Environmental Science and Pollution Research (2023) 30:83071–83092
https://doi.org/10.1007/s11356-023-27992-1

REVIEW ARTICLE

Quantitative analysis of the current status and research trends of biochar research - A scientific bibliometric analysis based on global research achievements from 2003 to 2023

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Received: 21 December 2022 / Accepted: 25 May 2023 / Published online: 20 June 2023

Abstract

Biochar has excellent physical and chemical properties such as porosity, high carbon content, high cation exchange capacity, and rich surface functional groups and has been widely used in environmental remediation. Over the past 20 years, although various reviews have described the application of biochar as an environmentally friendly multifunctional material in environmental remediation, no comprehensive summary and analysis of the research trends in this field exists. To promote the rapid and stable development of the field of biochar, the current state of research on biochar is clarified using the bibliometric method in this report, and potential development directions and challenges for the future are identified. All relevant biochar literature from 2003–2023 was collected from the Chinese National Knowledge Infrastructure and Web of Science Core Collection. A total of 6,119 published Chinese papers and 25,174 English papers were selected for the quantitative analysis. CiteSpace, VOSviewer, and Scimago graphics software was used to summarize the numbers of papers published over the years, as well as the countries, institutions, and authors that published the most articles. Secondly, using keyword co-occurrence and emergence analysis, the recognized research hotspots in different areas such as adsorbents, soil remediation, catalytic oxidation, supercapacitors, and "biochar-microbial" synergy were analyzed. Finally, the prospects and challenges of biochar were assessed to provide new perspectives for further promoting its development in technological, economic, environmental, and other aspects.

Keywords Biochar · Applications · Bibliometrics · CiteSpace · VOSviewer · Research hotspots · Research trends

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Introduction

Biochar is a low-cost, renewable, and sustainable multifunctional biomaterial that has attracted the attention of the scientific community wordwide (Amalina et al. 2022; Gwenzi et al. 2020). Biochar is a carbon-rich, porous solid product formed by thermal cracking of biomass materials in an oxygen-limited or oxygen-free atmosphere at a temperature of 300–900 °C (Farah et al. 2022). It has excellent physicochemical properties, such as large specific surface area, rich functional groups, and strong cation exchange capacity (Yang et al. 2021a; Godlewska et al. 2021). Biomass materials used for biochar preparation have various sources, which can be divided into three categories, namely plant, animal, and municipal waste. Table 1 shows different raw materials used to prepare biochar.

Biochar is an environmentally friendly material, with respect to both environmentally protection and sustainable development. This is because 1) biochar preparation can

Table 1 Raw materials of biochar.

Category	Biochar raw material	Reference
Plant source	Rice husk	Zeidabadi et al. 2018
	Bagasse	
	Wattle bark	Nguyen et al. 2021
	Corn straw	Das et al. 2021
	Pine needle	
	Corncob	Vu et al. 2017
	Miscanthus straw pellets	Shen et al. 2018b
	Rice husk	Yi et al. 2016
	Wood chip	
	Pine needles	Das et al. 2021
Animal source	Whole frozen livestock carcasses	Lei et al. 2018
	Air-dried cattle, swine, and Poultry manures	
	Lobster shell	Ma et al. 2021
	Chicken manure	Gui et al. 2020
	Pig manure	
	Cow manure	
Municipal waste	Food waste	Hu et al. 2022; Patra et al. 2021
	Sewage sludge	Shen et al. 2018a; Huang et al. 2020
	Iron loaded sludge	Wei et al. 2019
	Municipal solid waste	Li et al. 2021a
	Municipal sludge	Yang et al. 2022b
	Paper mill sludge	

effectively reduce the damage to the environment caused by greenhouse gases and other polluting gases generated by waste biomass piling or open burning; and 2) use of biomass materials as the raw material for biochar can lead to full utilization of resources and promote the development of a circular economy (Zhou et al. 2021b; Saletnik et al. 2019). According to the available literature, biochar can adsorb organic and inorganic pollutants present in aqueous solutions and soil (Islam et al. 2021), it can be used as a soil additive to effectively retain nutrients in the soil while having the ability to add water (Molnar et al. 2016); it can be used as a substrate for slow-release fertilizers (Marcinczyk and Oleszczuk 2022), and it can also increase the photosynthetic rate of plants (Gao et al. 2021). Moreover, it can be used as a catalyst or catalyst carrier for the production of biofuels from biomass (Gholizadeh et al. 2021; Yao et al. 2016). Although various reviews and research have described the application of biochar as an environmentally friendly multifunctional material in environmental remediation. No comprehensive summary and analysis of the research trends in this field exists. Thus, it is necessary to conduct a comprehensive quantitative analysis of biochar research through scientific methods.

Bibliometrics is an efficient method for summarizing and analyzing the current status of research in a discipline and predicting its development trends. It assesses the trends and hotspots of a discipline through the relationship between the information distribution of journals, research institutions, countries of publication, author groups, and keywords (Mao et al. 2018; Pauna et al. 2019). Recently, bibliometrics has been widely used to analyze the status and prospects of research in different fields. Example articles include "Research on biomass energy and environment from the past to the future: A bibliometric analysis" (Mao et al. 2018), "Bibliometric research on environmental, social and governance research using CiteSpace" (Zhao et al. 2023),"Knowledge Mapping of bioeconomy: A bibliometric analysis" (Wei et al. 2022), "Thirty years of research on physical activity, mental health and well-being: A scientometric analysis of hotspots and trends" (Sabe et al. 2022), and "COVID-19 and the emerging research trends in environmental studies: a bibliometric evaluation" (Usman and Ho 2021).

Therefore, we conducted a detailed and comprehensive analysis of research hotspots and trends in biochar applications using a bibliometric approach. Firstly, a search was conducted over the time span from 2003 to 2023 to observe the annual growth of all articles worldwide, the fund distribution, and the most influential journals, authors, countries, and institutions in publications for bibliometric analysis. The presentation of these findings in this article is followed by a detailed description and example discussion of highly cited papers and research hotspots. In the Chinese National Knowledge Infrastructure (CNKI) and Web of Science (WOS) databases, the first research published on biochar addressed its use as a link in the sewage treatment process and its application in activated carbon precursors, respectively. The 20-year period was divided into four periods for specific analysis: from 2003 to 2011, from 2012 to 2020, from 2020 to Oct. 2022, and from Oct. 2022 to Feb. 2023. Publications corresponding to the last period (Oct. 2022 to Feb. 2023) were analyzed separately to understand recent research developments. Finally, we identified the future trends and challenges faced by biochar application research. This report makes the following three contributions. (1) It fills the gap in biochar research analysis from a bibliometric perspective. By visualizing the knowledge mapping tool, the research contents in the field of biochar can be sorted out. (2) It provides a visualization and analysis of the papers in biochar research, major carrier journals, issuing countries, issuing institutions, keyword frequencies, and highly cited papers to reveal the research hotspots and challenges faced in this field. (3) It makes scientific and objective predictions regarding the research directions in this field and provides references and insights for future biochar-related research.

Data sources and analysis methods

Data sources and export methods

Selection of databases

Currently, data collection is mainly conducted with the help of literature databases, adopting a literature search strategy. There is some variability between the formats of different databases, and the data structure of WOS is the most complete. WOS is the core database of global academic information and includes data obtained from many authoritative and high-impact academic journals around the world (Olosutean and Cerciu 2022). According to the analysis of this database, China is the country with the most biochar research papers. Therefore, we also selected the CNKI database (an authoritative online academic search platform in China that provides access to most Chinese scientific publications) to analyze and compare the current status and hotspots of biochar research in China and internationally (Yi et al. 2017). Usually, the collected literature data will contain the PT literature type, AR-Author, SO-Journal, DE-Keyword, AB-Abstract, CL-Institution, and CR-Reference. It should be noted that the data downloaded from CNKI do not have reference information.

Data retrieval

An advanced search in the CNKI database was performed as follows: Subject = [biochar] OR Keyword = [biochar] OR Abstract = [biochar] OR Title = [biochar]. The source categories used were SCI source journals, EI source journals, Chinese core journals, and the Chinese Science Citation Database (CSCD). An advanced search in the WOS database was performed as follows: TS = (biochar) OR TI = (biochar) OR AB = (biochar) OR KP = (biochar), and the literature type was selected as "Article" or "Review." The WOS Core Collection database revealed that "biochar" first appeared in a manuscript in 2003, which was selected as the starting point for the analysis. The data were retrieved on Mar. 17, 2023.

