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RESEARCH ARTICLE

Biochar-related studies from 1999 to 2018: a bibliometrics-based review

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Abstract

Biochar has been paid great attentions during the last two decades, because of its resources potentials and environmental benefits. A bibliometric analysis was applied to assess the publications regarding the keyword biochar from the Web of Science database during the period of 1999 to 2018. A total of 8629 publications were obtained with a rapid increase of annual citations and number of papers. The research topics were diversified, which were mainly divided into "Environmental Sciences and Ecology," "Agriculture," and "Engineering." Bioresource Technology was the journal which published most of the relevant papers. China ranked first in the number of published papers, followed by the USA, Australia, UK, and Germany. Especially, China established close collaboration with the USA in joint publication. Analysis of the keywords indicated that biochar production, comparative sorption, soil-applied black carbon, and soil management were the main research hotspots of biochar. The burst detection reflected that the innovation of biochar production and the new application field of biochar was the future research trends. These results can provide insight into the research progress regarding biochar.

Keywords Biochar · Bibliometric · Research trend · Hotspots

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Introduction

Biochar is a typical category of biomass extracted from the thermochemical conversion in an oxygen limited environment (IBI 2012), which may source from wood waste, municipal waste, agricultural waste, etc (Yuan et al. 2017; Chen et al. 2008; Jang and Kan 2019). Because of its porous structure and diverse functional groups (Ahmad et al. 2014), biochar has been widely used in the field of agriculture and environmental protection (Wang and Wang 2019). For instance, biochar application to soil has been proposed for carbon sequestration and mitigating global warming, while simultaneously providing energy and increasing crop yields (Woolf et al. 2010). Chan et al. (2008) highlighted the role of biochar in improving nitrogen fertilizer use efficiency and improving soil quality, including increases in pH, organic carbon, and exchangeable cations as well as reduction in tensile strength. Many studies also found biochar application can remove organic contaminants and heavy metals (Devi and Saroha 2015; Zhang et al. 2015).

In recent years, researches on biochar have grown rapidly and more benefits and mechanism were discovered for

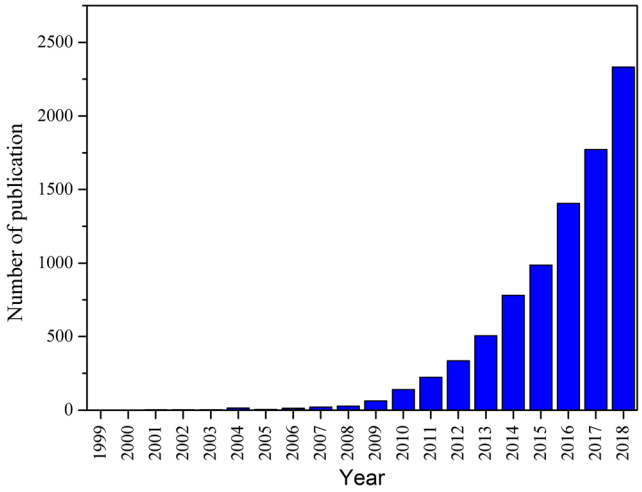

Fig. 1 Publication output performance during 1999–2018

biochar application. Studies have indicated that the preparation condition is critical to exert the utility of biochar, including feedstock, pyrolysis temperature, and modification (Zhang et al. 2017; Yu et al. 2018). The increasing interest and broaden application about biochar lead to the burst of biochar publications. There have been many published papers which review biochar application well. For example, O'Connor et al. (2018) reviewed biochar application for the remediation of heavy metal polluted land, and Kavitha et al. (2018) reviewed benefits and limitations of biochar amendment in agricultural soils. Others reviewed mechanisms of biochar in the adsorption of contaminants and the environmental characteristics of biochar (Abbas et al. 2018; Zhang et al. 2018a). However, these papers reviewed different perspectives of biochar and there are few attempts at gathering systematic data on the global scientific production of biochar research. The development trend of biochar, the research hotspots, and future research frontiers is not clear. It is critical to have a comprehensive literature review so that scholars in this field can understand current research progress and identify possible research directions for their future work.

This study proposed using a bibliometric analysis to review the biochar-related studies, for its advantages in bulk of information retrival to highlight the progress of publications, hotspots, and advanced research frontiers (Persson et al. 2004). Conventional bibliometric analysis mainly focused on the publication numbers, citations, publishing language etc., while giving little attention to the research contents (Wang et al. 2013). This study fills such gap by combining the generic analysis result from a bibliometric approach with a specific explanation of the key contents, to help readers better understand the research progress and future studies regarding biochar, as well as to help the new researchers to seize the research frontier in the biochar field.

Table 1 Characteristics of publication outputs

PY	P	PG	PG/P	NR	NR/P	AU	AU/P	J	P/J
1999	1	4	4.00	24	24.00	3	3.00	1	1.00
2000	2	16	8.00	39	19.50	5	2.50	2	1.00
2001	3	22	7.33	57	19.00	15	5.00	3	1.00
2002	4	24	6.00	25	6.25	17	4.25	1	4.00
2003	3	27	9.00	92	30.67	19	6.33	2	1.50
2004	14	99	7.07	330	23.57	53	3.79	10	1.40
2005	6	54	9.00	181	30.17	21	3.50	4	1.50
2006	11	85	7.73	280	25.45	47	4.27	5	2.20
2007	19	151	7.95	589	31.00	87	4.58	11	1.73
2008	26	226	8.69	1284	49.38	99	3.81	19	1.37
2009	62	487	7.85	2218	35.77	199	3.21	26	2.38
2010	138	1124	8.14	5345	38.73	586	4.25	53	2.60
2011	222	1939	8.73	8796	39.62	941	4.24	71	3.13
2012	335	2963	8.84	14232	42.48	1493	4.46	100	3.35
2013	505	4840	9.58	21364	42.30	2350	4.65	152	3.32
2014	780	7274	9.33	33170	42.53	3710	4.76	194	4.02
2015	987	9563	9.69	45047	45.64	4802	4.87	262	3.77
2016	1405	14551	10.36	67284	47.89	7108	5.06	312	4.50
2017	1773	18281	10.31	88106	49.69	9546	5.38	374	4.74
2018	2332	23720	10.17	115233	49.41	12546	5.38	414	5.63

