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REVIEW

Visualising the trends of biochar influencing soil physicochemical properties using bibliometric analysis 2010–2022

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Abstract
Based on bibliometric analysis, this paper summarized the research progress of the effects of biochar (BC) on soil physical and chemical properties and provided recommendations for future research. By using appropriate keywords, a total of 1,448 bibliographic records were retrieved from the Web of Science database, and these records were analysed on the basis of criteria, such as authors, keywords, citations, countries, institutions and journals. On the basis of these data, research advances were mapped to identify current scientific trends and the progress made, as well as knowledge gaps. The research began in the year 2010 and accelerated after the year 2015. Yong Sik Ok is the best-known and most productive author in the field. Moreover, China and America are important countries for BC research. Soil Biology and Biochemistry received the highest cocitation rate amongst active journals. Research hotspots can be separated into four distinct clusters, and future research can be summarised in these three directions: (1) the effects of BC mixed with organic and chemical fertilisers on crop growth and nitrogen use efficiency; (2) the response to a series of soil health problems, such as soil erosion and salinisation, by waste management to produce BC for bioremediation; and (3) the effects of BC on soil physicochemical properties from the perspective and mechanism of soil bacterial communities and other microorganisms.

Keywords Bibliometric · Biochar · Research hotspot · Soil property · Visualization

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1 Introduction

In recent years, land overuse has led to the degradation of land functions and has placed great pressure on the ecological environment. Agriculture, mining and heavy metal pollution have caused many negative impacts on soil (Cetin et al., 2022b). Given the occurrence of heavy metal contamination in soil, crops can accumulate heavy metals and affect human health (Cetin & Jawed, 2022). Furthermore, changes in soil quality due to soil contamination have considerable effects on ecosystems (Cetin et al., 2022a). The importance of improving soil quality, especially in arid, semi-arid and saline soil areas, cannot be overstated (Cicek et al., 2022). And biochar (BC) has now become a hot research topic in the fields of agriculture, environment and energy as an environmentally friendly soil improver. The application of BC for both agricultural and environmental benefits has been studied and reviewed extensively (Zhang et al., 2021).

BC is a highly aromatic carbon sequestration material that is produced by the pyrolytic carbonisation of biomass under anoxic or oxygen-limited conditions (Lehmann, 2007). It is known as “black gold” due to its remarkable ability to improve soil fertility (Marris, 2006). Researchers have discovered that BC has a high organic carbon content, a stable porous structure, a high charge density and a low bulk density (Zhang et al., 2023). Additionally, BC has a large specific surface area (Wang & Wang, 2019) and has the potential to take up and store various nutritional components, lessen the bulk density of the soil, increase the soil’s capacity to hold water and make the soil better able to support plant growth (Abujabhah et al., 2016; Lehmann et al., 2003; Liu et al., 2019). BC contains easily degradable carbon (Bakshi et al., 2018), which is mineralised and leached in the soil, where microorganisms utilise it effectively (Roberts et al., 2015). Thus, the application of BC increases soil biomass, the biomass of soil microorganisms and the activity of soil enzymes, which ultimately raise the amount of available soil nutrients (Abbas et al., 2018; Moura Chagas et al., 2022). In addition to carbon that can be easily broken down, BC contains a portion of the inert carbon pool, which is highly stable and difficult to break down through oxidation processes that involve either microbes or abiotic factors (Keith et al., 2011; Kuzyakov et al., 2009). The time it spends in the soil can range from hundreds to thousands of years, making it an invaluable resource for ensuring the long-term health of the soil (Glaser et al., 2001; Liang et al., 2008).

Numerous studies have shown that BC can function as a long-term carbon sink, which may improve soil carbon storage, decrease greenhouse gas (GHG) emissions and mitigate problems, such as reduced food production due to global warming; thus, BC is considered an important tool for addressing climate change (Aviso et al., 2019; Bis et al., 2018; Colantoni et al., 2016). In addition, the application of BC in agricultural fields can enhance soil quality and raise crop yields, which have significant positive impacts on the environment and the economy (Aydin et al., 2020; Li et al., 2021). As a result, BC may be utilised as a soil amendment that is favourable to the environment to manage environmental pollution, increase the number of agricultural carbon sinks and decrease the amount of GHG emissions to maintain sustainable farmland development (Kumar & Bhattacharya, 2021; Rombel et al., 2022; Woolf et al., 2010).