Data filtering and de-duplication

Between 2003 and Feb. 2023, we retrieved 6511 Chinese articles and 25,809 English articles, which were manually screened to remove duplicates and irrelevant literature. Finally, 6119 Chinese articles and 25,174 English articles (25,174 including raw data and supplementary data) were determined to be classified as valid data. The CNKI data were exported in "RefWorks" format, and the WOS data were exported in plain text format as "full records with cited references." The downloaded literature was renamed to a format that the analysis software could recognize as the basis for data analysis.

Analysis methods

Software function distinction

We used CiteSpace (6.1. R3) and VOSviewer (1.6.18) software to analyze trends in the number of publications, subject area distribution, journal publishing, institutions and countries publishing, and author groups to understand the current status and hotspot distribution of global research on biochar. CiteSpace is a statistical analysis tool based on the Java environment that analyzes domain-specific software by building visual graphs (Mao et al. 2018). In this study, the screened Chinese and English documents were imported into CiteSpace, the time zone was set as 2003–2023, the time slice was set as 1 year, the "Node type" was set as "Keyword" for clustering analysis, the "Pruning sliced networks" were selected as the clipping connection method, and the "Show merged network" was adopted to present the complete analysis map of the screened data. VOSviewer is a free computer program used to build and view bibliometric maps (Van and Waltman 2010). Keyword frequency analysis was often used to identify research hotspots and frontiers. Scimago Graphica (1.0.24) software was employed to visualize the author/country collaboration relationships.

Visual analysis description

The size of the nodes in the pictures obtained by visualization is proportional to the number of documents; the lines between the nodes represent the co-occurrence or co-citation relationship for both. The same color is considered as the same cooperative group. The circle size and font size and the distance between the location and the center point are positively correlated with the number of node occurrences. In the section on research hotspots (3.8), breakout time column Blue represents the timeline, red represent the breakout time.

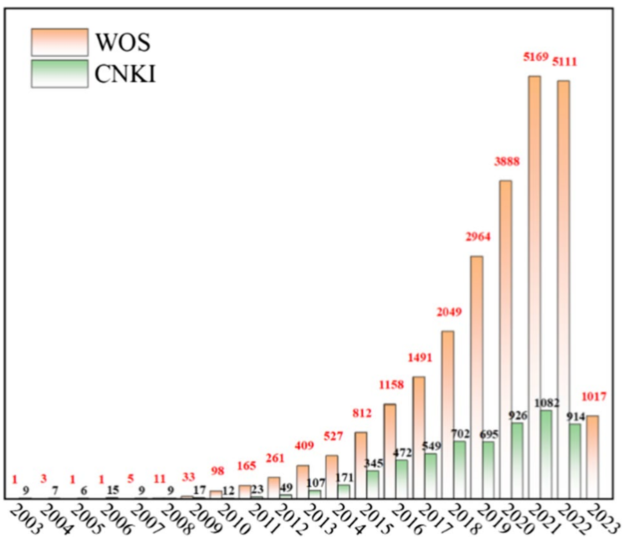


Fig. 1 Number of articles published per year from 2003 to 2023

Results and discussion

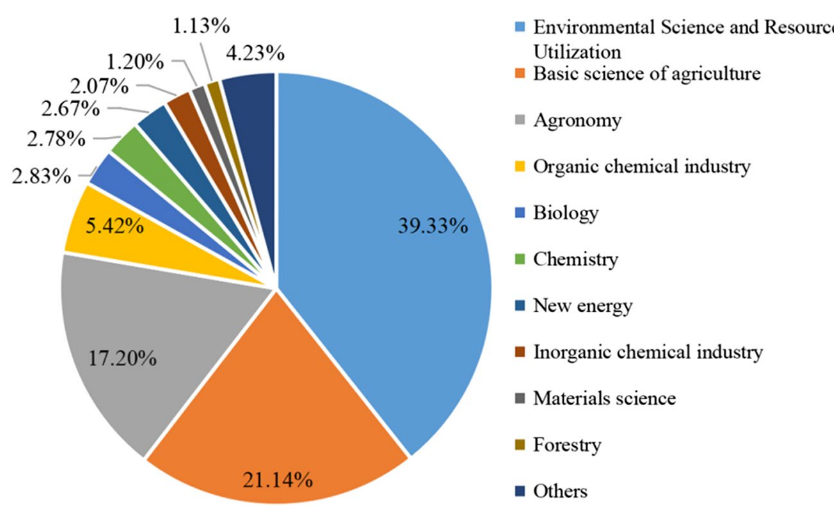
Publications and annual growth

The 23,374 articles published in 2003–Oct. 2022 consist of 21,771 research articles (93.2%) and 1,603 reviews (6.8%). These figures reveal a significant impact of the subject area on the global scientific community. The first study on the presence of biochar was published by Purevsuren et al. (2003). Figure 1 shows the number of articles published in the field of biochar between 2003 and 2023. The numbers of articles published on biochar between 2003 and 2011 in the CNKI and WOS databases demonstrate that research on biochar was in its initial stage, and the number of papers was small. Since 2012, the numbers of papers published on the topic in both databases have shown steady and rapid growth. The number of articles in English is growing at a faster rate than that of those in Chinese. However, similar trends are observed for both databases, which indicates a growing interest in biochar.

Subject area distribution

According to the CNKI database, the journals published 6,119 articles from 2003 to 2021. Figure 2 and 3 show the distribution of subject area on biochar in the CNKI and WOS databases. In the CNKI database, 6,119 articles from 2003 to 2022 were distributed in the following subject areas: Environmental Science and Resource Development; Basic agricultural science; Chemistry and New energy. Among them, Environmental Science and Resource Development accounted for the largest proportion (39.33%). In the WOS database, 23,374 articles from 2003 to 2022 were distributed in the following subject areas: Environmental Science, Energy and Fuel, Engineering Chemistry, Engineering

Fig. 2 Distribution map of main disciplines of biochar articles in CNKI database



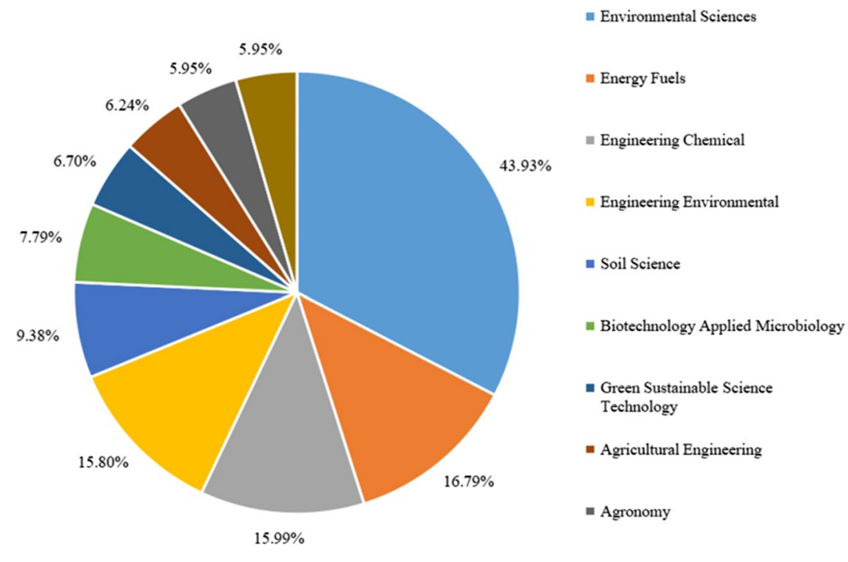


Fig. 3 Distribution map of main disciplines of biochar articles in WOS database

Environment and Soil Science. In the WOS database, certain articles more than one subject area; thus, the percentage sum was greater than one in the subject analysis. Results based on both databases revealed that research on biochar has been strongly focused on Environmental Science. This is achieved using the biochar produced by the pyrolysis of waste biomass as an absorption material (Yi et al. 2020), which has the following main advantages: (1) it can reduce the environmental impact caused by waste disposal, (2) it realizes the sustainable use of resources, and (3) the obtained biochar is an environmental-friendly material with excellent properties for environmental remediation.

