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Review

A bibliometric review of biochar for soil carbon sequestration and mitigation from 2001 to 2020

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ABSTRACT

To mitigate global warming and the greenhouse effect, biochar (BC) has been regarded as an important way of carbon sink. Therefore, this research explored the development trend of BC for soil carbon sequestration and mitigation from 2001 to 2020 based on bibliometric analysis. The results show that Yong Sik Ok and Johannes Lehmann are the top 2 high-impact authors. China, America, and Germany are the most widely collaborated countries, but China's research impact is lower than that of America. The Chinese Academy of Sciences has far more publications than any other institution, but Cornell University and Kangwon National University lead the way in terms of impact. Research hotspots can be divided into five clusters: (1) pyrolysis, nutrient, and microbial communities; (2) the immobilization of heavy metals; (3) crop yield and soil properties; (4) greenhouse gas, meta-analysis, and field experiment; (5) carbon fraction and sequestration. Reviews account for 60 % of the top 10 most highly cited papers, and eight of the top 10 focus on the early research period, setting the stage for the development of the BC field. Science of the Total Environment has the highest number of publications and total citations, and literature published in Soil Biology and Biochemistry is to some extent more likely to be cited. In the future, we need to carry out research in the following aspects: (1) Interaction mechanisms between BC, soil, and soil microbial communities. (2) Designing low-cost, high-yield, and high-effect optimization methods to improve the characteristics of BC. (3) Effect of BC on the environment and human health in long-term localization experiments. (4) Carbon sinks of BC need to be further evaluated on a global scale.

1. Introduction

In recent years, global warming has intensified. According to the Intergovernmental Panel on Climate Change (IPCC), mean land surface air temperature increased by 1.53 °C (likely range from 1.38 °C to 1.68 °C) while the global mean surface temperature increased by 0.87 °C (likely range from 0.75 °C to 0.99 °C) from 1850–1900 to 2006–2015 (IPCC, 2019). At the same time, it is accompanied by the increasing greenhouse effect. The concentration of greenhouse gas (GHG) in the atmosphere has continued to increase since 2010, with annual average concentrations of CO_2 reaching 410.53 cm^3/m^3, CH_4 reaching 1853 mm^3/m^3, and N_2O reaching 328.9 mm^3/m^3 in 2017 (Rhodes, 2017). The soil is a huge carbon pool on earth. The surface soil stores about two-thirds (about 1500 Pg) of carbon in the world, which is three times the carbon pool of the atmosphere (Mentges et al., 2016; Wang et al., 2016). Therefore, any small change in the soil carbon pool will have a huge impact on global GHGs. The soil carbon pool will continuously input carbon sources to the atmospheric carbon pool in various ways and contribute to global warming (Sigua et al., 2014; Raupach et al., 2007). Thus, how to reduce atmospheric CO_2 concentration and increase soil carbon sink has been deeply considered by scholars at home and abroad. They have begun to pay attention to an effective measure of soil carbon sequestration and mitigation using biochar (BC) technology. BC is a highly aromatic carbon sequestration material produced by pyrolysis carbonization of biomass under anoxic or oxygen-limited conditions (Lehmann, 2007b). BC is rich in N, P, and K, with high pH, high porosity, huge specific surface area, high carbon content, high cation exchange capacity, and high thermal stability (Gul et al., 2015). At present, measures to increase soil carbon pools by applying BC have been proposed as a potential solution to slow the increase in atmospheric CO_2

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concentration. The specific environmental effects of BC are mainly described in the following three aspects.

1.1. Effects of BC on soil GHG emissions

A large number of studies have shown that soil GHG emissions are reduced after BC application. Agegnehu et al. (2016) found that the GHG emissions in the BC treatment group were significantly lower than the control group. BC could reduce soil GHG emissions. In addition, volatile matter content may be a key characteristic of BC in explaining the short-term CO_2 and N_2O emissions of BC-applied soil (Ameloot et al., 2013). Xie et al. (2013) found that replacing straw amendment with BC could reduce CH_4 emissions and increase soil organic carbon (SOC) storage. However, some studies have shown that BC amendments have no effect and even promote GHG emissions. For example, Zhang et al. (2010) found that BC significantly increased total CH_4 emissions in paddy fields. Wang et al. (2012) discovered that the application of BC to dryland soil increased CH_4 emissions by 37 %. Moreover, the application of BC at high (10 %) rates increased forest soil CO_2 and N_2O emissions without urea-nitrogen fertilization (Hawthorne et al., 2017). According to a series of meta-analyses, the effect of BC on soil GHG emissions depends on many factors such as feedstock, pyrolysis temperature, and BC application rate (He et al., 2017; Wu et al., 2019). In addition, environmental conditions such as soil texture, fertilizer application, and climate also affect GHG emissions from BC-applied soils (Zhou et al., 2017).

1.2. Effects of BC on soil carbon fractions

SOC mainly includes readily oxidized organic carbon (ROC), particulate organic carbon (POC), and dissolved organic carbon (DOC) (Sheng et al., 2015). Thus, evaluating the effects of BC on different soil carbon fractions is of great significance for carbon sequestration and mitigation. Wang et al. (2018) found that the content of ROC fractions was significantly higher after the application of BC compared to chemical fertilizer alone. However, Zhang et al. (2018) found that the soil ROC content did not change significantly after BC correction. The moderate application of BC could increase soil POC, but the excessive application has no effect, or even the opposite effect (Wang et al., 2017). In addition, BC can reduce the leaching of DOC from soil (Eykelbosh et al., 2015). However, Li et al. (2018) found that BC significantly increased DOC at low temperature, while it significantly decreased DOC at high temperature. Therefore, types of BC and soil, BC application rate and time, and experimental conditions all have an impact on how BC affects SOC (Moura Chagas et al., 2022). Moreover, the application of BC also affected soil inorganic carbon (SIC). For example, Dong et al. (2019) found that BC application increased SIC content in 0–40 cm soil layer for 5 years. The results of a decade field experiment showed that the application of BC significantly enhanced the SIC content (3.2 %−24.3 %) (Shi et al., 2021b). SIC is very common in karst areas or arid and semi-arid areas in North China, which plays an important role in the carbon cycle of terrestrial ecosystems (Xu et al., 2019). Therefore, soil carbon sequestration in karst areas can be better understood by studying the effect of BC on the formation and dissolution of SIC (Liang et al., 2013).

1.3. Effects of BC on crop growth and yield

According to the meta-analysis, the application of BC may increase crop yield by 10 % in an agroecosystem (Jeffery et al., 2011), which can be attributed to the increased soil fertility, water use efficiency, and reduced bioavailability of heavy metals. Major et al. (2010) found that the treatment group using BC 20 t/ha had 28 %, 30 %, and 140 % higher crop yields than the control group in years 2–4, respectively. In addition, the application of BC can not only increase crop yield, but also improve crop quality, especially in special environments such as heavy metal pollution, salinization, and soil drying (Kavitha et al., 2018). However, Xin et al. (2022) found that rice yield decreased when BC was applied without nitrogen fertilizer. This was mainly due to the increase of the C/N ratio in BC-applied soil, which reduced the availability of soil nutrients in low-fertility soil. Moreover, excessive use of BC can harm crop growth and reduce crop quality (Peng et al., 2021). For example, Sun et al. (2019) found that excessive application of BC (over 30 t/ha) reduced nitrogen use efficiency and crop yield in wheat. At the same time, excessive BC inhibited the growth of flue-cured tobacco (Yang et al., 2019b). Therefore, the application rate, feedstock types, and production processes of BC should be optimized to improve crop yield and quality.

In this study, the role of BC for soil carbon sequestration and mitigation was used as an entry point in recent 10 years. VOSviewer of bibliometrics was used to quantitatively analyze the relationship between different countries and institutions in the world, visually analyze representative authors, highly cited literature and research hotspots, which can clarify the overall knowledge structure and context of the discipline (Pan et al., 2021; Shi et al., 2021a). The results of the bibliometric analysis are greatly significant for researchers to track popular research topics of BC for soil carbon sequestration and mitigation (Arfaoui et al., 2019). In the next few years, in addition to conducting in-depth research on current hot issues, we can also propose innovative questions and conduct innovative research based on the results of trend prediction (Md Khudzari et al., 2018; Tan et al., 2021).

2. Research methodology

2.1. Bibliometric analysis methods

At present, bibliometric analysis has emerged as one of the primary methods for analyzing large amounts of literature in any scientific field (Aznar-Sanchez et al., 2018a; Aznar-Sanchez et al., 2018b). A recent development in the field of bibliometric analysis is scientific mapping (Albort-Morant et al., 2017; Cahlik, 2000), which can show the origins of knowledge and its development law, as well as the relationship between knowledge structures and its evolution in related fields (Heersmink et al., 2011; Hood and Wilson, 2001; Janik et al., 2020). There are several tools available for knowledge graph analysis, each with its benefits and drawbacks (Bezak et al., 2021; Borner et al., 2003). In this research, two software programs, VOSviewer and Biblioshiny, are used for bibliometric mapping.

VOSviewer is a visualization software developed by Nees Jan Van Eck and Ludo Waltman from Leiden University in the Netherlands (Van Eck and Waltman, 2006). Authors, citations, keywords, and other data co-occurrence graphs can be created via VOSviewer (Waltman et al., 2010; Xie et al., 2020). This software offers distinct benefits in mapping and clustering (Nasir et al., 2020; Yahya Asiri et al., 2020). VOSviewer uses some factors (such as distance and density) to deconstruct the clustering relationship between nodes (Cobo et al., 2011; Garfield, 2006; Gutierrez-Salcedo et al., 2018). Using VOSviewer, we mapped the bibliometric knowledge map of BC for soil carbon sequestration and migration and discussed the important topics and frontiers in this field from 2001 to 2020 (Zhu and Liu, 2020). Publication type, publication year, countries, institutions, keywords, authors, journals, and papers are some of the bibliometric criteria taken into account in this study (Yang et al., 2022; Hauser-Davis et al., 2017; Koseoglu et al., 2018). Along with the above analysis, the bibliometrix package offers a collection of tools for quantitative bibliometrics research using the R programming language to find research streams and themes using keywords identified in papers (Aria and Cuccurullo, 2017). It utilizes the same file as VOSviewer's and loads it using the R-studio console loading *library (bibliometrix); biblioshiny*. After that, we selected the database to access the findings and see the maps of visualization (Mongeon and Paul-Hus, 2016). The program is structured following the process of scientific mapping (Opejin et al., 2020).