We discovered that majority of previous research has concentrated on the effects of BC on carbon sequestration and the reduction of emission levels, and only a few studies have been conducted on the effects of BC on soil physicochemical properties. Therefore, this study aims to provide a comprehensive review of studies on the influence of BC on soil physicochemical properties and to evaluate the level of development that has occurred in this field in the most recent few years (Shi et al., 2021; Zandi et al., 2019). A strong recent resurgence in bibliometric analysis methods occurred due to the increase in online databases that provide article and citation data and the development of new and improved analysis software (Zupic & Cater, 2015). They are based on cited references, which can be considered representatives of the publications themselves, as well as symbols of different methods, data types and theoretical statements (Kullenberg & Nelhans, 2015). Citations are also an expression of the importance of a publication. As scholars cite older publications to support their ideas, the total number of citations is the most critical indicator of the importance of a publication to a field of knowledge (Chubin, 1980). A bibliometric study aims to identify current trends in this field, which help identify shortcomings and areas for further improvement (Pan et al., 2021). These findings contribute to improving our understanding of the influence of BC on soil physicochemical properties and the development of further studies (Arfaoui et al., 2019). An analytical overview of the current status of this field helps support sound scientific conclusions based on the progress made, the evolutionary trends in this field, and the identification of gaps and future developments (Md Khudzari et al., 2018; Tan et al., 2021).

2 Materials and methods

2.1 Data collection and analysis

For bibliometric analysis, we chose the Web of Science (WoS), one of the world's most authoritative and extensive academic information databases encompassing most fields (Archambault et al., 2009). We utilised SCI-Expanded in the WoS core collection database to find articles published between 2010 and 2022 on the influence of BC on soil physicochemical properties (Uribe-Toril et al., 2019). The retrieval term was TS = (biochar* OR bio-char* OR "bio carbon" OR "biomass charcoal") AND ("soil physicochemical propert*" OR "soil physical and chemical propert*" OR "soil propert*" OR "soil physical and chemical characteristic*"). Amongst them, "propert*" included "property" and "properties". The TS search approach, based on Boolean logic, makes it easy to retrieve a wide variety of relevant literature records through a limited set of keywords (Li et al., 2020; Mongeon & Paul-Hus, 2016). After applying filters and performing comparisons, a total of 1,448 records covering the years 2010–2022 were obtained. The dataset fields consisted of authors, institutions, keywords, year of publication, journals and references (Abdeljaoued et al., 2020; Shi et al., 2021). Finding duplicate papers, fictional things or synonymous terms in raw data is common; thus, the extracted data were processed by eliminating duplicates, deleting nonsensical items and merging synonyms (Chen et al., 2021).

2.2 Bibliometric analysis methods

Currently, bibliometric analysis has become one of the main methods for analysing the vast literature in a subject area (Aznar-Sanchez et al., 2018). Several tools are available for analysis, and each has its advantages and disadvantages (Bezak et al., 2021; Borner et al., 2003). In the present study, VOSviewer and the programming language R were used for bibliometric mapping. After extracting data from 1,448 publications, authorship, country information and collaborations were analysed (Caparros-Martinez et al., 2021). Information, such as major keywords and authors, was also clustered and analysed, and network maps were drawn to illustrate collaboration amongst major research institutions, countries and authors, as well as the co-occurrence of major keywords (van Eck & Waltman, 2010). VOSviewer constructs bibliometric maps in three steps: Firstly, it uses a co-occurrence matrix to obtain a similarity matrix by correcting for differences in the number of occurrences or co-occurrence matrix. Secondly, it constructs a mapping by minimising a weighted sum of the squared Euclidean distances between all item pairs to locate items that are close to each other. Finally, it uses translations, rotations and reflections to obtain consistent results. Each cluster is assigned an item, whereas colours are used to distinguish different clusters (Van Eck & Waltman, 2006). Since its release, VOSviewer software has been widely used in bibliometric studies (Abejón, 2018). Bibliometric analysis allows us to infer the current focus and potential future directions of research on BC-influenced soil physicochemical property (Zhu & Liu, 2020). The data analysis methodology and framework of this study are schematically presented in Fig. 1.