Journals

The data that were exported from the CNKI database did not include journal titles; thus, the data could not be analyzed using CiteSpace. Information on journals that published articles on biochar and were included in the CNKI database was obtained from the CNKI website. The top 10 journals in the CNKI database in terms of the number of articles published are listed in Table 2. *Environmental Science* published the maximum number of articles on biochar research as per the data retrieved from the CNKI database (226 articles). Analysis of the WOS database using CiteSpace elucidated that 1,357 journals published articles on biochar research. Table 3 shows the top 10 journals with the highest number of articles in the WOS database on biochar research. *Science of the Total Environment* published the highest number of articles on the topic in the WOS database, with a total of 1,368 publications. The review article titled "Adsorptive removal of antibiotics from water and wastewater: Progress and challenges" was the most cited article in this journal, with a total of 621 citations.

Table 2 Top 10 journals publishing biochar research at CNKI

Journal Name	Amount	Percent of total documents (%)
Environmental Science	226	3.69
Transactions of the Chinese Society of Agricultural Engineering	109	1.78
Transactions of the Chinese Society for Agricultural Machinery	70	1.14
Journal of Plant Nutrition and Fertilizers	67	1.09
Chinese Journal of Applied Ecology	48	0.78
Journal of Agricultural Science and Technology	33	0.54
Chinese Journal of Eco-Agriculture	32	0.52
Agricultural Research in the Arid Areas	28	0.46
Scientia Agricultura Sinica	27	0.44
Acta Pedologica Sinica	26	0.42

Table 3 Top 10 journals publishing biochar research at WOS.

Journal Name	Amount	Percent of total documents (%)
Science of the Total Environment	1368	5.85
Bioresource Technology	1110	4.75
Chemosphere	983	4.21
Environmental Science and Pollution Research	785	3.36
Journal of Hazardous Materials	635	2.72
Journal of Environmental Management	551	2.36
Chemical Engineering Journal	507	2.17
Environmental Pollution	491	2.10
Biomass Conversion Journal	411	1.76
Journal of Environmental Chemical Engineering	359	1.54

Authors

The authors of the articles published on biochar retrieved from both databases were analyzed using CiteSpace. As per the CNKI database, the main researchers of the topic are as follows: First, Haibo Meng from the Center of Energy and Environmental Protection, Academy of Agricultural Planning and Engineering MARA, Key Laboratory of Energy Resource Utilization from Agriculture Residue MADA has published 46 articles, representing 0.75% of all articles included in the CNKI database. He is mainly engaged in research on agricultural waste resource utilization technology and equipment and has made important achievements in straw pyrolysis, clean combustion, and waste composting technology and equipment. Second, Lixin Zhao from the Institute of Agricultural Environment and Sustainable Development, Chinese Academy of Agricultural Sciences has published 46 articles, accounting for 0.75% of all articles included in the CNKI database. He is mainly engaged in the comprehensive utilization of crop straw and technology research and development. Third, Guoshun Liu from Henan Agricultural University has published 43 articles, accounting for 0.7% of all articles included in the CNKI database. He is mainly engaged in tobacco cultivation and other work. The aforementioned percentages were obtained by dividing the number of articles exported from the database. As per the CNKI database, the focus of research of these three authors was different and involved the following subject areas: New Energy, Basic Agricultural Sciences, Organic Chemicals, Fuel Chemicals, and Chemical Industry. This indicates that biochar research is in a state of diversification, and that biochar is a new material with greater development potential.

As per the WOS database, the main researchers of the topic are as follows: OK Yong Sik from Korea University, has published 358 articles, accounting for 1.53% of the 23,374 articles included in the WOS; Tsang Dan from Hong Kong Polytechnic University, has published 210 articles, accounting for 0.89% articles included in the WOS database; Gao Bin from the University of Florida, has published 180 articles, accounting for 0.77% of the 23,374 articles included in the WOS; Rinklebe Joerg from University of Wuppertal has published 138 articles, Wang Hailong from Foshan University has published 134 articles, Zeng Guangming from Hunan University has published 130 articles, and Kwon Eilhann E. from Hanyang University has published 101 articles. Figure 4 shows the co-occurrence map of the authors. The size and color of the circles in Fig. 5 represent the number of articles published by the authors, and the thickness and color of the middle curve represent the collaboration between the authors and the intensity of the relationship. OK Yong Sik and Tsang Dan were the closest collaborators, followed by Rinklebe Joerg and Vithanage Meththika. He appeared in several articles with the above authors.

Countries and institutions

VOSviewer and Scimago Graphica were used to analyze the countries where research on biochar was performed. However, because the articles retrieved from the CNKI database were from China, the countries analysis is only the WOS database. We observed that 147 countries/regions are currently investigation biochar, 89 of which have published ten or more articles on the topic. From 2003 to 2022, China has published the highest number of articles on biochar, with 11,416 publications, accounting for 48.48% of all publications; China is followed by the United States of America and India. The top 10 countries are listed in Table 4. Thus, China is the main force of research in the field of biochar. However, China's centrality was only 0.03. The highest centrality was observed in Germany at 0.15, which had the highest academic impact, and was followed by Australia. The analysis shows that 58 countries with fewer than 10 cumulative articles, accounted for 39.4% of these 147 countries. Figure 6 shows partnerships between some countries and intensity. China has cooperated with 107 countries/regions,

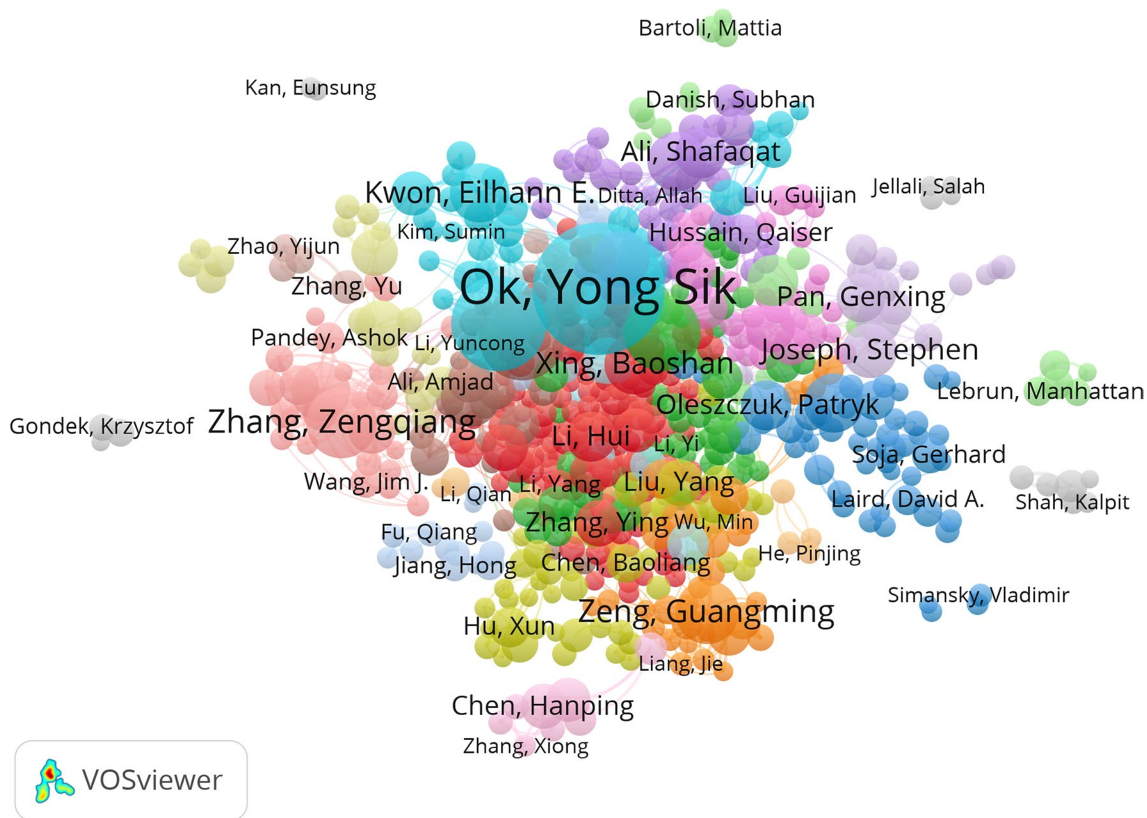


Fig. 4 Cooperation network of authors in the field of biochar (WOS)

Fig. 5 Author partnerships and intensity map (WOS)