2.2. Data collection and processing

Web of Science (WoS), Scopus, and PubMed are the bibliographic databases utilized for bibliometric analysis (Archambault et al., 2009; Bar-Ilan, 2008). In this study, we chose WoS for bibliometric analysis, which makes it easier to download data for bibliometric purposes, conforms to scientific coverage, and provides a powerful tool for measuring science (Rodriguez-Sabiote et al., 2020; Uribe-Toril et al., 2019). This bibliometric analysis uses the keyword search to identify the data source (Perianes-Rodriguez et al., 2016; Smyrnova-Trybulska, 2017). The analysis data is based on SCI-Expanded in the WoS core collection database of the Institute of Scientific Information. The specific process of bibliometric analysis is shown in Fig. 1.

The retrieval term is TS = soil* AND (biochar* OR bio-char* OR “biological carbon” OR “biomass charcoal”) AND (“GHG*” OR CO_2 OR “carbon dioxide” OR CH_4 OR methane OR N_2O OR “nitrous oxide” OR “emission* reduc*” OR “mitigat*” OR “carbon sequestrat*” OR “fixed carbon” OR “carbon stabili*” OR “soil carbon loss” OR “soil carbon” OR “soil organic carbon” OR SOC OR “soil inorganic carbon” OR SIC OR “microbial biomass carbon” OR MBC OR “dissolved organic carbon” OR DOC OR “crop* yield*” OR “grain yield*” OR “crop* production” OR “plant* grow*” OR “crop* grow*”). The asterisk in "mitigat* " is used to retrieve all potential derivatives of the words, while the quote marks are used to obtain accurate and exact formulations. As a result, "mitigat" serves as the root phrase for other words, including “mitigate”, “mitigation”, “mitigating”, and “mitigated”. TS represents the “theme subject” search in the WoS database search. Using keywords, the TS retrieval technique based on Boolean logic can quickly and simply find a large amount of literature data related to the topic (Mongeon and Paul-Hus, 2016). After the screening, comparison, and weighing, 4109 bibliography catalogs were finally obtained from 2001 to 2020. Each bibliography includes authors, institutions, abstract, keywords, publication year, journal, and references. Since duplicate papers, fictional items or synonymous keywords often appear in the original data, processing the literature data is a necessary condition to obtain accurate analysis results. If not handled properly, word frequencies may be overestimated or computed incorrectly, leading to unreliable or even opposite results (Van Eck and Waltman, 2006). The extracted data will be divided into three categories for processing: removing duplicate items, removing nonsense items, and merging synonyms (Van Eck and Waltman, 2010).

3. Results and discussion

3.1. General evolution trend analysis

Between 2001 and 2020, a total of 4109 articles related to BC for soil carbon sequestration and mitigation were published (Fig. 2). These publications are mainly divided into four types: 3692 original articles, 304 reviews, 75 proceedings papers, and 38 others. Original articles made up 89.85 % of all publications, followed by reviews (7.40 %) and proceedings papers (1.83 %). The cumulative number of publications in

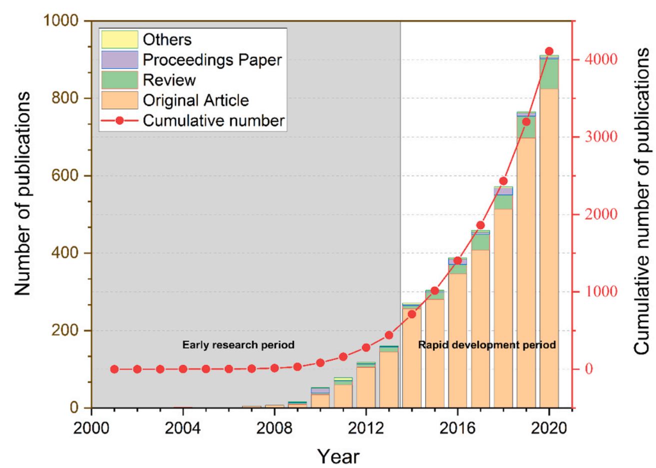

Fig. 2. Number, cumulative number, and types of publications from 2001 to 2020.

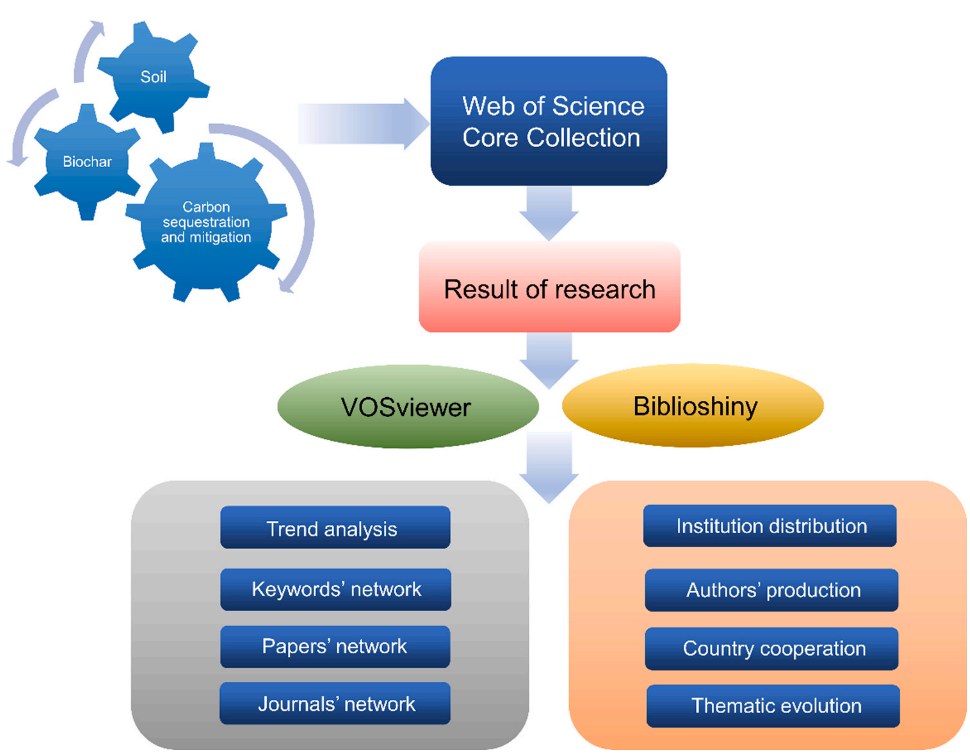

Fig. 1. The specific process of bibliometric analysis in this research.

the whole stage increased exponentially over time ($R^2 = 0.97$).

3.1.1. Early research period (2001–2013)

During this period, less than 34 papers were published on BC for soil carbon sequestration and migration every year on average. The number of papers published each year gradually increased with a total of 440 papers published in 13 years, but the growth rate was relatively slow. At this stage, people begin to pay attention to the application of BC as a carbon sink to reduce GHG emissions (Biederman and Harpole, 2013; Jones et al., 2012; Lehmann et al., 2011). Although there are few studies of this period, there is no shortage of high-quality literature in this field. For instance, Warnock et al. (2007) identified the importance of BC and reviewed hypotheses related to four mechanisms by which BC could affect mycorrhizal abundance or function. Moreover, Kuzyakov et al. (2009) found that the mean residence time of BC in the soil is about 2000 years by the C-14 labeling method, which was published in Soil Biology and Biochemistry. It is important to note that the majority of the highly cited papers in this field focus on this stage, which paved the road for subsequent research in the field of BC for soil carbon sequestration and mitigation.

3.1.2. Rapid development period (2014–2020)

At this stage, the number of publications is also increasing year by year, and the growth rate is getting faster and faster. Compared to 2013, there was a marked increase in the number of articles published in 2014, which can be considered a turning point. Such as Ahmad et al. (2014), Mohan et al. (2014), and Cayuela et al. (2014), these papers are important scientific achievements. During this period, a total of 3669 papers were published, which was 8.3 times the total number of papers published in the first stage. There were 271 papers published in 2014 and 912 papers published in 2020. The number of original articles has been the fastest growing. And the number of reviews has also increased significantly from 9 to 78. The number of the other types of publications has not changed significantly. Meanwhile, many hot papers emerge during this period, and research interest in the BC-related field continues to grow rapidly, demonstrating the great significance of this field among the global scientific community.

3.2. Interrelationship analysis of the institutions

The total citations and number of papers published by research institutions reflect, to a certain extent, the scale of research and research capacity in the field, as well as the degree of close cooperation between domestic and foreign research institutions. The institutions that publish papers are counted according to the institution of the first author. Based on the total link strength of publications on BC for soil carbon sequestration and mitigation from 2001 to 2020, the top 25 institutions worldwide are shown in Table 1 and the results of the analysis are presented in Fig. 3 and Fig. S1. There are 7 institutions from China, accounting for 28 % of the top 25 institutions. The rest are located in America, Pakistan, Korea, Britain, Germany, Australia, Saudi Arabia, and Egypt. The Chinese Academy of Sciences published 333 BC-related articles during 2001–2020, much higher than other domestic and foreign institutions. The Chinese Academy of Sciences is not only the most productive institution in the field, but it is also the institution with the broadest field relationships. It is followed by the University of Agriculture Faisalabad, Zhejiang Agriculture and Forestry University, Korea University, and Newcastle University, which have had significant impacts on this network's academic communication. It can be seen that there are still many institutions like Newcastle University. Its number of publications is only 57, however, its total link strength is as high as 237. From the ranking of total citations, although the number of publications is not dominant, Newcastle University, Kangwon National University, Cornell University, and the University of Florida still occupy the top 25 institutions, indicating that their publications have been widely recognized. Although universities, like the University of Orleans and the University of Molise, are marginally able to influence scientific outputs, the level of collaboration and linkage is not strong enough. Future efforts in the field of BC for soil carbon sequestration and mitigation must be directed at strengthening collaborations on the large scale, such as across regions and contexts. Moreover, Newcastle University, Cornell University, and the University of Wuppertal all have high centrality and total link strength, which are representative research groups on the network map. These groups reflect the current characteristic of institutional collaboration, which is geographic location has not been a limiting factor in inter-institutional collaboration. For example, institutions in Europe and North America have established very close

Table 1
Top 25 research institutions with high cooperation of BC for soil carbon sequestration and mitigation.