P: number of publications; PG: page count; NR: cited reference count; AU, J, and Country: number of authors, journals, and countries; PG/P, NR/P, and AU/P: average of pages, references, and authors in a paper; P/J: average of papers in a journal

Methods

Data collection and processing

We built the bibliometric database based upon the Web of Science (WoS) Core Collection, because it is regarded as the

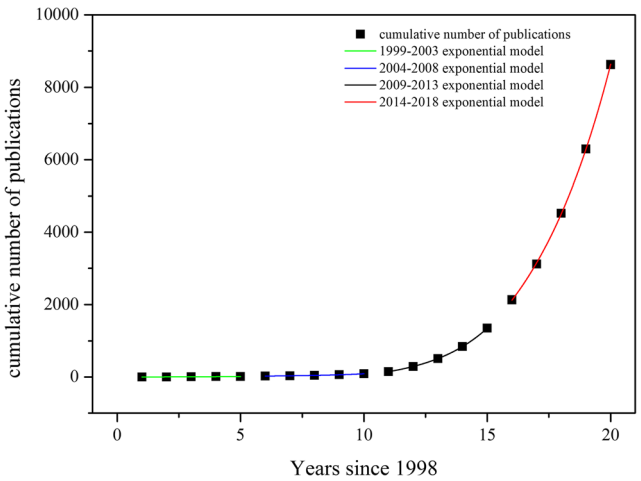

Fig. 2 Cumulative number of publications by year

Table 2 Top 10 subject categories

Subject categories	Publications	Percentage (%)
Environmental Sciences & Ecology	3081	35.66
Agriculture	2378	27.53
Engineering	2128	24.63
Energy & Fuels	1776	20.56
Chemistry	1290	14.93
Biotechnology & Applied Microbiology	811	9.39
Science & Technology - Other Topics	789	9.13
Materials Science	498	5.76
Water Resources	364	4.21
Plant Sciences	314	3.63

most reputational acdemic journal system in which the published papers are ensured with rigorous peer review process (Wang and Wang 2019). "Biochar," "biocarbon," and "biochar" were selected as the keywords to type into the search engines on February 28th, 2019, which allowed to locate publications that contain these search terms in titles, abstracts, or keywords. The data related to author's name and affiliation, subject category, journal name, publication type, keywords, publication year, etc., were obtained. We further sorted publications from England, Scotland, North Ireland, and Wales as from the United Kingdom (UK), while publications from Mainland China, Hong Kong, Macau, and Taiwan were classified separately. Collaboration was existed in multi authorships, i.e., international collaboration was depended whether the co-authors were from more than one country.

Seven categories of information were obtained for further analysis, given as follows:

- Types of documents and their publishing languages;
- Number of publications during 1999–2018;
- Distribution of publications in subject categories and journals;
- Author statistics;
- International collaborations;
- Keywords;
- Research hotspots and future trends

Table 3 Top 10 most productive journals during 1999–2018

Journal	TP	%	IF(2018)
Bioresource Technology	471	6.53	6.669
Science of the Total Environment	280	3.88	5.589
Chemosphere	257	3.56	5.108
Environmental Science and Pollution Research	217	3.01	2.914
Journal of Analytical and Applied Pyrolysis	178	2.47	3.470
Journal of Environmental Management	142	1.97	4.865
Environmental Science & Technology	126	1.75	7.149
Journal of Cleaner Production	110	1.52	6.395
Rsc Advances	104	1.44	3.049
Environmental Pollution	101	1.40	5.714

TP is the total publications, % is the share in publication, IF is the impact factor

Data analysis

Microsoft Office Excel was applied to analyze the general research performance of the literature such as publication, document type, language, subject category, journal, country, international collaborations, and keywords. Impact factor (IF) values were collected by Journal Citation Reports in 2019. Ucinet was used to visualize the collaboration network graph of countries. In addition, the research hotspots and frontiers were analyzed by combining co-occurring keywords analysis and burst detection conducted by using CiteSpace.

Results and discussion

Types of documents and their publishing languages

There were 8629 papers obtained during the period of 1999–2018 and were classified into seventeen document types, in which research article was the most common type of documents, which accounted for 83.6% of the total publications, followed by proceedings papers(4.6%), reviews (4.1%), article, proceedings paper (2.7%), meetings abstract (2.3%), book chapter (1.2%), and editorial material (0.5%). Regarding publishing languages, there were 12 languages used, of which 99.1% were English, indicating that English is the primary language for academic communication (Wang et al. 2012). Others contained Portuguese (25), Chinese (14), Finnish (10), and German (10).