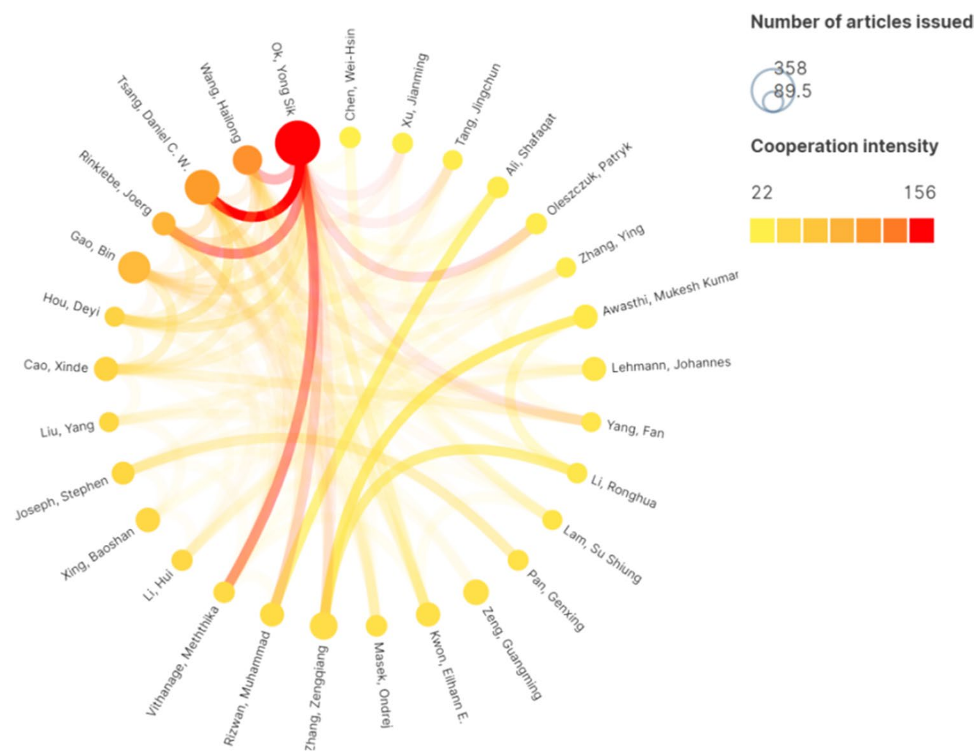


Table 4 Top 10 countries that published biochar research at WOS

Country	Count	Percent of total documents (%)	Centrality
China	11416	48.84	0.03
USA	3256	13.93	0.10
India	1453	6.22	0.04
Australia	1385	5.93	0.11
South Korea	1167	4.99	0.04
Pakistan	989	4.23	0.04
Germany	923	3.95	0.15
Canada	900	3.85	0.04
Brazil	732	3.13	0.04
Spain	693	2.96	0.10

with cooperation with the United States of America being the strongest.

CiteSpace was used to analyze the issuing institutions of the articles retrieved from the CNKI and WOS databases. Table 5 shows the top 10 Chinese institutions in terms of the number of articles published. The University of Chinese Academy of Sciences is the institution that publishes the most articles on biochar, with 111 articles, accounting for 1.81% of the 6,119 articles included in the CNKI articles. It hads a centrality of 0.17, which was the highest in the data retrieved from the CNKI database.

In total, 900 institutions worldwide have conducted biochar research and their articles were included in the WOS database. The top 10 institutions are listed in Table 6. Seven of these institutions are from China, one from the United States, one from South Korea and the other from Saudi Arabia. The Chinese Academy of Sciences has published 1,439 articles, making it the institution with the highest number of published articles. The first article on biochar research included in the WOS database was published in 2009, which is later than the first article on the topic in the CNKI database; however, since 2017, the number of articles has increased rapidly. High academic status and influence on biochar research.

Moreover, in both the CNKI and the WOS databases, the intensity of cooperation between countries/institutions that had published papers on the topic is low and the network of cooperation is loose. International and inter-institutional cooperation should be strengthened in future biochar research.

Citation analysis

The data exported from the CNKI database did not contain references; therefore, the highly cited literature could not be analyzed using CiteSpace software. Therefore, the data exported from the WOS database was analyzed to assess the number of possible citations (Sorensen and Jovanovic 2021). A total of 23,374 publications were cited 685,672 times, with an average of 29.3 citations per article. Moreover, the highest number of citations was observed in 2020, with a cumulative total of 50,484 citations.

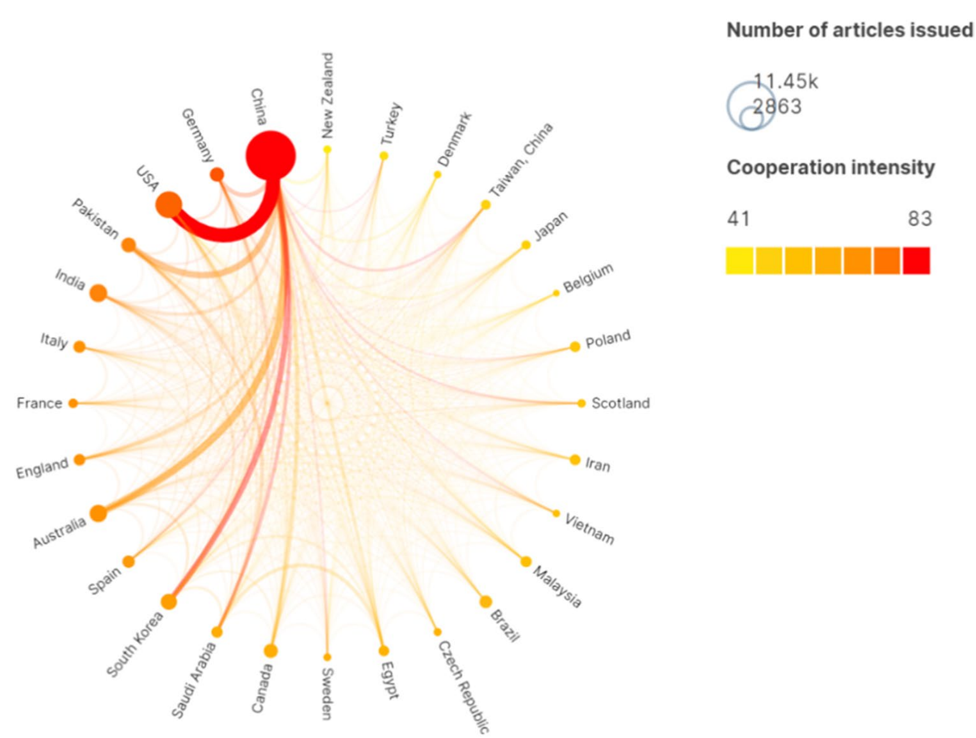


Fig. 6 Map of the intensity of cooperation in partial countries.

Table 5 Top 10 institutions publishing biochar research at CNKI

Institution	Count	Percent of total documents (%)	Centrality
University of Chinese Academy of Sciences	111	1.81	0.17
College of Natural Resources and Environment, Northwest Sci-Tech University	87	1.42	0.12
College of Environmental Science and Engineering, Kunming University of Science and Technology	66	1.08	0.02
College of Resources and Environment, Southwest University	57	0.93	0.00
College of Environmental and Municipal Engineering, Lanzhou Jiaotong University	53	0.87	0.01
College of Resources and Environment, Yunnan Agricultural University	42	0.69	0.01
College of Resources and Environment, Northeast Agricultural University	42	0.69	0.03
Institute of Environment and Sustainable Development in Agriculture	41	0.67	0.01
College of Resource and Environment, Hunan Agricultural University	38	0.62	0.04
College of Nature Resources and Environment, South China Agricultural University	36	0.59	0.02

Table 6 Top 10 institutions publishing biochar research at WOS

Institution	Country	Count	Percent of total documents (%)	Centrality
Chinese Academy of Science	China	1439	6.16	0.12
Zhejiang University	China	522	2.23	0.03
University of Chinese Academy of Sciences	China	513	2.19	0.01
Northwest A&F University	China	407	1.74	0.03
Nanjing Agricultural University	China	342	1.46	0.03
University of Florida	USA	326	1.39	0.06
Korea University	South Korea	315	1.35	0.04
China Agricultural University	China	306	1.31	0.01
Chinese Academy of Agricultural Sciences	China	298	1.27	0.02
King Saud University	Kingdom of Saudi Arabia	281	1.20	0.04

Table 7 shows the CiteSpace (6.1.R3) and the WOS search function to obtain the top 10 most-cited articles. These ten articles include both research and review article and have a high academic impact worldwide. They were centrally published around 2010–2011. The review papers include the following topic: biochar as a soil amendment; biochar as a sorbent for pollutant management in soil and water; potential mechanisms for biochar to realize agricultural benefits; and research progress on biochar preparation, modification, and environmental applications. Woolf et al. (2010) explored the role of biochar in global climate mitigation; their experimental stuides focused on the effect of different temperatures on the preparation of biochar.