Rank	Institution	NP	C	TL	TLS	TC	CPP	APY
1	Chinese Academy of Sciences	333	China	196	602	14365	43.14	2017.67
2	University of Agriculture Faisalabad	105	Pakistan	87	300	5827	55.50	2018.44
3	Zhejiang Agriculture and Forestry University	80	China	85	278	3995	49.94	2018.24
4	Korea University	55	Korea	83	262	3795	69.00	2018.85
5	Newcastle University	57	UK	93	237	6083	106.72	2017.18
6	Government College University	74	Pakistan	61	222	4719	63.77	2018.47
7	University of Chinese Academy of Sciences	123	China	78	221	5078	41.28	2017.98
8	Sejong University	42	Korea	57	220	3110	74.05	2018.74
9	University of Wuppertal	32	Germany	54	213	2466	77.06	2019.13
10	Foshan University	36	China	62	202	1658	46.06	2019.33
11	Kangwon National University	58	Korea	67	195	8880	153.10	2016.60
12	Nanjing Agricultural University	134	China	78	195	8979	67.01	2016.90
13	Hong Kong Polytechnic University	43	China	55	184	3038	70.65	2018.88
14	King Saud University	63	Saudi Arabia	72	183	3477	55.19	2018.21
15	Zhejiang University	107	China	87	172	5705	53.32	2017.69
16	Bahauddin Zakariya University	58	Pakistan	49	152	3185	54.91	2018.40
17	Cornell University	81	America	70	134	15277	188.60	2014.57
18	Chinese Academy of Agricultural Sciences	74	China	69	119	2359	31.88	2018.22
19	United States Department of Agriculture- Agricultural Research Service	82	America	67	112	5757	70.21	2015.90
20	University of Florida	73	America	67	111	8948	122.58	2016.38
21	University of Western Australia	57	Australia	56	111	4114	72.18	2016.84
22	The University of New South Wales	28	Australia	53	107	1357	48.46	2018.07
23	Agricultural Research Service	61	America	57	105	4500	73.77	2015.25
24	University of Minnesota	29	America	51	105	3026	104.34	2016.45
25	Kafrelsheikh University	14	Egypt	35	103	1275	91.07	2019.14

NP: the number of papers. C: country. TL: total link. TLS: total link strength. TC: total citations. CPP: citations per paper. APY: average publication year.

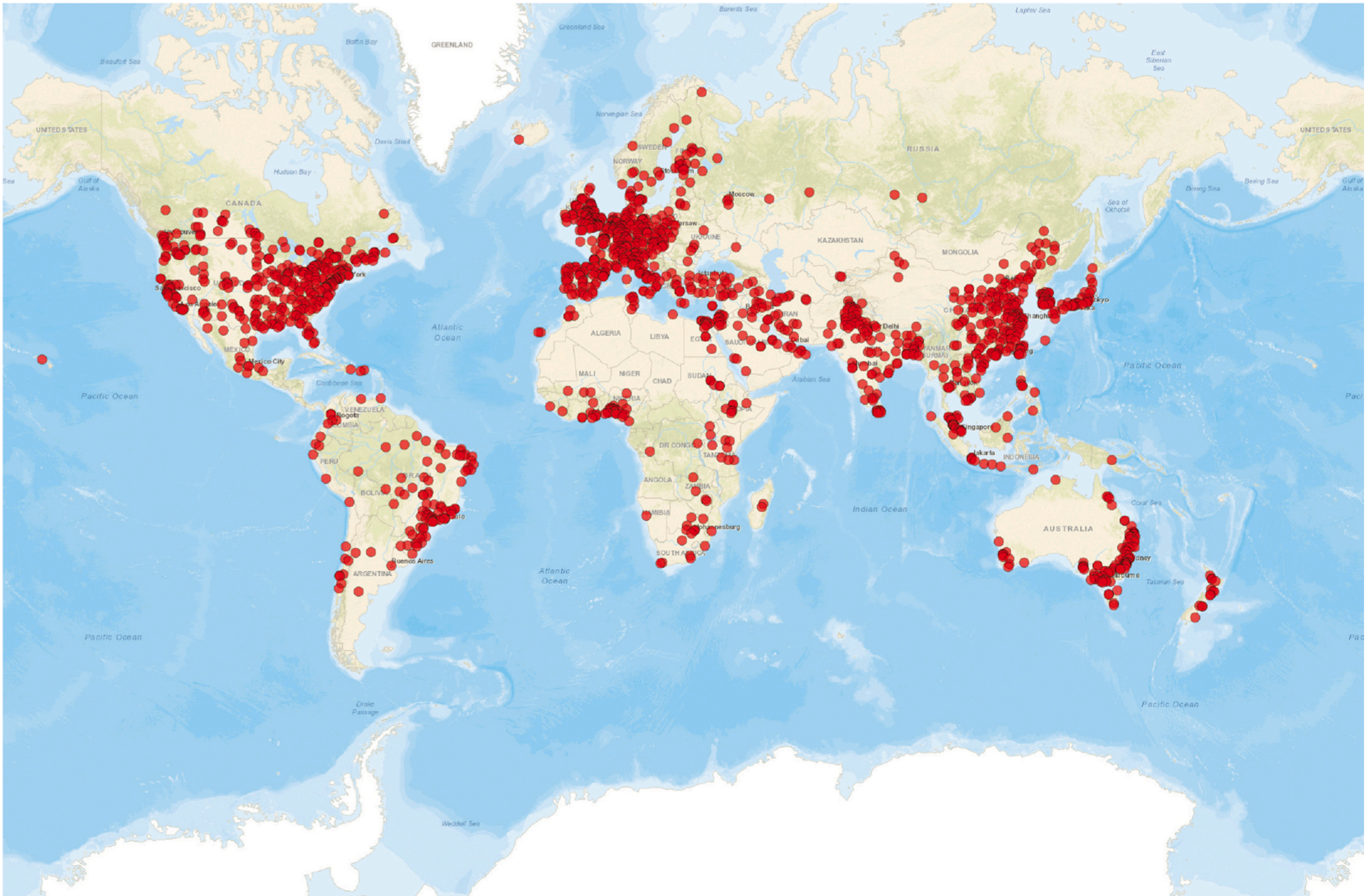

Fig. 3. Institution distribution of the publications of BC for soil carbon sequestration and mitigation.

links.

To better precisely describe each institution's domain influence and research quality, we have also introduced the CPP indicator, to define it as the citations per paper. Cornell University, Kangwon National University, the University of Florida, Newcastle University, and the University of Minnesota are at the top of this field. Their studies received more attention and were influential. Compared with them, Hong Kong Polytechnic University has the highest CPP (70.65) among Chinese institutions. This suggests that in the BC-related field, the quality of research from Chinese institutions is lower than that in America, the UK, and Korea, which may be that the larger number of publications is mixed with some low-quality papers. In terms of APY, it depicts the concentrated time of BC research that is conducted by institutions. Compared to other institutions, Cornell University conducts research at an earlier age on average.

3.3. Network analysis of the authors

Several author groups work together closely and have significant links to other groups, including the clustering of an important collaborative team with Yong Sik Ok and Daniel C.W. Tsang as the core (Fig. 4). Early in the study, there was a collaborative team with Johannes Lehmann as the core, while in the middle of the study, a collaborative team was formed with Pan Genxing and Li Lianqing as the core. Recently, the emergence of collaborative teams was represented by Daniel C.W. Tsang, Joerg Rinklebe, Muhammad Zia-Ur-Rehman, Shafaqat Ali, and Feng Yanfang. This suggests that proper scientific communication has been established worldwide, which will facilitate information sharing in the field of BC for soil carbon sequestration and mitigation. Additionally, it is beneficial for researchers to develop a collaborative network with other active researchers in their field or related fields. However, authors with similar backgrounds in terms of nationality and institution tend to collaborate more frequently and easily. Therefore, cross-background, cross-institutional, and cross-national collaboration should be prioritized as well as the role of inter-discipline, as these are beneficial for the mutual learning among different teams and contribute to the rapid advancement and diverse development of BC for soil carbon sequestration and mitigation.

It can be found that the number of publications and total citations per year determines the influence of authors. Yong Sik Ok, Muhammad Rizwan, Wang Hailong, Shafaqat Ali, Daniel C.W. Tsang, Xing Baoshan, and Joerg Rinklebe all have a large number of publications per year, but only Yong Sik Ok has the highest total citations (Fig. 5). Meanwhile, the number of publications every year on average is low, however, Johannes Lehmann's high total citations per year places him second on the author influence list. Moreover, there are authors such as Stephen Joseph, Lukas Van Zwieten, Pan Genxing, Wang Hailong, Li Lianqing, and Bhupinder Pal Singh. They published fewer papers each year and the total citations were low, compared with others, but they started publishing the literature early and the total period was long, which made them rank higher in author influence.