Number of publications during 1999–2018

Figure 1 shows the number of publications related to biochar during the period of 1999–2018. The annual publications have increased from 1 to 2332, with an average growth of 50.4% for the past two decades. Especially, the number of publications increased dramatically since 2010, indicating that biochar was given considerable attentions during the past decade.

In addition to the number of publications, cited references, pages, authors, and journals demonstrated varying degree of growth, as shown in Table 1. The average number of references per article increased from 24 to 49.41, and the average article lengths from 4 pages to 10.17 pages, as well as the average number of authors per article increased from 3.00 to 4.46.

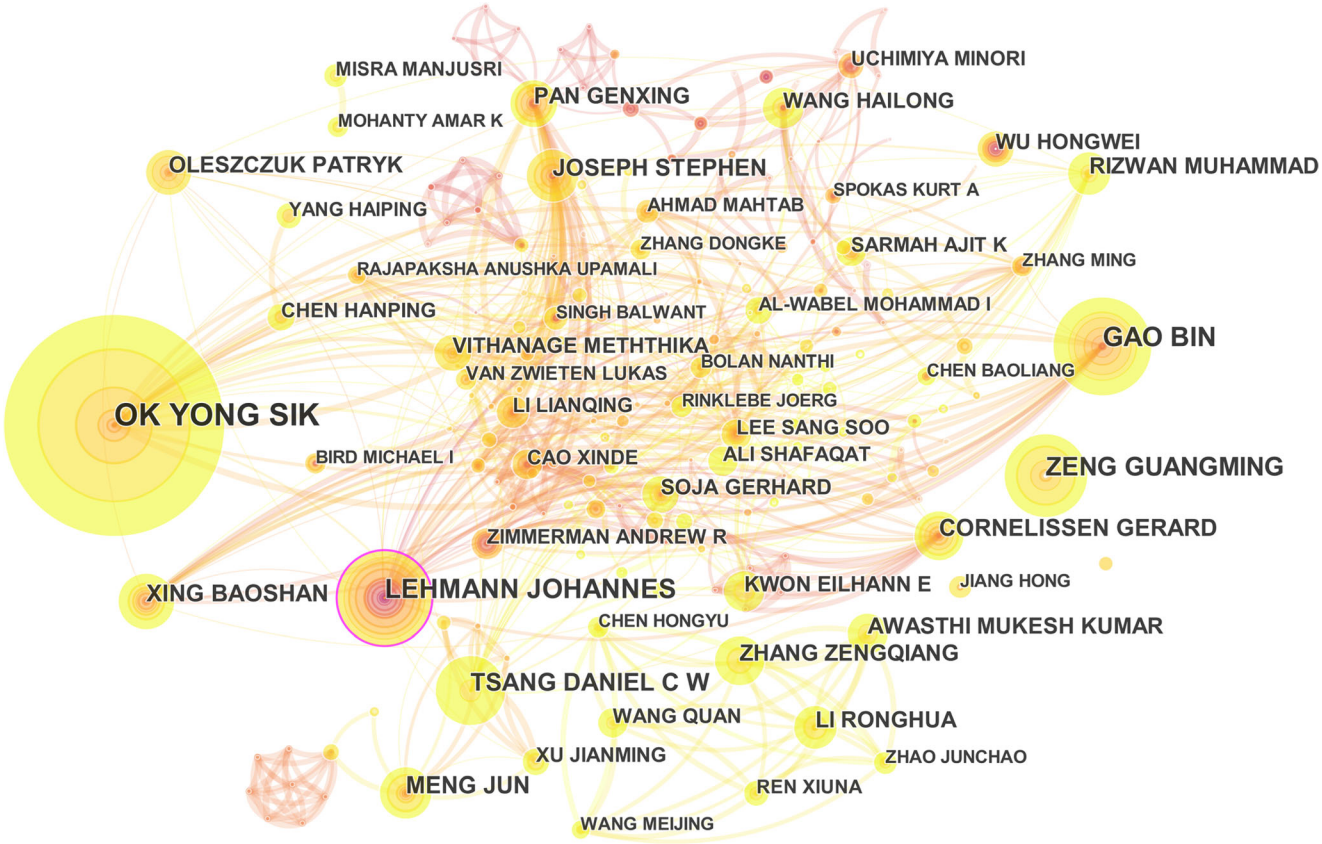

Fig. 3 Co-authorship analysis map

There was a significant correlation between the number of publications and time, shown in Fig. 2. The fitness degree exhibited an increasing tendency, i.e., $R^2 = 0.990$ during the period of 1999–2003, $R^2 = 0.998$ during the period of 2004–2008, $R^2 = 0.999$ during the period of 2009–2013, and $R^2 = 0.999$ during the period of 2014–2018. In particular, the growth rate of publication was the highest during the period of 2014–2018. It was implied such growth would be lasting, approximately 3879 in 2019 in terms of the trend prediction.

Subject categories and journals

There was a great diversity in the research topic of biochar with 76 subject categories identified during the past 20 years, and the top 10 subject categories were shown in Table 2. The most common categories were "Environmental Sciences and Ecology" which accounted for 35.66%, followed by "Agriculture," "Engineering," Energy & Fuels, Chemistry, Biotechnology & Applied Microbiology, Science & Technology—Other Topics. It was implied that biochar is a multidisciplinary research field.