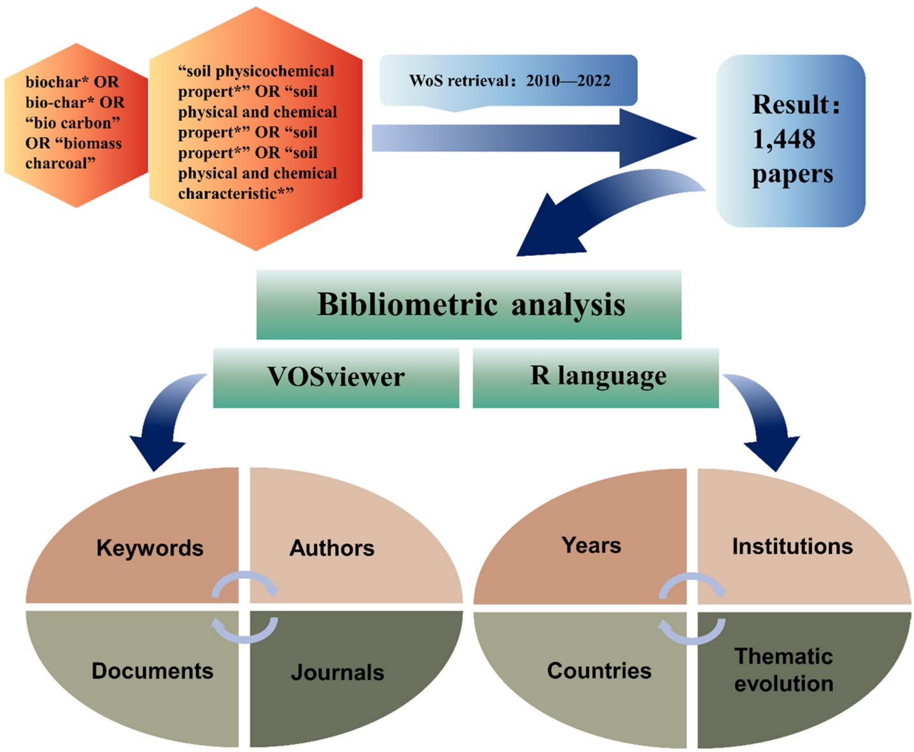

Fig. 1 Methodology flowchart of bibliometric analysis

3 Results and discussion

3.1 Distribution of publications over the years

During the entire study period, 1,448 papers were published. Research articles accounted for the largest proportion of all publications at 91.2%. After this came reviews with a percentage of 7.3%, then proceeding papers with 0.9% and finally others with 0.6%. Throughout the study, three main types of publications were released, allowing for a comprehensive understanding of developments in the field. In this regard, we analysed the year-by-year number of publications extracted from various countries researching the influence of BC on soil physicochemical properties. The findings (Fig. 2) show that the number of publications in this field grew slowly from 2010 to 2015, which can be considered the start-up phase of the field's development. It entered a phase of tremendous development after the year 2015. A considerable increase in the number of published papers in 2016 compared with 2015, especially in China and Germany, can be considered a turning point. For example, Jin et al. (2016), Kim et al. (2016) and Liu et al., (2016a, 2016b) reported important scientific results at the turning point (Jin et al., 2016; Kim et al., 2016; Liu et al., 2016b). In general, the total number of papers demonstrates an exponential increase, and the number of papers that have been published has recently reached a certain degree of maturity.