The most frequently cited paper is the review article "Biochar effects on soil biota - A review" published by Lehmann J et al. in 2011, with a total of 2,671 citations. This article systematically summarizes the effects of biochar adding to soil on plant root behavior. This study provides a theoretical basis for future research on biochar. The second most frequently cited article, "Biochar as a sorbent for contaminant management in soil and water: A review" by Ahmad et al. (2014) was cited 2,416 times; it reviewed the application of biochar as a sorbent in soil and water pollution management. Moreover, it has been argued that biochar application will provide a method for carbon sequestration and mitigate climate change. The third most frequently cited article, "Dynamic molecular structure of plant biomass-derived black carbon (Biochar)" by Keiluweit et al. (2010) has 1,803 citations; it used physical and chemical data of biochar to develop an integrated model to understand the physical properties of plant biochar at different temperatures.

Table 7 Top 10 articles with the most citations for biochar research at WOS

Title	First Author	Journal name	Publication Year	Total Citations	Reference
Biochar effects on soil biota - A review	Lehmann Johannes	*Soil Biology and Biochemistry*	2011	2671	Lehmann et al. 2011
Biochar as a sorbent for contaminant management in soil and water: A review	Ahmad Mahtab	*Chemosphere*	2013	2416	Ahmad et al. 2014
Dynamic Molecular Structure of Plant Biomass - Derived Black Carbon (Biochar)	Keiluweit Marco	*Environmental Science & Technology*	2010	1803	Keiluweit et al. 2010
Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - A critical review	Mohan Dinesh	*Bioresource Technology*	2014	1387	Mohan et al. 2014
A quantitative review of the effects of biochar application to soils on crop productivity using meta - analysis	Jeffery S.	*Agriculture, Ecosystems & Environment*	2011	1328	Jeffery et al. 2011
Sustainable biochar to mitigate global climate change	Woolf Dominic	*Nature Communications*	2010	1323	Woolf et al. 2010
Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review	Atkinson Christopher J.	*Plant and Soil*	2010	1307	Atkinson et al. 2010
A Review of Biochar and Its Use and Function in Soil	Sohi S. P.	*Advances in Agronomy*	2010	1285	Sohi et al. 2010
Preparation, modification and environmental application of biochar: A review	Wang Jianlong	*Journal of Cleaner Production*	2019	1244	Wang and Wang 2019
The forms of alkalis in the biochar produced from crop residues at different temperatures	Yuan JinHua	*Bioresource Technology*	2011	1125	Yuan et al. 2011

Keyword analysis

We used CiteSpace to analyze keywords frequency, centrality and clustering. We used VOSviewer to visualize the results. Figure 7 shows the co-occurrence of keywords in various articles on biochar in the WOS database. Keywords in the CNKI and WOS databases were analyzed using CiteSpace.

Keyword frequency analysis

Keywords reflect the core areas of research, and their importance can be assessed by their frequency and centrality. If the centrality of a keyword is larger than those of the other keywords, then the keyword is more important in the research field. The 10 most frequent keywords in the field of biochar are listed in Table 8. In the CNIKI database, 205 keywords appeared more than 10 times and 15 keywords appeared more than 100 times. In the WOS database, 311 keywords appeared more than 100 times and 28 keywords appeared more than 1,000 times. The frequencies of the keywords revealed that the main focus of the research is on biochar as an adsorbent material. In the WOS database, the applications adsorbents mainly focus on aqueous solutions. The keywords with centrality over 0.1 are "biochar," "biomass carbon," "aqueous solution," "heavy metals," and "activated carbon."

Keyword clustering analysis

In order to clarify the affiliation of each keyword in the study, keyword clustering analysis was performed by CiteSpace, and the clustering labels that could not reasonably express the clustering results were removed from the clustered words to obtain the keyword co-occurrence clustering map. The

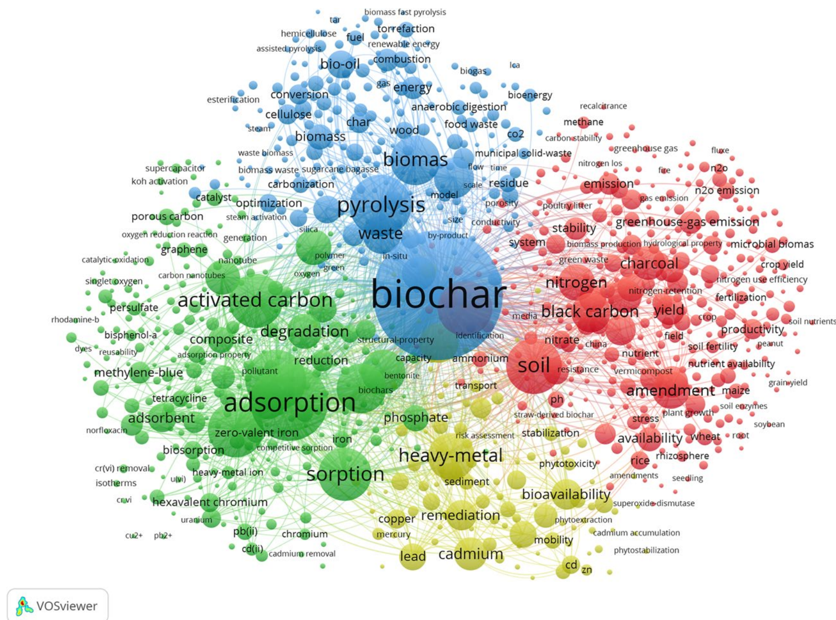


Fig. 7 Co-occurrence map of keywords published biochar studies at WOS

Table 8 Top 10 keywords of frequency in the field of biochar

CNKI database			WOS database		
Keywords	Frequency	Centrality	Keywords	Frequency	Centrality
Biochar	3419	1.01	Biochar	4594	0.10
Adsorption	781	0.07	Adsorption	3782	0.08
Heavy metals	360	0.07	Removal	3435	0.05
Soil	309	0.07	Aqueous solution	3025	0.14
Output	295	0.04	Heavy metals	2895	0.11
Biomass carbon	190	0.11	Activated carbon	2831	0.11
Pyrolysis	151	0.04	Carbon	2801	0.06
Straw	140	0.04	Sorption	2427	0.03
Biomass	135	0.07	Biomass	2408	0.09
Soil remediation	125	0.02	Water	2395	0.03

smaller the number after "#," the greater the number of keywords in that cluster and the better the clustering effect.

Keyword clustering of the CNKI database is shown in Fig. 8, which is as following: #0, adsorption; #1, biochar; #2, aqueous solution; #3, heavy metals; #4, organic compound; #5, physical and chemical properties; #6, environmental remediation. The WOS database keyword clustering is shown in Fig. 9, which is as following: #0, adsorption; #1, biochar; #2, soil; #3, aqueous solution; #4, organic material; #5, heavy metals; #6, modification; #7, mechanisms. It is easy to see that the major direction of biochar research is adsorption (Zhang et al. 2018). Biochar has been used as a catalyst and electrode material in recent years (Lyu et al. 2019; Lee et al. 2020).