Biochar-related studies were published in 824 journals, among which 52 journals published over 30 articles. Table 3 showed the distribution of outputs in the top 10 journals, which covered 27.52% of biochar-related studies, including the number of publications, and their corresponding impact factors. Bioresource Technology is the most productive journal with 471 related articles, which covered the topics of biochar, biological waste, biomass etc. Followed by Science of the Total Environment, which contributed 3.88% to the entire publications. Chemosphere is the third most productive journal which contributed 3.56% with a total number of 257 researches. Most of the top 10 journals had an impact factor above 4.00. A journal with a higher impact factor might demonstrate its academic reputation based upon the frequency of citations.

Author statistics

There were 18,327 authors who contributed to the studies related to biochar in the past 20 years. Co-authorship map was drawn by using the Citespace software packaging, shown in Fig. 3. Each node represents an author, while its size denotes the total number of this author's papers. Yong Sik Ok from Korea University contributed most of the publications, about 170 articles so far, followed by Bin Gao (84), Johannes Lehmann (83), Guangming Zeng (66), Daniel C.W. Tsang (57), and Stephen Joseph (52). Among the top 10 most contributed authors, six were from China, two from the USA, one from Australia, and one from South Korea. It was implied that China had a significant impact on this research field.

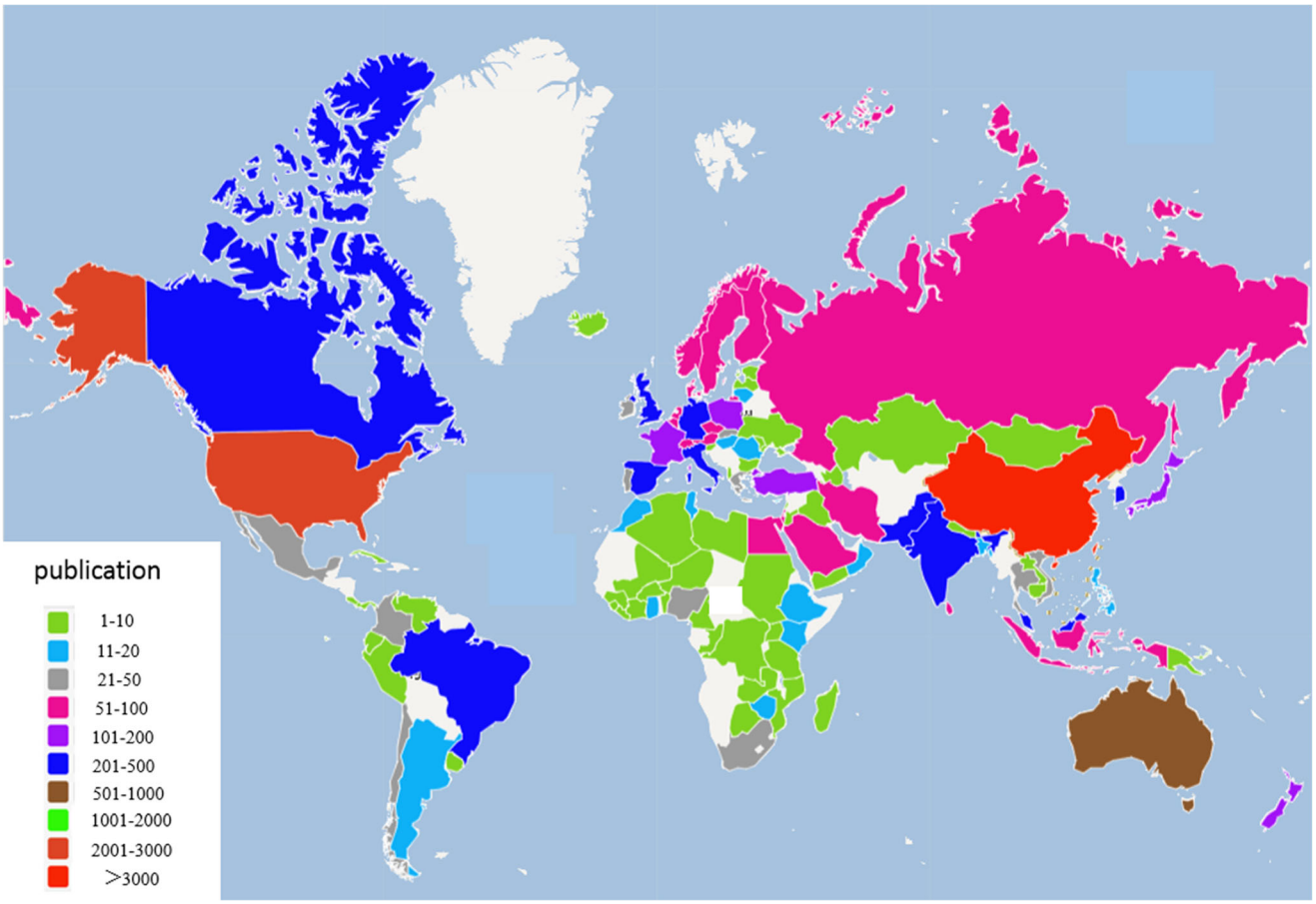

Fig. 4 Countries and regions contributed to biochar research during 1999–2018

International collaborations

There were 117 countries and regions involved in the studies on biochar, shown in Fig. 4. Among them, 9 countries and regions published more than 300 articles, and 20 countries published more than 100 articles. 71.5% of the total publications were independent published by 88 countries. Additionally, 28.5% of the total publications were international joint publications.