Importantly, Yong Sik Ok, Johannes Lehmann, Daniel C.W. Tsang, and Pan Genxing were recognized as the highly cited authors in the field of BC for soil carbon sequestration and mitigation based on the HI and CPP indicators. Combined with Fig. 4 and Table S1, there are scientific groups with significant scientific outputs but limited levels of cooperation with other groups among the most influential authors in this field. For example, the collaborative team with Xing Baoshan as the core, which is at the edge of the entire network map, is less collaborative in intensity than those located near the center of the map. In addition,

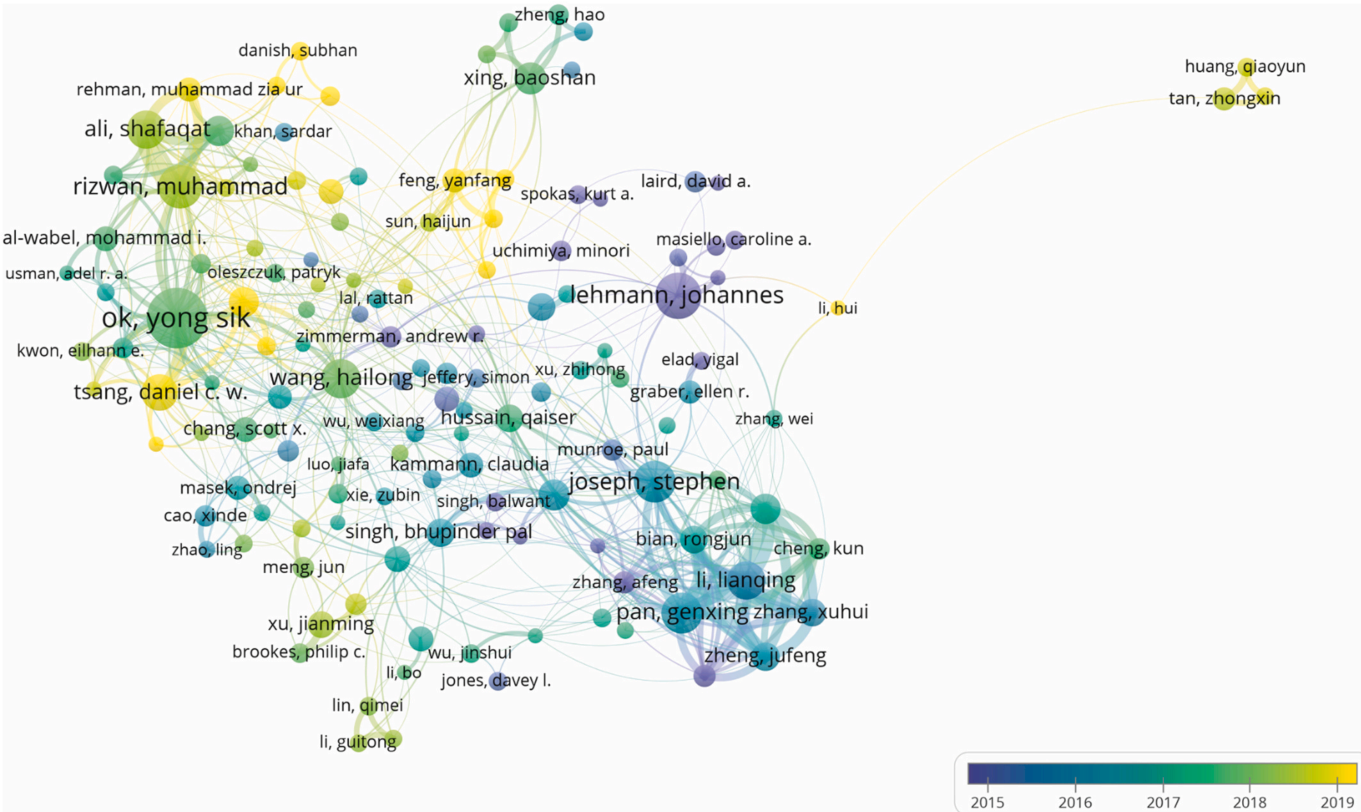

Fig. 4. Network analysis of collaboration between authors of BC for soil carbon sequestration and mitigation (color shades indicate the average publication year of the author).

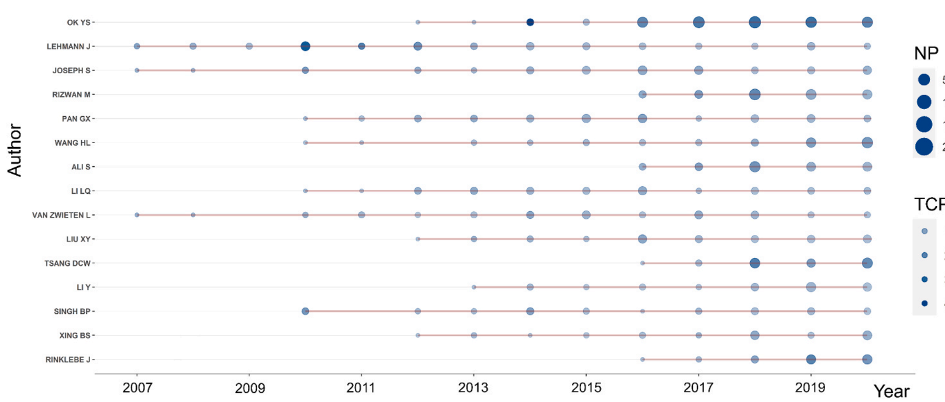

Fig. 5. Top 15 authors in terms of quantity and quality of publications (NP: the number of papers; TCPY: total citations per year).

Stephen Joseph plays an important bridging role, connecting Johannes Lehmann's team with Pan Genxing and Li Lianqing's team. Wang Hailong's team is located near the center of the map, which shows that it cooperates with most of the teams, among which are Yong Sik Ok's, Muhammad Rizwan's, Shafaqat Ali's, and Daniel C.W. Tsang's.

3.4. Network analysis of cooperation between countries

Different countries have different research strengths, thus geographical location can also have an important impact on the research (Fig. 6). From 2001 to 2020, 112 countries published research papers on BC for soil carbon sequestration and mitigation around the world. In terms of the number of publications, China (1546 papers, 37.62 %) and America (841 papers, 20.47 %) were the two countries with the largest number of publications, followed by Australia (398 papers, 9.69 %), Germany (340 articles, 8.27 %), and Pakistan (304 articles, 7.40 %). Combining the TL indicator, Germany has the most widespread collaboration with 59 countries, followed by China (56) and America (54) (Table 2). According to the connection intensity (TLS indicator), China has the highest level of international collaboration, far more than any other country, and holds the leading position in the BC field internationally. Especially, China and America play a significant part in this cooperation network (Fig. S2 and Fig. S3). There is no denying that other countries also have made significant contributions to the advancement of BC-related research, which suggests that the diverse collaborative growth of various countries and regions will continue to be a trend in this field. Although China produces the most scientific outputs and has the highest total citations, its impact is slightly less widespread than that of Germany (TL indicator) and substantially less global than that of America, Australia, and Korea (CPP indicator). This suggests that China

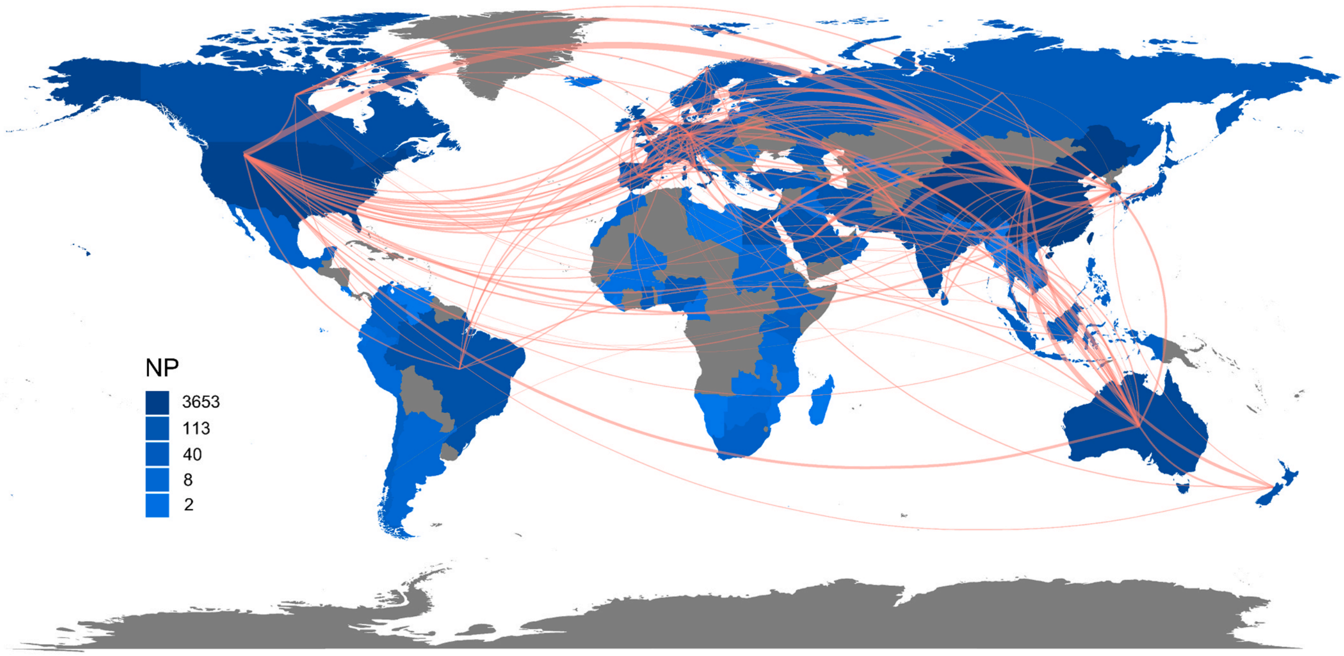

Fig. 6. Network map of cooperation between countries of BC for soil carbon sequestration and mitigation (NP: the number of papers).

Table 2
Top 20 countries with high cooperation of BC for soil carbon sequestration and mitigation.