These clusters can be devided into the following four categories: (1) Function: "biochar" and "adsorption". Biochar is a popular material with a wide range of applications. However adsorption by biochar is currently the mainstay of the research on this topic. (2) Object of adsorption: "soil" and "aqueous solution". Many studies have shown that biochar can be used to remove pollutants present in soil and aqueous solutions (Chi et al. 2017; Yang et al. 2022b). (3) Adsorbed substances: "heavy metals" and "organic matter". Biochar has been shown to adsorb heavy metal pollutants organic pollutants inorganic nitrogen and phosphate (Table 9). (4) Mechanism of action: "modification" and "mechanism". Biochar performance can be significantly improved by optimizing the biochar preparation process (Li et al. 2021a, b, c, d). High temperatures produce biochar with high surface area porosity pH and mineral content. These factors may improve the adsorption efficiency and other properties of biochar (Li et al. 2017). The adsorption mechanisms include physical adsorption ion exchange and surface

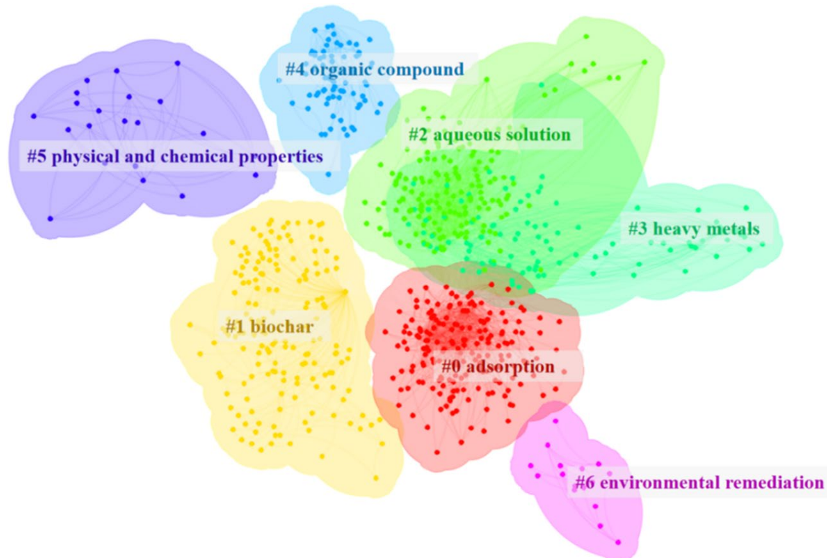


Fig. 8 Keyword clustering map of biochar studies at CNKI

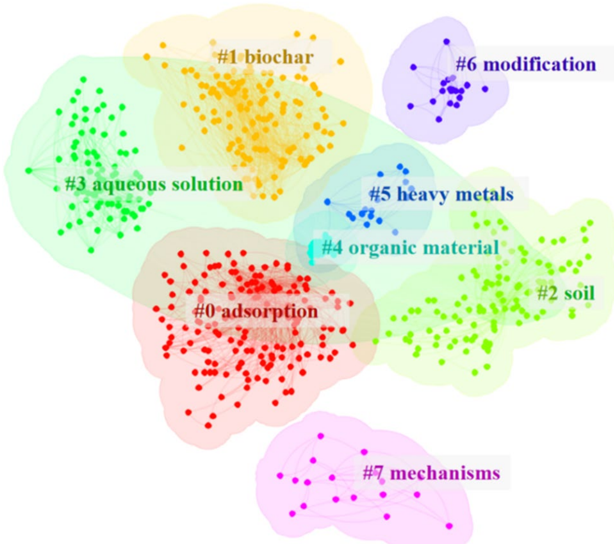


Fig. 9 Keyword clustering map of biochar studies at WOS

complexation electrostatic interactions redox effects and precipitation effects (Inyang et al. 2016)

Research hotspots

High-frequency keywords can highlight the research hotspots in the research field (Wei et al. 2020). Based on the number of papers published per year in these two databases, the 20-year research process of biochar can be divided into three periods for hotspot analysis.

Nascent period (2003–2011)

The keyword burst table of the CNKI database for biochar research is presented in Table 10. Chen and Jia (2006) described the application of a biochar-ozone technology in a water treatment project and reported that is can effectively decolorize and deodorize, remove some pollutants, and reduce the Chemical Oxygen Demand (COD) in water. Guo et al. (2010) designed a coagulation-hydrolysis-aerobic bio-contact oxidation-PACT process to treat printing and dyeing wastewater. During this period, the articles included in the CNKI database mainly reported application of biochar in wastewater treatment processes. To provide useful and feasible methods for the treatment of difficult-to-degrade chemical wastewater, research is inclined toward environmental engineering.

The keyword burst table of the WOS database for biochar research is presented in Table 11. In 2003, Purevsuren et al. (2003) prepared biochar by pyrolysis of casein and found void spaces on its surface, which could be further used to prepare activated carbon. Ozcimen and Karaosmanoglu (2004) prepared biochar and bio-oil from pressed rapeseed cake, using agricultural residues as a source for biochar preparation for the first time. In 2008, Azargohar and Dalai (2008) used biochar as a source of activated carbon via physical steam and chemical activation processes. Lal (2009) reported that biochar application can improve soil fertility; thus, interest in biochar as a soil additive is gradually increasing. In general, in the primary stage, scholars of the articles retrieved from the WOS database have elucidated that biochar has the potential to be used as activated carbon and that biochar can effectively improve soil properties and enhance soil fertility. It established the foundation for the next stage of research on biochar as adsorbent and soil amendment.

Table 9 Biochar adsorption of pollutants and adsorption capacity

Category	Pollution	Adsorption capacity(mg/g)	References
Heavy metals	Cd	64.40	Deng et al. 2018
	Cd	36.36	Bogusz et al. 2017
	Ni	31.35	
	Pb	157.95	Cao et al. 2019
	Pb	146.84	Wang and Wang 2018
	Cr	117.70	Zhang et al., 2022b
	Cr	291.54	Zeng et al. 2021
	Hg	401.80	Zhao et al. 2022
	As	20.10	Li et al. 2021a, b, c, d
	Cu	24.21	Yilmaz and Guzel 2020
	Sm	40.00	Serra-Ventura et al. 2021
Organic pollutants	levofloxacin	7.72	Yi et al. 2016
	MeHg	108.16	Zhao et al. 2022
	Chlortetracycline	627.00	Chen et al. 2021
	2,4-dichlorophenol	259.50	Taheri et al. 2022
	Ciprofloxacin	62.48	Li et al. 2020b
	Carbofuran	161.00	Mayakaduwa et al. 2017
	Congo red	404.40	Wu et al. 2020
	Malachite green	246.80	
	Tetracycline	451.45	Li et al. 2021a, b, c, d
	Aniline	360.00	Mehmood et al. 2022
	Nitrobenzene	193.00	
Nitrogen and phosphorus compounds	Phosphate	37.37	Liu et al. 2021
	phosphorus	314.22	Wang et al. 2018
	NH_4^+-N	5.38	Yang et al. 2018
	NH_4^+-N	11.68	Li et al. 2021a, b, c, d
	PO_4^{3-}-P	26.14	

Table 10 Keyword burst table for biochar research (CNKI, 2003–2011)

Keywords	Strength	Begin	End	2003–2011
Ozone	2.33	2003	2006	
In-depth treatment	1.46	2003	2004	
Contact Oxidation	1.24	2003	2005	
Biochemical treatment	0.96	2003	2005	
Wastewater reuse	0.96	2003	2005	
Water reuse	0.86	2005	2006	
Hydrolysis acidification	0.99	2007	2011	
Printing and dyeing Wastewater	0.82	2008	2009	
Air floatation	0.65	2008	2009	
Chemical wastewater	0.9	2009	2011	

Development period (2012–2019)

The keyword burst tables of CNKI and WOS databases for biochar research are presented in Table 12 and 13. Gao et al. (2012) combined biochar with fertilizers to produce biochar-based fertilizers. They reported that it improved the quality of soil and promoted crop growth and yield, which enhances the benefits of biochar in agriculture. Some

Table 11 Keyword burst table for biochar research (WOS, 2003–2011)

Keywords	Strength	Begin	End	2003–2011
Carbon	2.15	2003	2007	
Plant	1.24	2004	2007	
Chemical activation	1.28	2007	2008	
Manure	0.36	2007	2008	
Soil organic matter	2.3	2008	2009	
Temperature	1.58	2008	2009	
Bio oil	1.23	2008	2009	
Aromatic hydrocarbon	1.17	2009	2011	
Biofuel	1.17	2009	2011	
Climate change	0.83	2009	2011	

Table 12 Keyword burst table for biochar research (CNKI, 2012–2019)

Keywords	Strength	Begin	End	2012–2019
Crop yield	2.91	2012	2016	
Greenhouse gases	2.75	2012	2013	
Soil fertility	2.72	2012	2015	
Chemical properties	1.76	2012	2014	
Crop growth	1.73	2012	2013	
Soil improvement	1.62	2012	2013	
Acid soil	2.14	2013	2014	
Red soil	1.16	2013	2015	
Influencing factors	0.77	2013	2014	
Carbonization temperature	2.53	2014	2016	
Fertilizer	2.15	2014	2016	
Degradation	0.63	2014	2015	
Chemical form	2.57	2015	2016	
Desorption	1.11	2015	2016	
Thermodynamics	2.3	2016	2017	
Municipal sludge	1.46	2016	2017	
Constructed wetland	2.29	2017	2019	
Mechanism	2.05	2017	2019	
Persulfate	1.72	2017	2019	
Composite material	0.70	2017	2019	

studies have investigated the carbon sequestration activity of biochar, which can sequester carbon and mitigate global warming. Thus, it is considered to be a promising material for a wide range of applications (Mohan et al. 2014; Li et al. 2013). Tang et al. (2017) explored the best adsorption conditions of biochar for microorganisms through repeated experiments, and developed effective treatments of constructed wetland wastewater. Chen et al. (2013) investigated the effects of different pyrolysis temperatures on the adsorption of organic pollutants by biochar.