Figure 5a highlighted the temporal variation of countries that contributed to the studies of biochar. The number of countries participating in biochar research increased and was apparent since 2010. Figure 5b reflected that the number of countries participating in internationally collaborated publications (ICPs) was almost equal with the number of countries without participation from 2003 to 2012. Since 2013, the number of countries participating collaborative publication increased gradually. The 5 years average percentages of ICAs were 20.4%, 24.4%, and 29.0% for the period of 2004–2008, 2009–2013, and 2014–2018, respectively. This illustrated that international collaboration was a future trend to reinforce academic communication on biochar study.

Table 4 gave the top 20 countries/regions that contributed the most papers in biochar field, among which 8 were from Asia, 7 were from Europe, 2 from North America, 2 from Oceania and Africa, and 1 from South America. China published the most number of publications in this area with the most independent (1882) and internationally collaborative (1160) articles. This indicated that China played an important role in this area, which might be attributed to the fact that China is the world largest producer of crop residuals (Chen et al. 2019). This was different from prior studies that indicated the USA dominated agricultural waste management (He et al. 2019). The USA published the second-highest number of total publications (2069), followed by Australia (608), the UK (458), Germany (398), and South Korea (388). Among the top 20 countries/territories, it is interesting to find Hong Kong had the highest percentage of international collaborated publications which was 99.12%, followed by France (70.00%) and Pakistan (69.59%). The well-developed economies had a relative higher percentage of internationally collaborated articles (France, UK, Germany, USA, and Japan were more than 50%) than developing countries (Brazil and China are less than 40%, India and Malaysia are less than 30%).

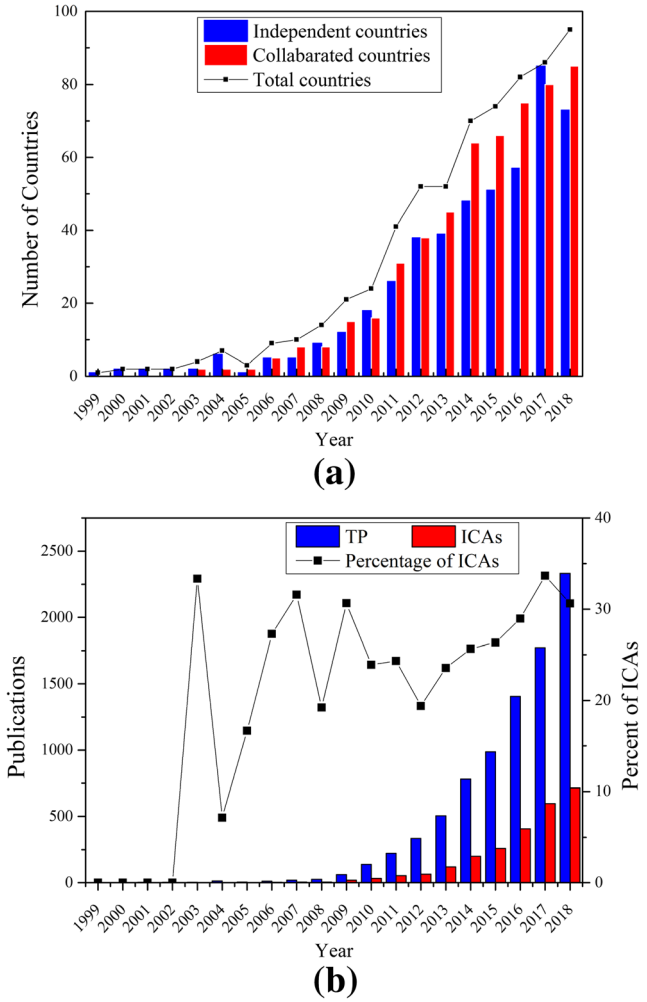

Fig. 5 Trend of the number of countries (**a**) and percentage of internationally collaborated articles (**b**)

In order to assess the collaboration and activity levels of country/territory in biochar research, the collaboration network of the top 20 most productive countries was visualized using Ucinet and showed in Fig. 6. Each point represents one country/territory and the thickness of inter-connecting lines represents the strength of collaboration. China, the USA, UK, and Pakistan had international collaboration with all the 19 other countries/regions. Collaboration between China and the USA was the most closest with 624 collaboration publications. Nine countries and regions, including the USA, Australia, UK, India, Pakistan, New Zealand, Hong Kong, Japan, and Taiwan had the strong collaborations with China, while 8 countries (China, Germany, South Korea, Canada, Spain, Brazil, Poland, and Turkey) had the strong collaborations with the USA. This further indicated that China and the USA were active in collaboration.

Table 4 Top 20 most productive countries from 1999 to 2018

Country/territory	TP	TP R(%)	SP	SP/TP(%)	CP	CP/TP(%)
China	3042	35.41	1882	61.87	1160	38.13
USA	2069	24.09	986	47.66	1083	52.34
Australia	608	7.08	328	53.95	280	46.05
UK	458	5.33	162	35.37	296	64.63
Germany	398	4.63	188	47.24	210	52.76
South Korea	388	4.52	165	42.53	223	57.47
Canada	349	4.06	211	60.46	138	39.54
India	315	3.67	227	72.06	88	27.94
Spain	314	3.66	153	48.73	161	51.27
Italy	281	3.27	160	56.94	121	43.06
Brazil	235	2.74	144	61.28	91	38.72
Malaysia	233	2.71	168	72.10	65	27.90
Pakistan	217	2.53	66	30.41	151	69.59
Poland	163	1.90	108	66.26	55	33.74
France	130	1.51	39	30.00	91	70.00
New Zealand	127	1.48	58	45.67	69	54.33
Turkey	126	1.47	102	80.95	24	19.05
Hong Kong	113	1.32	1	0.88	112	99.12
Japan	109	1.27	54	49.54	55	50.46
Taiwan	107	1.25	62	57.94	45	42.06

TP: total publications, SP: single country publications, CP: internationally collaboration publications,

R (%): percentage of the country in the field

Keywords

Keywords are descriptive words, and through the analysis of keywords, the characteristics and development trends of the field can be revealed (Zhi and Ji 2012; Chang et al. 2017). During the process, the same keywords with different writings were unified, such as “Heavy metals” and “heavy metal,” “hydrochar,” and “Hydrochars,” we unified them with “heavy metal” and “hydrochar”, and so on.