Rank	Country	Continent	NP	APY	TC	TL	TLS	CPP
1	China	Asia	1546	2018.01	67721	56	1162	43.80
2	America	North America	841	2016.40	67626	54	764	80.41
3	Germany	Europe	340	2016.74	25170	59	628	74.03
4	Australia	Oceania	398	2016.46	36237	51	515	91.05
5	Pakistan	Asia	304	2018.24	16874	40	426	55.51
6	Korea	Asia	180	2017.66	15309	37	382	85.05
7	England	Europe	160	2016.49	13842	40	310	86.51
8	Spain	Europe	191	2016.96	11571	42	246	60.58
9	Italy	Europe	177	2017.12	9454	38	234	53.41
10	Saudi Arabia	Asia	90	2018.40	4865	31	224	54.06
11	Scotland	Europe	118	2015.78	10444	39	205	88.51
12	Egypt	Africa	92	2018.65	3756	29	203	40.83
13	France	Europe	101	2017.55	4418	45	188	43.74
14	Canada	North America	189	2017.02	13727	33	179	72.63
15	Switzerland	Europe	71	2017.06	4044	33	148	56.96
16	Brazil	South America	127	2017.41	3864	35	133	30.43
17	New Zealand	Oceania	98	2016.06	7292	25	130	74.41
18	Austria	Europe	57	2016.88	4896	37	129	85.89
19	Netherlands	Europe	55	2016.00	4113	32	120	74.78
20	Norway	Europe	49	2016.57	3500	32	116	71.43

NP: the number of papers. C: country. TL: total link. TLS: total link strength. TC: total citations. CPP: citations per paper. APY: average publication year.

has not reached the level of a strong country in the BC field in terms of research quality, probably because there are still some low-quality scientific papers that make little progress in terms of increasing the country’s influence. Thus, it is important to promote innovative exploration while minimizing repeated research.

In terms of the total link strength, most of the top 20 countries are in Europe, followed by Asia, North America, and Oceania (Table 2). North America and Oceania do not have the same advantages in terms of the number of countries as Europe and Asia, but America, Canada in North America and Australia, New Zealand in Oceania are countries that publish a large number of papers and have extensive exchanges and cooperation with other countries, thus making up for their disadvantages. South America and Africa have only one country in the ranking, Brazil and Egypt, respectively. This shows that these two continents have insufficient research strength in the field of BC for soil carbon sequestration and mitigation, and cooperation with neighboring countries should be strengthened to enhance academic influence and competitiveness.

3.5. Co-occurrence analysis of the keywords

Through the co-occurrence analysis of the keywords in papers, we can explore the research hotspots and future directions in the field of BC for soil carbon sequestration and mitigation (Tan et al., 2021). Table S2 selects the top 30 keywords with high occurrences. And the link between different keyword clusters is shown in the network map (Fig. 7). The degree of similarity between keywords increases with their proximity, whereas those with greater separation will create other branch groups

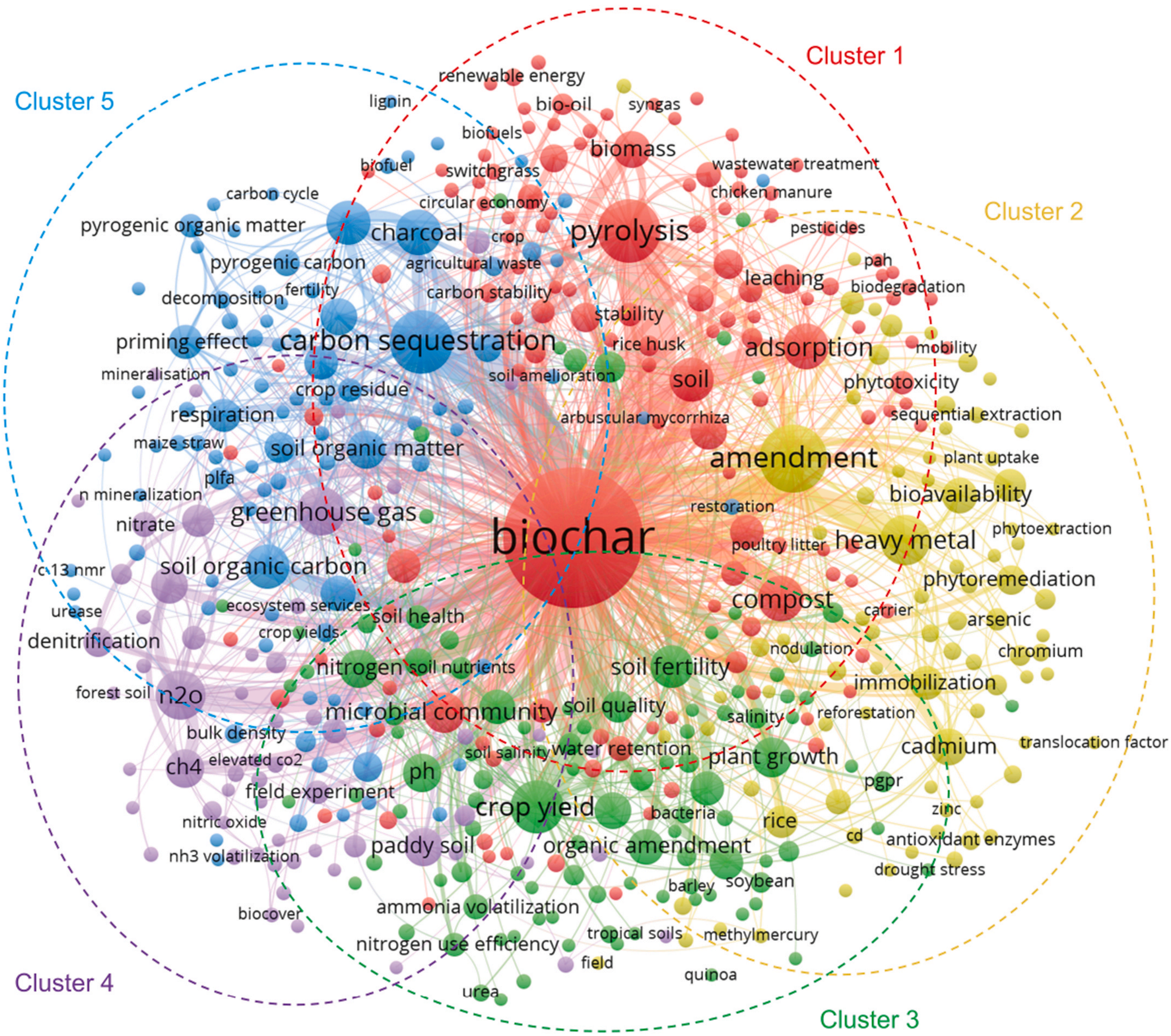

Fig. 7. Cluster analysis of the keywords' co-occurrence of BC for soil carbon sequestration and mitigation.

(Wang et al., 2021). These keywords can be divided into five different clusters.

The red cluster is related to the pyrolysis of feedstock, nutrient leaching, and microbial community. And high-frequency keywords include pyrolysis, pyrolysis temperature, biomass, bioenergy, sewage sludge, compost, fertilization, nutrient, leaching, soil, microbial community, adsorption, and degradation. The application of BC from the pyrolysis of feedstock to the soil reduces nutrient leaching and changes the microbial community. The conversion of biomass wastes by pyrolysis to produce BC is a potential option, McHenry (2009) quantified the amount of renewable energy generation and net carbon sequestration possible when using farm bio-waste to produce BC. Rubin et al. (2020) found that the increase of BC reduced nutrient leaching and GHG emissions under different hydrological conditions. And Laird et al. (2010) found that the application of BC to soil could significantly reduce nutrient leaching and showed that BC can be an effective management option to reduce nutrient leaching in agricultural production. Moreover, BC may alter the composition and abundance of the soil's microbial community (Hussain et al., 2017). Zhao et al. (2020) found that BC enhanced microbial biomass and activity, and that fine BC had a stronger effect on soil microbial communities than coarse BC. The yellow cluster represents the immobilization of heavy metals and phytoremediation by BC. High-frequency keywords include heavy metal, bioavailability, immobilization, contamination, cadmium, rice, amendment, phytoremediation, and photosynthesis. As a soil amendment, BC performs well in interacting with heavy metals, organic and inorganic pollutants. At the same time, the accumulation of heavy metals in the roots and the low transfer to the edible parts make phytoremediation show great potential. Lebrun et al. (2018) found that the combined effect of phytoremediation and BC can significantly improve soil physical and chemical properties and reduce Pb concentration in soil pore water. Que et al. (2019) found that BC is useful for the immobilization of heavy metals. Thus, BC can be used as a low-cost and environmentally friendly material for the remediation of heavy metals contaminated sites. However, there are still instances of the BC amendment having a negative or ineffectual impact on heavy metal immobilization (Guo et al., 2020). Therefore, remediation of contaminated soil through a combination of phytoremediation and BC amendment is an important idea. The green cluster's keywords are connected with crop yield and growth, soil physicochemical and biological indexes. And high-frequency keywords include crop yield, plant growth, corn, wheat, soil fertility, soil quality, phosphorus, nitrogen, pH, microbial activity, organic amendment, and agriculture. BC is of great importance for agricultural recycling development and soil improvement. Importantly, regulating microbial communities by improving the physicochemical properties of soil is an effective way to improve the stability and condition of soil systems with BC. Zhang et al. (2016) found that balanced BC and fertilization increased crop yield and partial nutrient productivity. Wang et al. (2020a) indicated that BC promoted crop growth and increased the abundance of bacterial communities. According to Pandian et al. (2016), BC enhanced soil pH from 5.7 to 6.3. And there were clear differences in the population of bacteria, fungi, and actinomycetes between BC treatments and the control. The application of BC increased pH, soil porosity, water-holding capacity, and microbial activity. At the same time, BC sometimes negatively affects soil properties, as evidenced by loss of crop yield, which may be influenced by factors such as soil texture (Murtaza et al., 2021). The purple cluster is correlated with the GHGs mitigation, meta-analysis, and field experiments. High-frequency keywords include climate change, GHG, N_2O, CH_4, CO_2, anaerobic digestion, denitrification, nitrate, meta-analysis, field experiment, and paddy soil. Combining the meta-analysis and field experiment, we find that the effect of BC on GHGs is variable and the duration of the impact remains uncertain, which is decided by various management strategies, the BC characteristics, and soil properties. A meta-analysis indicated that BC application increased soil CH_4 and CO_2 emissions by an average of 15 % and 16 %, but reduced N_2O emissions by 38 %. Soil pH, C/N ratio of BC, and the BC application rate were the most influential variables on soil CH_4, CO_2, and N_2O emissions, respectively (Zhang et al., 2020). In addition, long-term field experiments are required to clarify the mechanisms of BC's effects on GHG. Yang et al. (2020) found that BC amendments reduced CO_2 emissions by 18–25 % and 19–41 % in the first and second growing seasons, respectively, while N_2O emissions decreased by 71–110 % and 39–47 %. Yang et al. (2019a) found that the application of BC significantly decreased CH_4 and N_2O emissions from paddy fields under controlled irrigation. The blue cluster mainly focuses on various soil carbon fractions, different types of BC, and soil carbon sequestration. And high-frequency keywords include charcoal, black carbon, carbon, soil organic matter (SOM), SOC, DOC, soil microbial biomass, carbon sequestration, priming effect, carbon mineralization, and respiration. According to the meta-analysis, BC carbonization temperature, feedstock type, incubation time, and soil properties are the main factors that determine the priming effect of BC on various soil carbon fractions. Malghani et al. (2013) used BC from slow pyrolysis and hydrothermal carbonization of the same feedstock as amendments to soils and found differences in their effects on carbon sequestration and carbon mineralization. The application of BC significantly increased the SIC content, POC content, and total SOC content, which had a positive contribution to soil carbon sequestration (Shi et al., 2021b). Liu et al. (2022) found that the application of BC during rice cultivation resulted in higher concentrations of SOC and lower concentrations of DOC and active labile organic carbon in the soil and increased the capacity of soil carbon sinks due to greater stability of the SOC pool. However, Han et al. (2013) found that the application of BC could provide significant soil carbon sequestration with large uncertainty. The mechanisms of BC affecting the priming effect of the SOC pool are not clear (Rasul et al., 2022).