In addition to these applications, research on biochar has mainly focused its use as an adsorbent for the removal of heavy metal contaminants and organic pollutants from aqueous solutions and soils. Scholars are also interested in the influence of the preparation conditions, modifications of the adsorption efficiency and mechanism of action of biochar (Bashir et al. 2018).

Prosperous period (2020–)

The keyword burst tables of CNKI and WOS databases for biochar research are shown in Table 14 and 15, respectively. As research progressed, scholars began to explore new preparation methods that could compensate for the high energy

Table 13 Keyword burst table for biochar research (WOS, 2012–2019).

Keywords	Strength	Begin	End	2012–2019
Charcoal	122.15	2012	2015	
Soil	28.49	2012	2013	
Manure	25.30	2012	2015	
Sustainable agriculture	8.91	2012	2013	
Adsorptive property	8.50	2012	2015	
Chemical property	7.98	2012	2015	
Bioenergy	6.34	2012	2016	
Soil fertility	3.27	2012	2013	
Greenhouse gases	1.28	2012	2013	
Soil amendment	5.34	2013	2014	
Polychlorinated biphenyl	5.22	2013	2014	
Herbicide	5.14	2013	2016	
Crop straw	4.19	2013	2014	
Restoration	3.01	2016	2017	
Environment	1.67	2016	2017	
Adsorption characteristics	5.23	2017	2019	
Different temperature	4.58	2017	2019	
Agricultural residue	4.39	2017	2019	
Competitive adsorption	3.15	2017	2019	
Waste management	2.55	2017	2019	

Table 14 Keyword burst table for biochar research (CNKI, 2020–2022)

Keywords	Strength	Begin	End	2020–2022
Phosphate	4.66	2020	2022	
Passivation repair	3.52	2020	2022	
Saline soils	3.37	2020	2022	
Catalytic	3.05	2020	2022	
Mechanism of action	2.96	2020	2022	
Food waste	2.92	2020	2022	
Stabilization	2.69	2020	2022	
Ecological risk	2.59	2020	2022	
Hydrochar	1.99	2020	2022	
Environmental remediation	1.51	2020	2022	

consumption of the traditional thermal cracking method. Hydrothermal carbonization is a green, low-energy and inexpensive method for treating waste biomass (Li et al. 2022). Zhou et al. (2021a) prepared biochar from corn stover using a hydrothermal method to adsorb organic matter in water. Azzaz et al. (2020) used olive mill wastewater as a carbon source to prepare biochar by hydrothermal carbonization and investigated the effect of the hydrothermal char temperature on the yield and content of each element. As research on biochar has progressed, the directions have diversified. Hydrothermal carbon materials have a wide range of applications in environmental remediation, catalyst carriers and supercapacitors (Cui et al. 2021; Zhang et al. 2022a). Moreover, Rathnayake et al. (2020) compared the adsorption efficiency of fresh and aged biochar for environmental pollutants. Based on several studies, biochar is considered to have great potential for environmental and agricultural sustainability. Thus, continuous research on the topic is essential. Scholars have begun to focus on the environmental toxicological effects of biochar. Kong et al. (2021) prepared biochar by the pyrolysis of sewage sludge and found that biochar produced at high temperatures had low potential environmental risk and ecotoxicity. In the context of "peak carbon dioxide emissions" and "carbon neutrality," Song

Table 15 Keyword burst table for biochar research (WOS, 2020–2022)

Keywords	Strength	Begin	End	2020–2022
Soil health	4.08	2020	2022	
Challenge	3.32	2020	2022	
Enhancement	3.29	2020	2022	
Porosity	3.28	2020	2022	
Electrode material	3.25	2020	2022	
Gaseous emission	2.75	2020	2022	
Ammonia	2.49	2020	2022	
Nitrogen retention	1.7	2020	2022	
Rhodamine b	1.21	2020	2022	
Adsorption behavior	0.52	2020	2022	

et al. (2022) suggested that the Government should include biochar in the carbon trading market based on its role in soil management. He argued that biochar can contribute to both “peak carbon dioxide emissions” and “carbon neutrality”. Yang et al. (2021b) weighed three factors, namely technical, economic and environmental factors, and found that biochar could have significant impact on achieving national and global greenhouse gas reduction targets.

Latest international research on biochar (Oct. 2022–Feb. 2023)

In this section, we focus on publications from the last five months (from Oct. 2020 to Feb. 2023) to summarize the latest research achievements in biochar analysis from a bibliometric perspective. We retrieved recent studies at WOS in the time period as supplementary content. The search method was the same as that described in Section 2.2.1. We retrieved a total of 1804 articles and obtained 1800 valid data after de-duplication. A total of 963 articles were published from Oct. 27, 2022 to Dec. 31, 2022, and 837 articles were published from Jan. 01, 2023 to Feb. 28, 2023.

The co-occurrence and keyword burst of the latest international research on biochar are shown in Fig. 10 and Table 16. Comparison with the keyword burst tables of the previous three periods visually demonstrates that in addition to the familiar keywords "adsorption capacity," "heavy metals," and "physicochemical properties," new keywords such as "phytotoxicity," "tolerance," and "resistance" were also present. A recent study revealed that biochar has the potential to reduce phytotoxicity based on its strong adsorption function. Li et al. (2023) prepared biochar that could effectively reduce the toxic effects of polyvinyl chloride microplastics on plant seedlings but exacerbated the toxic effects on the root system. This study provides a basis for understanding the removal of phytotoxicity by biochar. Biochar also can improve the salt tolerance of plants and improve fruit quality (Abd et al. 2023). The "biochar-microbial" synergy is constantly being attempted, developed, and explored for its effects on the community structure (Yang et al. 2023; Wang et al. 2023). In addition, exploring the life cycle assessment of biochar plays an increasingly important role, this helps bridge the gap between biochar production and biochar application (Kumar et al. 2023). Biochar has also been shown to improve the flexural strength and splitting tensile strength of concrete, and replacing some cement with biomass char for concrete offers a sustainable option for municipal solid waste management and building energy efficiency (Jia et al. 2023). In general, biochar research has recently shown diversification and extension to different fields, which has laid a solid foundation for the development of biochar.

Future research trends and challenges

Biochar as a new type of environmental protection material has been receiving more and more attention. The research enthusiasm in the next few years may not be weaker, for the following reasons.

(1) Demand for environmental protection

As a sustainable and environmentally friendly material with various environmental protection functions, biochar is an effective means of dealing with global climate change and environmental pollution.