Table 5 shows the descriptive statistics regarding the keywords during the period of 1999–2018. There were 12,658 keywords obtained among which 9138 keywords appeared only once 1535 keywords appeared twice and 429 keywords appeared more than 10 times. The large number of less frequently used keywords indicated the wide application of biochar and a wide disparity in research focuses. From the perspective of the keywords frequency where a small number of keywords appeared most frequently and most keywords were rarely used a power-law distribution was exhibited. During the retrieval period “biochar,” “pyrolysis,” “adsorption,” “Biomass,” and “heavy metal” were the top 5 keywords with the highest frequencies indicating these were full of research interests. Furthermore it was worth noticing that the frequency percentage of the keywords including “Adsorption,” “heavy metal,” “Sewage sludge,” “Compost,”

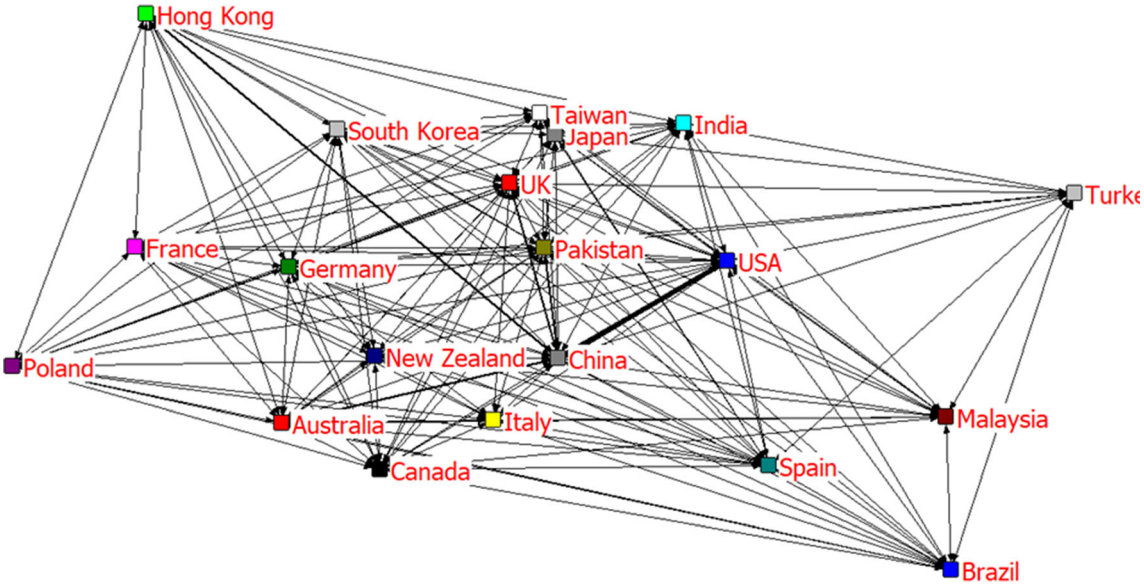

Fig. 6 Collaboration among the top 20 countries

"kinetics," "hydrochar," "Immobilization" and "Pyrolysis temperature" increased gradually during the time period which implied they would be research hotspots

We have also conducted the correlation analysis between the top 10 keywords and the five countries with the most contributions to biochar, given in Table 6. It was apparent that pyrolysis was used the most frequently in the 5 countries. However, there were significant differences, e.g., China paid more attentions to adsorption, heavy metal, and sewage sludge, accounted for 10.52 %, 5.49 %, and 2.37 % of their total publications. Australia mainly focused on compost, contributed 3.13% to the total publications. Germany paid great interests on hydrothermal