In recent years, the research heat of some keywords has increased first and then decreased, including sewage sludge, microbial biomass, nitrogen, and carbon sequestration (Fig. 8). Among them, carbon sequestration became a research hotspot in 2012, peaking in 2015, but research heat declined from 2016 to 2020. There are also some keywords whose research heat continues to increase, including pH, immobilization, climate change, phosphorus, plant growth, SOC, compost, soil, soil quality, heavy metal, crop yield, soil amendment, pyrolysis, GHG, and BC. There are also some keywords whose research heat

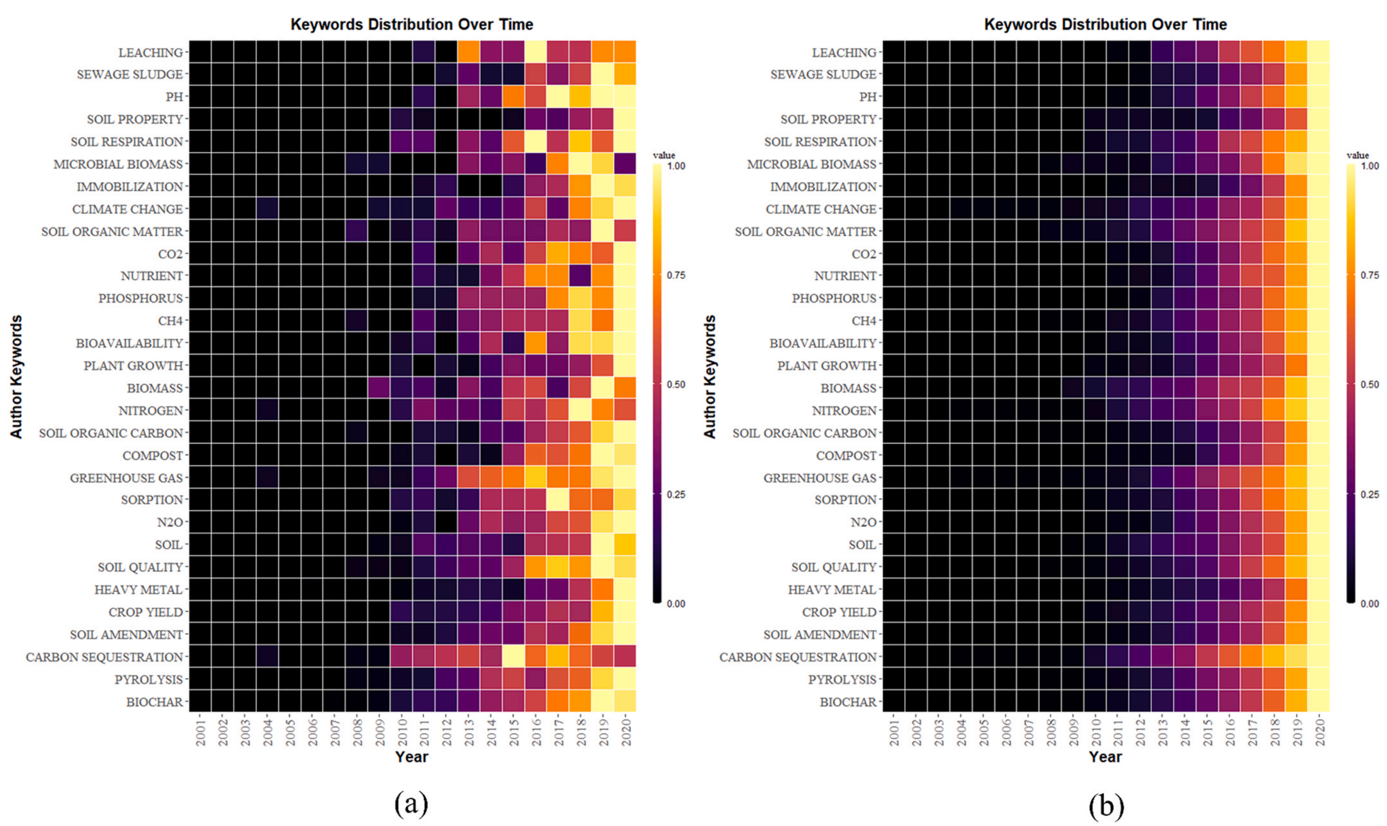

Fig. 8. (**a**) Keywords frequency distribution heatmap; (**b**) keywords cumulative frequency distribution heatmap.

changes repeatedly, including leaching, soil respiration, bioavailability, and biomass. Such as soil respiration, and its research heat increased suddenly in 2016, but it dropped in 2017 and then increase continuously from 2018 to 2020. The remaining keywords are those that have undergone a sudden change in a given year, such as soil property, SOM, nutrient, and sorption. In addition, the research heat of CO_2, CH_4, and N_2O show good consistency, because they belong to GHGs, and most research on GHG emissions does not focus solely on a single GHG. The cumulative distribution of keyword frequency shows that the first to appear in yellow is the first to reach the highest research heat, including microbial biomass, carbon sequestration, nitrogen, SOM, biomass, GHG, leaching, soil quality, pH, sorption, and BC. It can be seen that the research results mainly focused on these important keywords above between 2001 and 2020.

With the evolution of time, there are different research hotspots in different periods. In recent years, BC has been used as a soil amendment to study nitrogen cycling and soil microorganisms. In consideration of these findings, it is advised that more studies from the following perspectives be conducted in this field: (1) BC can potentially affect soil physicochemical properties, soil carbon pool, GHG emissions, and crop yield by altering the composition and activity of microbial communities in soils (Harter et al., 2014; Meschewski et al., 2019). However, the mechanisms of interaction between BC and soil microbial communities have not been systematically studied (Wang et al., 2020b; Xu et al., 2014). (2) The environmental effect of BC is influenced by its characteristics, including biomass feedstock, operating conditions, and desired functionalization (Abbas et al., 2018; Kong et al., 2019; Panahi et al., 2020). Then, optimization methods with low cost, high yield, and high effect are gradually developed (Pokharel et al., 2020; Uchimiya et al., 2011; Xiao et al., 2020; Yuan et al., 2019). (3) The possible effects of BC application on the environment and human health need to be further investigated through long-term localization experiments (Aller et al., 2018; Bai et al., 2019; Farkas et al., 2020; Liu et al., 2019b; Qin et al., 2016). (4) Uncertainties in the retention time of BC applied to soil and carbon sinks of BC need to be further evaluated on a global scale as data support (Bell and Worrall, 2011; Chiaramonti and Panoutsou, 2019; Ren et al., 2018).

3.6. Network analysis of paper citations

The citations can reflect the degree of connection and structural relationship between the papers (Fig. 9), which helps to evaluate the contribution of a single paper to the entire field of BC for soil carbon sequestration and mitigation (Chuang et al., 2007; Fetscherin and Heinrich, 2015). The three most highly cited papers are "BC effects on soil biota - A review" (Lehmann et al., 2011), "BC as a sorbent for contaminant management in soil and water: A review" (Ahmad et al., 2014), and "Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (BC)" (Keiluweit et al., 2010) (Table 3). These three papers laid an important foundation and pointed out the future research direction for BC from the perspective of microorganisms, soil and water adsorbent, and aromatic carbon, respectively.

