because we only used the WOS database, the omission of publications may have an impact on our final analysis results. In future research, in order to avoid bias, data sources can be expanded to collect more comprehensive data for analysis. Second, the results of the VOSViewer can be influenced by algorithmic noise and sampling bias. In addition, this study specifically focuses on the changing trends and cooperation patterns of cooperation in carbon neutrality research in the United States and China. In future research, the scope of the study can be expanded to explore international collaborations among other countries.

Author contribution statement
Qiang Wang: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Supervision, Writing-Reviewing and Editing. Min Zhang: Methodology, Software, Data curation, Investigation Writing- Original draft, Writing- Reviewing and Editing. Xueling Jiang: Writing- Original draft, Writing- Reviewing. Rongrong Li: Conceptualization, Methodology, Data curation, Investigation Writing- Original draft, Writing- Reviewing.

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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References
[1] C. Zou, H. Xue, B. Xiong, G. Zhang, S. Pan, C. Jia, Y. Wang, F. Ma, Q. Sun, C. Guan, M. Lin, Connotation, innovation and vision of “carbon neutrality”, Nat. Gas. Ind. B (2021) 523–537.
[2] X. Shi, Y. Zheng, Y. Lei, W. Xue, G. Yan, X. Liu, B. Cai, D. Tong, J. Wang, Air quality benefits of achieving carbon neutrality in China, Sci. Total Environ. 795 (2021) 148784.
[3] V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R.祐, Global warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5°C, 2018.
[4] A. Öhlof, J.M. Christensen, Emissions Gap Report 2018, UNEP DTU Partnership, Copenhagen, Denmark, 2018.
[5] X. Wu, Z. Tian, J. Guo, A review of the theoretical research and practical progress of carbon neutrality, Sustain. Oper. Comput. 3 (2022) 54-64.
[6] D. Broadstock, Q. Ji, S. Managi, D. Zhang, Pathways to carbon neutrality: Challenges and opportunities, Resour. Conserv. Recycl. 169 (2021), 105472.
[7] B. Statistical Review of World Energy, 2022.
[8] B. Mallapally, How China could be carbon neutral by mid-century, Nature 586 (2020) 482–484.
[9] B. Harris, The Biden Plan for a Clean Energy Revolution and Environmental Justice, 2021.
[10] W.H. Organization, Listings of WHO’s Response to COVID-19, 2020.
[44] D. Wang, Y. Huangfu, Z. Dong, Y. Dong, Research hotspots and evolution trends of carbon neutrality—visual analysis of bibliometrics based on CiteSpace, Sustainability 14 (2022), 1079.

[45] É. Archambault, D. Campbell, Y. Gingras, V. Larivière, Comparing bibliometric statistics obtained from the Web of science and Scopus, J. Am. Soc. Inf. Technol. 60 (2009) 1320–1326.

[46] P. Mongeon, A. Paul-Hus, The journal coverage of Web of Science and Scopus: a comparative analysis, Scientometrics 106 (2016) 213–228.

[47] V.K. Singh, P. Singh, M. Karmakar, J. Leta, P. Mayr, The journal coverage of Web of Science, Scopus and Dimensions: a comparative analysis, Scientometrics 126 (2021) 5113–5142.

[48] X. Zhao, J. Zuo, G. Wu, C. Huang, A bibliometric review of green building research 2000–2016, Architect. Sci. Rev. 62 (2019) 74–88.

[49] G. Mao, X. Liu, H. Du, J. Zuo, L. Wang, Way forward for alternative energy research: a bibliometric analysis during 1994–2013, Renew. Sustain. Energy Rev. 48 (2015) 276–286.

[50] A. Pouris, A. Pouris, Scientometrics of a pandemic: HIV/AIDS research in South Africa and the World, Scientometrics 86 (2011) 541–552.

[51] S. Haustein, V. Larivière, The use of bibliometrics for assessing research: possibilities, limitations and adverse effects, Incentives and performance, Springer (2015) 121–139.

[52] B. Hammarfelt, A.D. Rushforth, Indicators as judgment devices: an empirical study of citizen bibliometrics in research evaluation, Res. Eval. 26 (2017) 169–180.

[53] J.-J. Wang, H. Chen, D.S. Rogers, L.M. Elizam, S.J. Gravo, A bibliometric analysis of reverse logistics research (1992-2015) and opportunities for future research, Int. J. Phys. Distrib. Logist. Manag. 47 (2017) 666–687.

[54] B. Fahimnia, J. Sarkis, H. Davarzani, Green supply chain management: a review and bibliometric analysis, Int. J. Prod. Econ. 162 (2015) 101–114.

[55] J. Fu, J. Ding, Comparison of visualization principles between Citespace and VOSviewer software (Chinese), Agric. Lib. Inf. 31 (2019) 7.

[56] S. Liao, The comparative study on the scientific knowledge mapping tools: VOSviewer and Citespace (Chinese), Sci.-Tech. Inf. Dev. & Econ. 21 (2011) 137–139.

[57] J.J. Lee, J.P. Haupt, M. Chang, Scientific Collaboration on COVID-19 amidst Geopolitical Tensions between the US and China, 2021.

[58] H. Dehghbanbandaki, F. Seif, V. Vahidi, F. Razi, E. Hashemi, M. Khoshmirsafa, H. Aazami, Bibliometric analysis of global scientific research on Coronavirus (COVID-19), Med. J. Islam. Repub. Iran 34 (2020) 51.

[59] M. Choi, H. Lee, H. Zoo, Scientific knowledge production and research collaboration between Australia and South Korea: patterns and dynamics based on co-authorship, Scientometrics 126 (2021) 683–706.