Table 5 Frequency of keywords used in publications—top 25

Keywords	1999–2018		2004–2008		2009–2013		2014–2018	
	P	R (%)	P	R (%)	P	R (%)	P	R (%)
Biochar	3455	1(40.04)	13	1(17.11)	523	1(41.44)	2917	1(40.09)
pyrolysis	809	2(9.38)	10	2(13.16)	145	2(11.49)	652	2(8.96)
Adsorption	619	3(7.17)	3	14(3.95)	56	6(4.44)	559	3(7.68)
Biomass	380	4(4.40)	5	9(6.58)	75	3(5.94)	300	4(4.12)
heavy metal	308	5(3.57)	0	/	41	11(3.25)	267	5(3.67)
bio-oil	244	6(2.83)	7	3(9.21)	56	7(4.44)	180	7(2.46)
Sorption	236	7(2.73)	0	/	39	12(3.09)	197	6(2.71)
black carbon	211	8(2.45)	3	15(3.95)	70	4(5.55)	138	11(1.90)
Charcoal	206	9(2.39)	1	36(1.32)	55	8(4.36)	145	9(1.99)
Carbon sequestration	196	10(2.27)	0	/	64	5(5.07)	131	13(1.80)
Bio-char	185	11(2.14)	7	4(9.21)	45	9(3.57)	133	12(1.83)
Compost	180	12(2.09)	0		15	26(1.19)	165	8(2.27)
Soil	173	13(2.00)	0	/	42	10(3.33)	131	14(1.80)
Soil amendment	172	14(1.99)	0		25	14(1.98)	142	10(1.95)
Activated carbon	166	15(1.92)	3	16(3.95)	35	13(2.77)	128	15(1.76)
Sewage sludge	145	16(1.68)	0		14	26(1.11)	119	16(1.64)
hydrothermal carbonization	141	17(1.63)	0	/	24	15(1.90)	117	17(1.61)
bioavailability	108	18(1.25)	0		17	21(1.35)	91	21(1.25)
hydrochar	108	19(1.25)	0	/	9	43(0.71)	99	18(1.36)
kinetics	106	20(1.23)	0	/	11	34(0.87)	95	20(1.31)
Cadmium	106	21(1.23)	1	36(1.32)	7	56(0.55)	96	19(1.32)
Phosphorus	99	22(1.15)	0	/	15	25(1.19)	84	24(1.15)
Gasification	97	23(1.12)	0	/	19	18(1.51)	78	25(1.13)
Immobilization	95	24(1.10)	0	/	10	36(0.79)	85	23(1.17)
Pyrolysis temperature	95	25(1.10)	0	/	10	36(0.79)	86	22(1.18)

P: publications during the study period; R (%): the rank and percentage of the author keyword

Table 6 Frequency of keywords used in publications from five most productive countries during 1999–2018

World		China		USA		Australia		UK		Germany	
Keywords	P	Keywords	P	Keywords	P	Keywords	P	Keywords	P	Keywords	P
biochar	3455	biochar	1252	biochar	765	biochar	253	biochar	210	biochar	163
pyrolysis	809	adsorption	320	pyrolysis	140	pyrolysis	67	pyrolysis	59	Hydrothermal carbonization	49
Adsorption	619	pyrolysis	179	adsorption	125	black carbon	37	charcoal	28	Hydrochar	32
Biomass	380	heavy metal	167	Biomass	75	charcoal	32	Carbon sequestration	24	pyrolysis	22
heavy metal	308	Sorption	132	black carbon	72	Biomass	31	black carbon	24	Carbon sequestration	20
Bio-oil	244	Biomass	83	Sorption	65	Carbon sequestration	28	Biomass	23	black carbon	19
Sorption	236	Sewage sludge	72	charcoal	63	adsorption	23	soil	20	charcoal	14
black carbon	211	Cadmium	64	heavy metals	59	Compost	19	Bio-oil	14	Soil amendment	14
Charcoal	206	Bioavailability	60	Bio-oil	59	Soil fertility	13	heavy metal	13	Sorption	12
Carbon sequestration	196	Pyrolysis temperature	58	Activated carbon	52	soil carbon	13	Bio-char	13	Soil fertility	10

P: publications in the study period from 1999 to 2018; %: the percentage of the author keyword in the total publications of a country

carbonization and hydrochar analysis, accounted for 12.3% and 8.0% of their total publications.

Research hotspots and future trends

In order to identify the research hotspots and future trends of biochar research, keywords co-occurrence analysis was conducted by using the CiteSpace software package to examine whether there were certain correlations among the keywords. Each cluster was labeled by titles and the log-likelihood ratio (LLR) test method.

There were 8 clusters for all the keywords, and all their associated silhouette values were more than 0.5, as shown in Fig. 7, indicating a matching network was created. Particularly, there were 4 clusters with more than 20 members, which implied they were the current research hotspots. The largest cluster (#0) was comparative sorption, focusing on sorption mechanism, desorption, and sorption kinetics regarding biochar applied to the sorption of organic compounds and heavy metals. The second cluster (#1) was labeled as "bio-char production,"

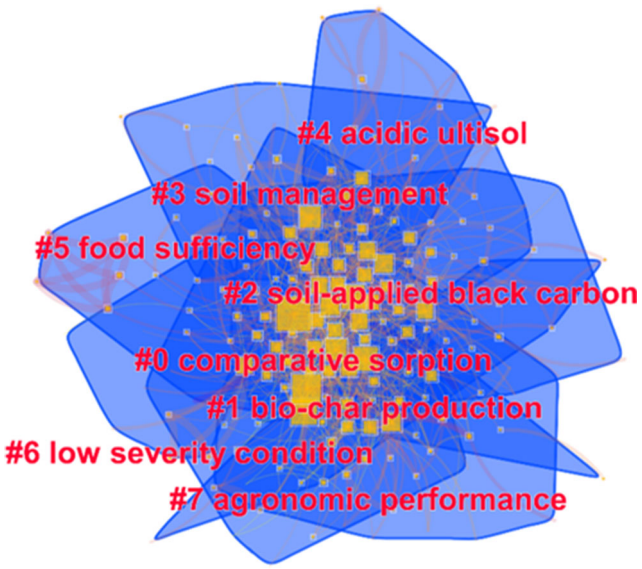

Fig. 7 Keywords co-occurrence clusters of biochar research

covering thermochemical conversion for biochar production and characterization, including slow and fast pyrolysis, gasification, torrefaction, and hydrothermal carbonization. The third cluster (#2) was labeled as "soil-applied black carbon," indicating soil remediation using biochar to investigate the soil physical and hydraulic properties, such as soil pH, organic carbon content, water-holding capacity, and cation exchange capacity. The cluster (#3) was labeled as "soil management," by taking carbon capture and fixation into account, as well as mitigating global climate change and improving soil fertility.