(2) Energy crisis

With the increasing scarcity of fossil fuel resources and the intensification of the energy crisis, biochar could be important in replacing traditional energy sources and developing new sustainable energy sources. Biochar is an important form of biomass energy, which also has the

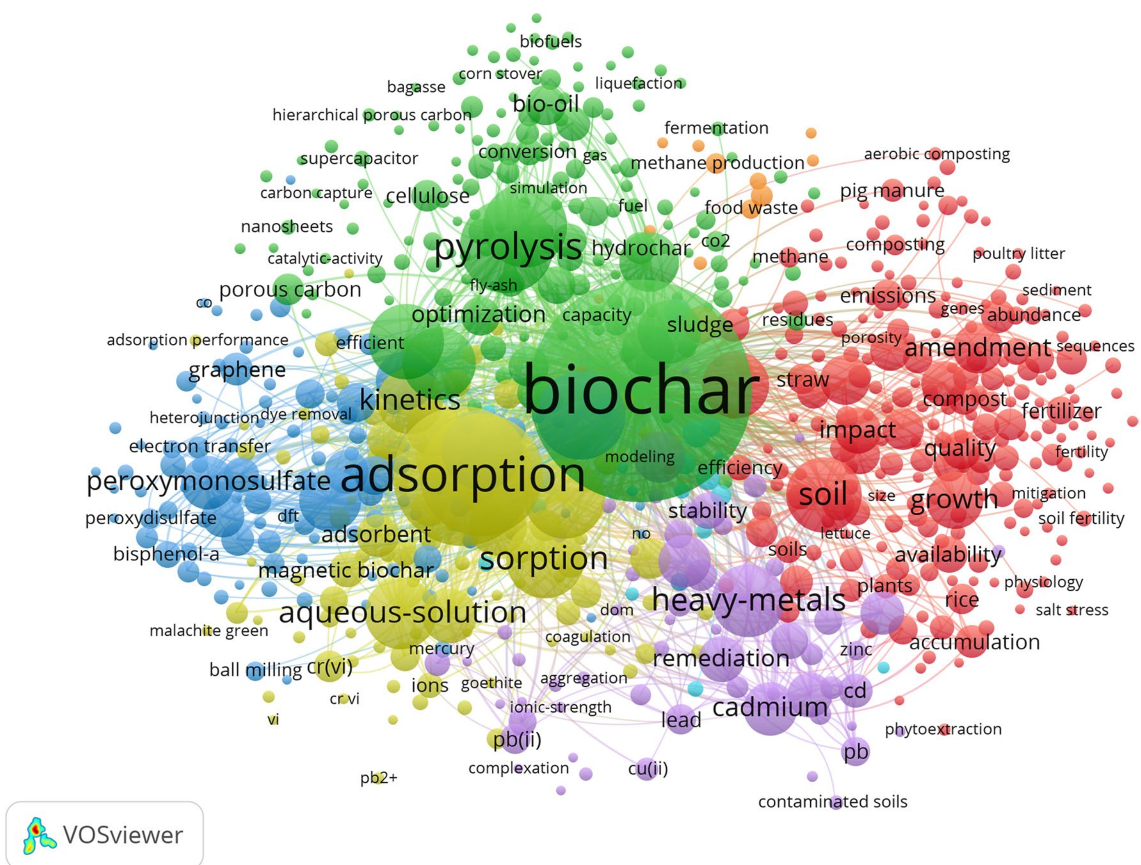


Fig. 10 Co-occurrence map of keywords published biochar the latest studies at WOS

advantage of environmental protection and is expected to become an important source of energy in the future.

(3) Agricultural demand

With the transformation of agricultural production methods and the requirements of sustainable agricultural development, biochar is important in improving soil, enhancing agricultural production efficiency. and properly disposing of agricultural waste. It is expected to play a key role in agricultural production.

(4) Economic benefits

Research on and the application of biochar is expected to bring economic benefits and promote the development of biochar industry. In addition, a close connection exists between biochar and carbon trading. The preparation and application of biochar can provide a reliable means for enterprises to reduce emissions, thus lowering their carbon emissions and reducing costs. With the gradual development and improvement of the carbon trading market, carbon trading can also provide more economic support and market demand for the development of biochar, further promoting the development of biochar.

The development of biochar research is a comprehensive issue, one must always adhere to the principles of sustainable development, environmental protection, science, economy, and social responsibility. In the future, biochar research challenges may include the following aspects.

(1) Controlling the cost of biochar preparation

The current biochar preparation technology is relatively mature, but some problems remain, such as complicated charring process conditions and high production costs. These issues make it difficult to implement large-scale production of biochar. Future research should be devoted to developing more efficient and environmentally friendly preparation technologies to solve these problems.

(2) Physicochemical properties of biochar

The physicochemical properties of biochar considerably affect its application effects. Future research will

Table 16 Keyword burst table for biochar the latest research (WOS, Oct. 2022–Feb. 2023)

Keywords	Year	Strength	Begin	End	Oct. 2022–Feb. 2023
Phytotoxicity	2022	1.5	2022	2023	
Life cycle assessment	2022	1.5	2022	2023	
Pollutants	2022	1.35	2022	2023	
Agricultural soils	2022	1.2	2022	2023	
Contamination	2022	1.2	2022	2023	
Resistance	2022	1.2	2022	2023	
Tolerance	2022	1.05	2022	2023	
Photocatalytic degradation	2022	1.05	2022	2023	
Green synthesis	2022	0.9	2022	2023	
Adsorption capacity	2022	0.9	2022	2023	
Physicochemical properties	2022	0.75	2022	2023	
Heavy metal ions	2022	0.75	2022	2023	
Heavy metal removal	2022	0.75	2022	2023	
Catalytic activity	2022	0.75	2022	2023	
Progress	2022	0.75	2022	2023	
Functionalized biochar	2022	0.75	2022	2023	
Microorganisms	2022	0.6	2022	2023	
Community structure	2022	0.6	2022	2023	
Constructed wetlands	2022	0.6	2022	2023	
Functional gene	2022	0.6	2022	2023	

investigate further the physicochemical properties of biochar to improve its application effects.

(3) Application fields of biochar

The application fields of biochar are very wide and include soil improvement, water purification, and energy development. Future research will explore more application fields, such as biochar in metal pollution treatment, catalytic oxidation, and biochar-microbial synergy.

(4) Evaluation of environmental effects of biochar

Although biochar has an important role in environmental protection, its effects on the environment have not been fully clarified. For example, during the application of biochar, harmful substances left over from the modification process may be released, causing potential effects on the environment and human health.

(5) Evaluation of the environmental benefits of biochar

The application of biochar has certain effects on the environment, such as carbon fixation, soil fertility improvement, and water purification. In future research, in-depth environmental benefit evaluation will be performed to elucidate fully the environmental benefits of biochar.

(6) Establishing a standard and certification system for biochar

Establishing a standard and certification system for biochar is essential to ensure its quality and marketability. Through the establishment of a perfect standard and certification system, the production, sales, and application behaviors of biochar can be regulated, and the development and promotion of biochar industry can be promoted.

Conclusions

In this study, we used a bibliometric approach and data from the CNKI and WOS core journal database. We explored the research dynamics and research gaps in the field of biochar since 2003. By identifying research themes and hotspots based on keyword analysis, combined with relevant literature, we conducted an in-depth assessment to determine the latest and most comprehensive research situation and results in this field. We also identified the future research trends and challenges in biochar. The results show that biochar has been widely used for soil improvement and water purification in the past 20 years. It is mainly involved in environmental remediation and biomass energy utilization.

Among the latest research results, some emerging keywords have appeared in biochar research, including catalytic oxidation, supercapacitor, microorganism, resistance gene, phytotoxicity, tolerance, and concrete. Although the considered studies are preliminary to some extent, such advances still provide new directions for researchers to delve into biochar research. We expect future work to continue this innovation and integration and to continue to broaden the application areas of biochar. Overall, in an era in which "peak carbon" and "carbon neutrality" are strongly promoted, the prospects and areas of application for biochar have unlimited possibilities.

Acknowledgments The study was financially supported by the National Natural Science Foundation of China (22166034), the Project of Science and Technology Department of Jilin Province (China) (YDZJ202201ZYTS542), and the National College Students' innovation and entrepreneurship training program (China) (202210184151).

Author Contributions All authors contributed to the study conception and design. The authors Tianming Yang and Zixuan Zhang contributed equally to complete the experiment and wrote the main manuscript. Long-Yue Meng and Weihong Zhu provided research ideas and suggestions for revision. All the authors reviewed the manuscript.

Funding The study was financially supported by the National Natural Science Foundation of China (22166034), the Project of Science and Technology Department of Jilin Province (China) (YDZJ202201ZYTS542), and the National College Students' innovation and entrepreneurship training program (China) (202210184151).

Data availability The original data for this work comes from the Web of Science and CNKI databases.

Declarations

Ethical Approval Compliance with Ethical Standards.

Consent to Participate All authors whose names appear on the submission made substantial contributions to the conception or design of the work.

Consent to Publish All authors whose names appear on the submission approved the version to be published.

Competing interests The authors declare no competing interests.

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