Moreover, America overtook China in terms of the number of publications produced in the years 2010, 2012 and 2014. However, compared with other nations, China produced a greater number of publications between the years 2016 and 2022. America, Australia, Pakistan and Germany are the nations to be mentioned in this list. Furthermore, Pakistan has quickly eclipsed affluent nations, such as America, in terms of the number of publications in recent years, notably in 2021. This pattern first appeared in 2021 and has continued up to the current day.

3.2 Network analysis of the institutions

From 2010 to 2022, 1,683 scientific institutes or universities published 1,448 papers on the influence of BC on soil physicochemical properties (Fig. 3). The top 25 research institutes published 640 papers, accounting for 44.19% of the total (Table 1). On the

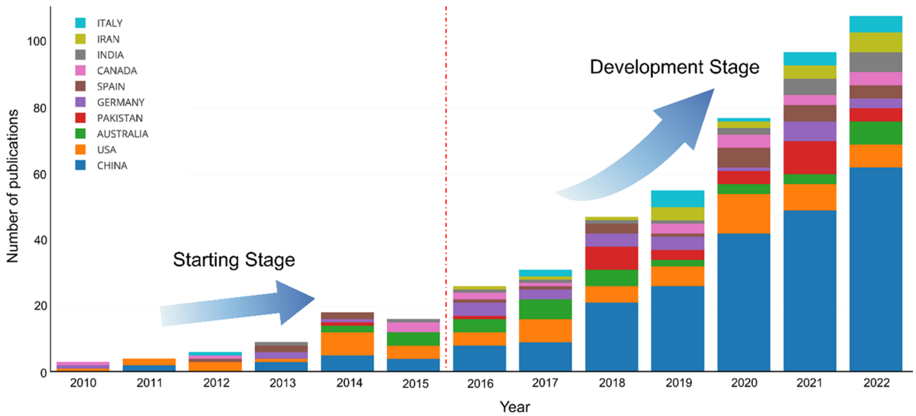

Fig. 2 Number of publications from 2010 to 2022

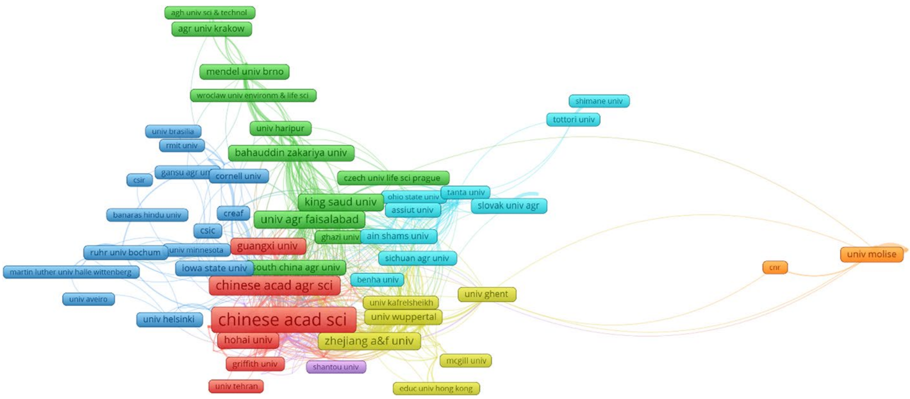

Fig. 3 Network analysis of collaboration between institutions researching on the influence of BC on soil physicochemical properties

basis of the total link strength (TLS) indicator ranking, we found that eight of the top 25 institutions have published more than 30 papers on this topic. The Chinese Academy of Sciences published the largest number of publications on the influence of BC on soil physicochemical properties (102 papers), followed by the Chinese Academy of Agricultural Sciences (51 papers) and the University of Chinese Academy of Sciences (44 papers). We also discovered that 36% of the top 25 institutions were located in China, and 20% was in Pakistan, constituting a research network with these Chinese and Pakistani research institutions at its centre, which demonstrates the important scientific significance and impact of these institutions. In Pakistan, scholars from the University of Agriculture Faisalabad, Bahauddin Zakariya University and Government College University have published numerous publications in this field. The large TLS indicator suggests a high level of collaboration between research institutes. We found that eight of the top 10 institutes are in Asia, whereas the rest are in Europe. In general, the number of research institutions concerned with the influence of BC on soil physicochemical properties is substantial, although a certain number of large international institutional cooperation clusters have not yet been established. Notably, the Chinese Academy of Sciences published the most articles, which is in large part attributable to the Chinese national setting. China has a large population, the ecological state of the land is strongly tied to the sustainable growth of agriculture, and preserving soil health is a crucial step in ensuring food security (Goodland, 2013). Consequently, the Chinese government is extremely concerned about BC and has enacted several regulations to steer and encourage it (Meng et al., 2019).