The HI means that there are h papers that have each been cited at least h times, which excludes academic spammers. Greater scientific achievement is typically indicated by a higher H index value (Costas and Bordons, 2007; Hirsch and Buela-Casal, 2014). It can be seen that Johannes Lehmann, Dinesh Mohan, and Kwong Yin Chan have a higher H index value in the ranking, indicating that they have great academic influence and that most of the publications are not only highly cited but also of high quality. Among the top 10 papers with high citations, reviews account for 60 %. These reviews often explore the basic or hot issues of BC for soil carbon sequestration and mitigation, with comprehensive content, thorough analysis, and strong conclusions. For example, Mohan et al. (2014) summarized the adsorption capacity of

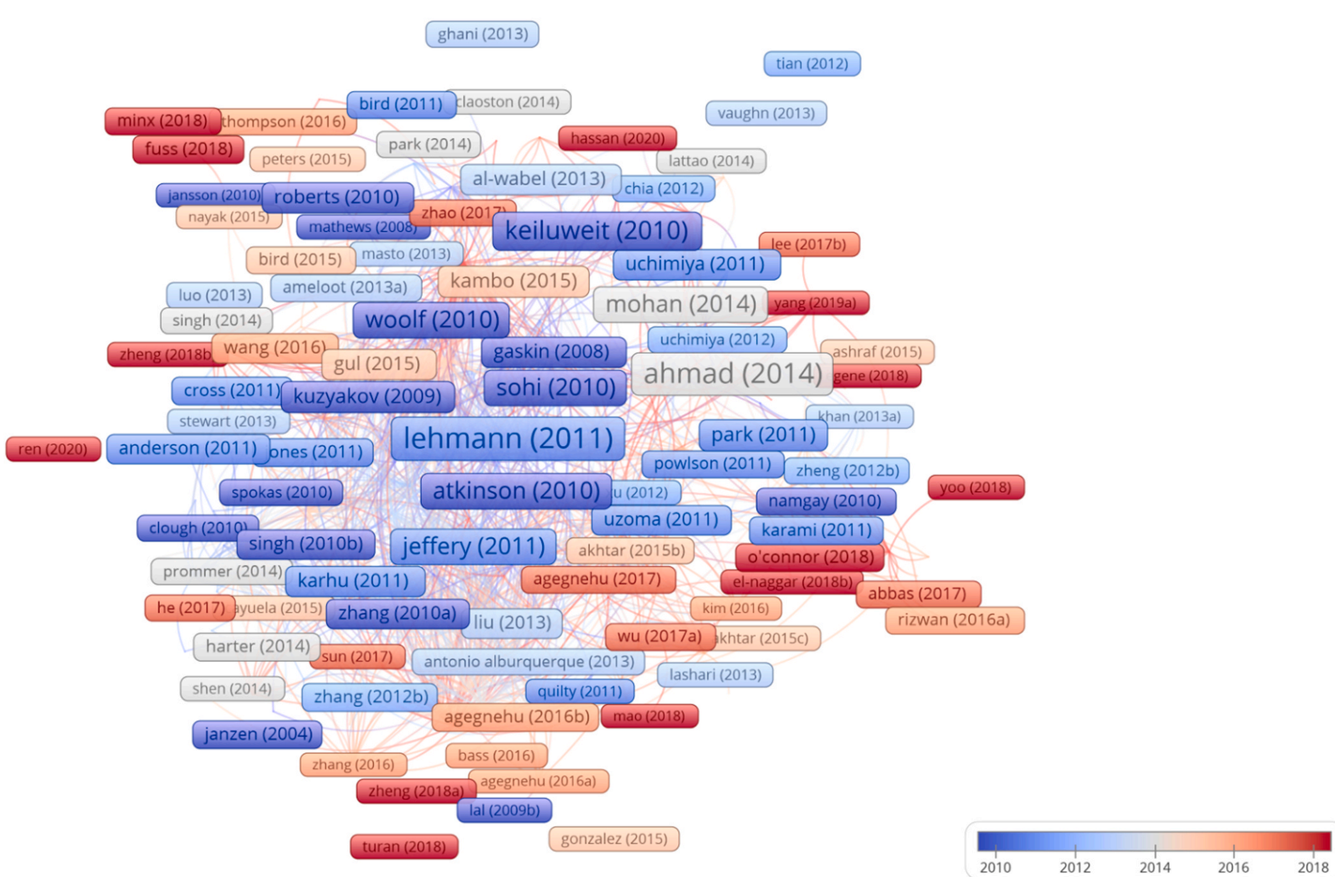

Fig. 9. Network analysis of the paper citations of BC for soil carbon sequestration and mitigation (color shades indicate the publication year of the paper).

Table 3
Top 10 papers with high citations of BC for soil carbon sequestration and mitigation.

Rank	Title	FA	PY	Journal	C	IF	HI	TC	TL
1	Biochar effects on soil biota - A review	Johannes Lehmann	2011	Soil Biology and Biochemistry	America	9.956	83	2627	446
2	Biochar as a sorbent for contaminant management in soil and water: A review	Mahtab Ahmad	2014	Chemosphere	Saudi Arabia	8.52	31	2375	135
3	Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	Marco Keiluweit	2010	Environmental Science and Technology	America	12.154	23	1778	136
4	Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review	Dinesh Mohan	2014	Bioresource Technology	India	11.139	66	1371	42
5	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis	Simon Jeffery	2011	Agriculture Ecosystems and Environment	UK	7.088	18	1306	298
6	Sustainable biochar to mitigate global climate change	Dominic Woolf	2010	Nature Communications	America	17.763	12	1301	226
7	Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review	Christopher John Atkinson	2010	Plant and Soil	UK	5.44	14	1292	265
8	A review of biochar and its use and function in soil	Saran Sohi	2010	Advances in Agronomy	UK	9.756	38	1269	238
9	Agronomic values of greenwaste biochar as a soil amendment	Kwong Yin Chan	2007	Australian Journal of Soil Research	China	2.179	41	1114	236
10	Bio-energy in the black	Johannes Lehmann	2007	Frontiers in Ecology and the Environment	America	15.827	83	1080	188

FA: first author. PY: publication year. C: country. IF: impact factor. HI: h index. TC: total citations. TL: total link.

different BCs for pollutants under different operating conditions and put forward some suggestions for further research. And in terms of the limitations of the study area, Atkinson et al. (2010) seek to ascertain how well the majority of empirical inferences from tropical regions can be transferred to temperate soils. Notably, Lehmann's team published two of the top 10 papers, demonstrating that they are significant originators in the BC field. There are eight highly cited papers among the top 10 focusing on the early research period (2001–2013), therefore it is conceivable that they contributed to the development of theories, concepts, and methodologies as well as the foundational ideas for the maturity of the BC field. According to Table 3, there was a connection between the most authoritative journals and the highly cited papers in the field of BC for soil carbon sequestration and mitigation. Additionally, the majority of publications with over 400 citations were published between 2009 and 2014. The quick emergence of highly cited publications suggested that BC-related research has steadily gained universal recognition and that this field has seen significant development.

By sorting out the top 20 highly cited papers in the BC field, the mainstream directions are clarified. In terms of research content, the most highly cited BC studies focus on the following aspects: (1) BC is an important carbon sink that can mitigate global climate change (Chmura et al., 2003; Lehmann, 2007a; Sohi et al., 2010; Woolf et al., 2010); (2) As a soil amendment, BC can improve soil fertility, crop yield, and agronomic quality (Jeffery et al., 2011; Biederman and Harpole, 2013; Major et al., 2010; Chan et al., 2007; Novak et al., 2009); (3) BC affects the composition and activity of microbial communities in soil (Lehmann et al., 2011; Warnock et al., 2007); (4) BC acts as a sorbent for soil and water, removing heavy metals, organic and inorganic pollutants (Ahmad et al., 2014; Mohan et al., 2014; Beesley et al., 2010; Park et al., 2011); (5) The characteristics of BC and assessment of aromatic carbon structure (Keiluweit et al., 2010; Kambo and Dutta, 2015); (6) BC's stability in soil and the priming effect brought by positive and negative carbon mineralization (Zimmerman et al., 2011; Kuzyakov et al., 2009); (7) BC can change soil physiochemical properties (Atkinson et al., 2010).

3.7. Network analysis of journal coupling and co-citations

The most significant sources and indicators of scientific outputs are journals. The primary focus and research importance of this field can be identified by analyzing the distribution of journals. From 2001–2020, all research results connected to BC have been published in 502 different journals (Fig. S4). Based on the total link strength ranking, the top 10 journals of BC for soil carbon sequestration and mitigation are listed in Table 4. Among them, the top 5 journals are Science of the Total Environment, Global Change Biology Bioenergy, Soil Biology and Biochemistry, Geoderma, and Agriculture Ecosystems and Environment, respectively. The co-citation analysis of the journals shows that Soil Biology and Biochemistry is the No.1 journal in the field of BC for soil carbon sequestration and mitigation (Fig. S5). A great number of papers published in this journal further prove the significance of BC for soil carbon sequestration and mitigation. In addition to Lehmann et al. (2011), Soil Biology and Biochemistry also has a highly cited article: Zimmerman et al. (2011). They found that BC-soil interactions enhance soil carbon storage through the process of organic matter adsorption to BC and physical protection in the long run. It can be seen that Soil Biology and Biochemistry focuses on the mechanism and application of BC on microorganisms.

The coupling analysis of journals shows which journals are the papers mainly published in, and the co-citation analysis of journals shows which journals have a higher co-citation intensity (Vogel, 2012; Wang

Table 4
Top 10 journals with the high coupling of BC for soil carbon sequestration and mitigation.