To discover the keywords that have not reached the frequency threshold, but may have academic contribution, the study further employed the burst detection to identify whether there is any change in the determined hotspots. There were 39 keywords with the strongest bursts, as shown in Fig. 8, implying that the research interests were extended to a wider area. The development of biochar studies in the past 2 decades was mainly divided into three stages: The first stage was from 1999 to 2010, with the burst keywords containing bio-char, black carbon, charcoal, biogas, bio-oil, etc. Bio-char and charcoal belong to black carbon as proposed by Zimmerman 2010, and biogas and bio-oil were related to biochar production, which reflected an initial recognition stage of biochar research. The second stage was from 2011 to 2015, with the keywords booming, not only including the biochar production, but also covering crop residue, slow pyrolysis, fast pyrolysis, feedstock, lignin, etc. In this stage, a number of studies focused on biochar preparation, biochar application to soil remediation, and greenhouse gases reduction. Besides soil pH, soil organic carbon, microbial community, fertilizer, nitrification, and nutrient were the main burst keywords to highlight that biochar amendment may be full of research interests.

In the third stage (2016-2018), except for the research topics during 1999–2015, the study of biochar has been further deepened; biochar related with anaerobic digestion and microwave become new research hotspots and attained increasing attention. During this stage, a number of studies have systemically assessed the performance of biochar on anaerobic digestion to decrease lag time (Li et al. 2018), enhance hydrolysis

Keywords	Year	Strength	Begin	End	1999 - 2018
biomorphic ceramics	1999	4.1315	**2002**	2007	
biotemplating	1999	4.1385	**2002**	2004	
sic	1999	4.1344	**2004**	2007	
bio-char	1999	4.9966	**2004**	2012	
charcoal	1999	8.8284	**2007**	2010	
biogas	1999	3.6939	**2008**	2015	
bio-oil	1999	3.5998	**2008**	2009	
bioma	1999	4.2417	**2008**	2009	
black carbon	1999	11.0849	**2008**	2012	
biofuel	1999	3.6109	**2009**	2012	
carbon	1999	7.9753	**2009**	2014	
terra preta	1999	3.3921	**2009**	2013	
carbon sequestration	1999	12.552	**2010**	2012	
climate change	1999	5.2566	**2010**	2014	
crop yield	1999	4.2997	**2010**	2014	
greenhouse gas emission	1999	7.4504	**2011**	2014	
crop residue	1999	4.1517	**2011**	2013	
rice	1999	3.9697	**2011**	2014	
soil ph	1999	4.0325	**2011**	2015	
char	1999	7.8742	**2011**	2015	
soil organic carbon	1999	3.9697	**2011**	2014	
herbicide	1999	4.1517	**2011**	2013	
fast pyrolysis	1999	9.5508	**2011**	2015	
microbial community	1999	3.7651	**2012**	2014	
lead	1999	8.8526	**2013**	2016	
fertilizer	1999	4.4636	**2013**	2014	
feedstock	1999	7.2879	**2013**	2015	
microbial bioma	1999	3.9051	**2013**	2014	
leaching	1999	8.5056	**2013**	2016	
combustion	1999	6.4288	**2013**	2015	
pah	1999	8.6011	**2014**	2016	
lignin	1999	4.4817	**2014**	2016	
nitrification	1999	5.6254	**2014**	2015	
slow pyrolysis	1999	5.2632	**2014**	2018	
carbon dioxide	1999	4.1824	**2014**	2016	
nutrient	1999	3.9371	**2015**	2018	
temperature	1999	6.3344	**2015**	2016	
anaerobic digestion	1999	8.0244	**2016**	2018	
microwave	1999	6.9551	**2016**	2018	

Fig. 8 Top 39 keywords with the strongest citation bursts during 1999–2018. The blue line stands for years from 1999 to 2018, the red line indicates the years in which keywords had the strongest citation bursts

process and methane production (Yin et al. 2019), and alleviate pH decrease (Wang et al. 2018). In addition, most studies focused on the new method of microwave assisted pyrolysis to produce biochar in this stage (Zhang et al. 2018b; Sun et al. 2018). For example, Nhuchhen et al. (2018) produced biochar using a bench

scale fixed bed microwave reactor. It is indicated that the innovation of biochar production and the new application field of biochar may be the future research directions. Researchers have found that biochar can be used as material in supercapacitor for energy storage (Caguiat et al. 2018; Gao et al. 2018), and also acted as catalysts to produce hydrogen (Chen et al. 2018) and promote oil recovery (Areeprasert and Khaobang 2018).

Conclusions

This study employed a bibliometrics-based review on the biochar-related studies during the period of 1999 to 2018, to identify the research hotspots and future directions. The results showed that the biochar-related publications grew rapidly since 2010, with 76 subject categories and 824 published journals. "Environmental Sciences and Ecology" and "Bioresource Technology" were the primary subject category and the published journal. China published the most of publications, and especially six of the top 10 authors were from China as well suggested China's focus on this field. Collaboration and ICAs papers were more prevalent in recent years than in earlier years. China and the USA were most active in publications collaboration. Developed economies had a larger percentage of internationally collaborated articles than that of developing economies.

Biochar production, biochar application related to comparative sorption, and soil remediation were the main research hotspots. The burst detection of biochar application to anaerobic digestion and microwave-based pyrolysis for biochar preparation in recent years highlighted that the innovation of biochar production and the new application field of biochar may be the future research directions.

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