Rank	Journal	IF	NP	TC	APY	TL	TLS	CPP
1	Science of the Total Environment	10.237	294	14514	2018.20	491	947107	49.37
2	Global Change Biology Bioenergy	6.293	74	5933	2016.34	483	436347	80.18
3	Soil Biology and Biochemistry	9.956	99	14014	2015.16	483	433212	141.56
4	Geoderma	7.444	92	6687	2017.32	487	408547	72.68
5	Agriculture Ecosystems and Environment	7.088	77	8781	2015.58	482	383881	114.04
6	Journal of Soils and Sediments	3.821	96	3670	2017.63	487	366597	38.23
7	Environmental Science and Pollution Research	5.053	153	4648	22018.01	489	364302	30.38
8	Chemosphere	8.520	132	10232	2017.30	486	361559	77.52
9	Journal of Environmental Management	8.549	112	5329	2017.76	489	323430	47.58
10	Plant and Soil	5.440	58	9029	2014.48	480	300387	155.67

IF: impact factor. NP: the number of papers. TC: total citations. APY: average publication year. TL: total link. TLS: total link strength. CPP: citations per paper.

et al., 2011). In the journal coupling analysis, Science of the Total Environment, Environmental Science and Pollution Research, and Chemosphere are the mainly published journals in the BC field (Fig. S4). And highly cited journals are Science of the Total Environment, Soil Biology and Biochemistry, and Chemosphere. It also can be seen that the number of publications of Science of the Total Environment exceeds that of Soil Biology and Biochemistry, but the total citations of the two are relatively close. In the network analysis of journal co-citations, the co-citation intensity of Soil Biology and Biochemistry is much higher than that of Science of the Total Environment, indicating that papers published in Soil Biology and Biochemistry are more easily cited to some extent. Notably, the relationship reflected by journal co-citation is changing or temporary, while coupling reflects a fixed long-term relationship between journals (Muessigmann et al., 2020). Future research should be based on highly cited papers in mainstream journals and adopt multiple perspectives to address the problem in the field of BC for soil carbon sequestration and mitigation.

According to correlation analysis, the total citations and impact factor are closely associated, with a correlation coefficient of $r = 0.795$. On the other hand, the total link strength of journal coupling is moderately associated with total citations ($r = 0.610$) and impact factor ($r = 0.543$). In Table S3, the total link strength of journal co-citations is highly correlated with total co-citations ($r = 0.979$) and moderately correlated with impact factor ($r = 0.551$). Thus, priority can be given to increasing the total citations and the total link strength of co-citations for any journal to enhance its impact factor. From the indicator of COPP, we found that in the BC field, papers published in Soil Biology and Biochemistry, Environmental Science and Technology, Plant and Soil, and Bioresource Technology are more likely to be co-cited, indicating that these journals are more influential, generally recognized, and interconnected. And the primary active journals with the largest total citations are mostly focused on the impacts of BC on climate change and microbial communities or activities in soils.

Soil Biology and Biochemistry is the biggest node, followed by Chemosphere, which means that they are the reputable journals that researchers frequently cite (Fig. S5). However, because the above two journals have different research focuses, their reference points for studies connected to BC are distinct. Soil Biology and Biochemistry is primarily concerned with and explains the biological processes that occur in BC-applied soil, while Chemosphere favors the application of BC on the environment and human health. Regarding the co-citation intensity, the connection between Soil Biology and Biochemistry and Plant and Soil is the closest. Additionally, Soil Biology and Biochemistry and Agriculture Ecosystems and Environment's link line is the second-largest, followed by Environmental Science and Technology and Chemosphere. The journal coupling and co-citation relationships clearly show that journals of the soil biology and environmental science type can measure the development process of the field of BC for soil carbon sequestration and mitigation.

3.8. The relationship between the use of BC and climate change

Agricultural soils are the most important carbon pools on the Earth's surface and a source or sink of GHGs. The carbon cycle is one of the crucial biogeochemical processes in agroecosystems, which is a major contributor to climate change. When the cycle is disrupted, it can cause the air temperature to rise or fall. The relationship between the carbon cycle and climate change is complex, and it is influenced by both biotic and abiotic factors. These factors driving the carbon cycle vary over time and between soil types (Yu et al., 2020). The carbon cycle requires microorganisms' participation in many important carbon cycle pathways, such as carbon fixation and carbon degradation. Zhou et al. (2012) concluded that microorganisms played a key role in regulating soil carbon dynamics and that elucidating microbial-mediated feedbacks was essential for understanding ecosystem responses to climate warming. In addition, abiotic factors include soil physical and chemical properties, plant factors, and climate conditions, which are central to shaping the functional genetic structure associated with the carbon cycle. Luo et al. (2021) found the importance of abiotic factors in the carbon cycle through pathway analysis. Therefore, the involvement of BC in the carbon cycle in soils as an external carbon source may have profound feedback effects on global climate change (Fig. 10).

BC can increase the net primary productivity of crops and can lead to a greater transfer of carbon to the soil carbon pool where it can be stored over time. At the same time, BC act as the negative feedback to the rise in atmospheric CO_2. What's more, Sarma et al. (2018) found that the application of BC produced a more stable carbon fraction, which may be influenced by microbial, soil aggregate turnover and organic matter-mineral interactions, with more conversion of the labile soil carbon pool to the stable soil carbon pool. The production of BC also results in the release of CO_2 into the atmosphere, however, the overall net effect of using BC is thought to be positive concerning climate change according to several meta-analyses (He et al., 2017; Liu et al., 2019a; Zhang et al., 2020). Therefore, soil properties, land use types, agricultural practices, and characteristics of BC should be considered when assessing the actual potential of BC to mitigate climate change (Liu et al., 2016). Lehmann (2007b) proposed that BC was more stable relative to biomass return and could result in a net carbon sink of up to 20 % when applied to the soil. Thus, the application of BC can replace straw and other biomass. Currently, research is being conducted to determine the most effective applications and strategies for the application of BC, which has emerged as a valuable carbon sequestration technology for climate change mitigation.

4. Conclusion and outlook

At present, BC for soil carbon sequestration and mitigation has attracted extensive attention. China and America are the two countries with the largest number of publications, followed by Australia, Germany, and Pakistan. China has the largest number of publications and total citations, but its international impact is lower than that of America, Australia, and Korea. The Chinese Academy of Sciences has the most

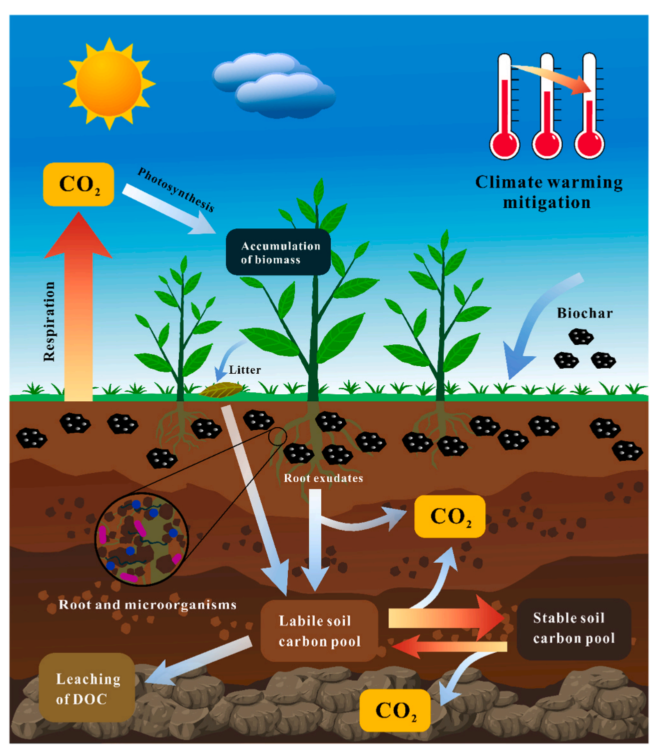

Fig. 10. The application of BC has a significant impact on climate change.

extensive cooperation with other institutions, followed by the University of Agriculture Faisalabad, Zhejiang Agriculture and Forestry University, Korea University, and Newcastle University. Yong Sik Ok, Johannes Lehmann, and Stephen Joseph rank are the top 3 highly productive authors. Yong Sik Ok, Johannes Lehmann, Daniel C.W. Tsang, and Pan Genxing are recognized as the highly cited authors in the field of BC for soil carbon sequestration and mitigation based on HI and CPP indicators.

Research hotspots are divided into 5 clusters: (1) the pyrolysis of feedstock, nutrient leaching, and microbial community; (2) the immobilization of heavy metals and phytoremediation by BC; (3) crop yield and growth, soil physicochemical and biological indexes; (4) GHGs mitigation, meta-analysis, and field experiment; (5) various soil carbon fractions, different types of BC, and soil carbon sequestration. The cumulative distribution of keyword frequency shows that these keywords including soil microbial biomass, SOM, nitrogen, and carbon sequestration are the first to reach a higher research interest. In recent years, BC has been used as a soil amendment in the field of nitrogen cycling and soil microorganisms. Among the top 10 highly cited papers, reviews accounted for 60 %, which frequently explore the fundamental or hot issues of BC for soil carbon sequestration and mitigation, with detailed content, thorough analysis, strong conclusions, and wide audiences. The highly cited journals are Science of the Total Environment, Soil Biology and Biochemistry, and Chemosphere. Science of the Total Environment has the largest number of publications and total citations, but papers published in Soil Biology and Biochemistry are more likely to be cited. From the COPP indicator, papers published in Soil Biology and Biochemistry, Environmental Science and Technology, Plant and Soil, and Bioresource Technology are more likely to be co-cited, indicating that these journals are more influential, generally recognized, and interconnected. Soil biology and environmental science journals can measure the development of the field of BC for soil carbon sequestration and mitigation. Currently, considering the BC field is in a period of rapid development, future research should be based on the highly cited papers in mainstream journals, combine various research methods and perspectives, and actively explore the following questions: (1) The interaction mechanisms between BC, soil, and soil microbial communities. (2) Designing low-cost, high-yield, and high-effect optimization methods to improve the characteristics of BC. (3) Effect of BC on the environment and human health in long-term localization experiments. (4) Carbon sinks of BC need to be further evaluated on a global scale. The above future roadmap could be a big step toward “Carbon neutrality”.

CRediT authorship contribution statement

Study conception and design: Tongkun Zhang, Jianzhong Cheng, Xinqing Lee; Acquisition of data: Tongkun Zhang, Jianzhong Cheng; Analysis and interpretation of data: Tongkun Zhang, Jianzhong Cheng, Xinqing Lee; Drafting of manuscript: Tongkun Zhang; Critical revision: Tongkun Zhang, Yuan Tang, Huan Li, Wei Hu, Jianzhong Cheng, Xinqing Lee.

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2023.115438.

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