In terms of the citations per paper (CPP) indicator, we discovered that the leading institutions are Newcastle University, Korea University, Kafrelsheikh University, Sejong University, King Abdulaziz University and the University of Wuppertal. However, Chinese research institutes are a substantial amount lower than them. This result suggests that the quality of findings is not just influenced by the number of publications and that China has to enhance the quality of its papers to increase its academic impact.

Table 1 Top 25 research institutions with high cooperation of research on the influence of BC on soil physicochemical properties

Rank	Institution	NP	C	TL	TLS	TC	CPP	APY
1	Chinese Academy of Sciences	102	China	156	259	2737	26.83	2019.50
2	Zhejiang Agriculture and Forestry University	32	China	72	143	1385	43.28	2019.38
3	University of Wuppertal	17	Germany	60	140	1171	68.88	2020.00
4	Foshan University	19	China	65	126	951	50.05	2019.84
5	University of Chinese Academy of Sciences	51	China	65	123	1368	26.82	2019.39
6	Sejong University	16	Korea	50	118	1166	72.88	2019.94
7	Newcastle University	14	UK	73	109	1280	91.43	2018.64
8	Korea University	16	Korea	55	107	1237	77.31	2019.56
9	King Saud University	27	Saudi Arabia	81	106	1050	38.89	2019.38
10	University of Agriculture Faisalabad	32	Pakistan	70	106	476	14.88	2019.90
11	Bahauddin Zakariya University	18	Pakistan	63	96	523	29.06	2019.89
12	Chinese Academy of Agricultural Sciences	44	China	69	96	512	11.64	2020.70
13	Zhejiang University	41	China	55	80	1816	44.29	2018.70
14	Northwest Agriculture and Forest University	34	China	55	77	620	18.24	2019.91
15	Kafrelsheikh University	8	Egypt	44	75	607	75.88	2020.75
16	King Abdulaziz University	9	Saudi Arabia	41	72	645	71.67	2020.44
17	Mendel University in Brno	15	Czech	42	68	137	9.13	2020.67
18	Nanjing Agricultural University	35	China	45	67	1970	56.29	2018.21
19	University of Western Australia	20	Australia	49	67	529	26.45	2019.37
20	University of Haripur	11	Pakistan	39	65	102	9.27	2020.67
21	Ain Shams University	13	Egypt	44	64	398	30.62	2020.17
22	Government College University	12	Pakistan	43	58	581	48.42	2019.00
23	Huazhong Agricultural University	23	China	41	56	844	36.70	2019.91
24	The Islamia University of Bahawalpur	11	Pakistan	42	52	61	5.55	2020.38
25	University of Florida	20	America	46	52	951	47.55	2017.45

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

3.3 Network analysis of authors

The author analysis depicts the contributions made by authors of publications on the influence of BC on soil physicochemical properties (Fig. 4). The nodes in this network reflect contributing authors in this field, whereas the linkages indicate the collaborative relationships between these authors. Some of the scattered nodes in Fig. 4 are grouped closely together, which suggests the high level of collaboration that exists between these various research authors. The higher the size of the typeface used, the more substantial the authors' contributions were. We found that Wang Hailong of China has a total of 21 papers, Yong Sik Ok of Korea has a total of 18 papers and Sylvain Bourgerie and Domenico Morabito of France have a total of 18 papers. They are considered the most influential authors in this field. Yong Sik Ok, the node in the network that is the most essential to the complete

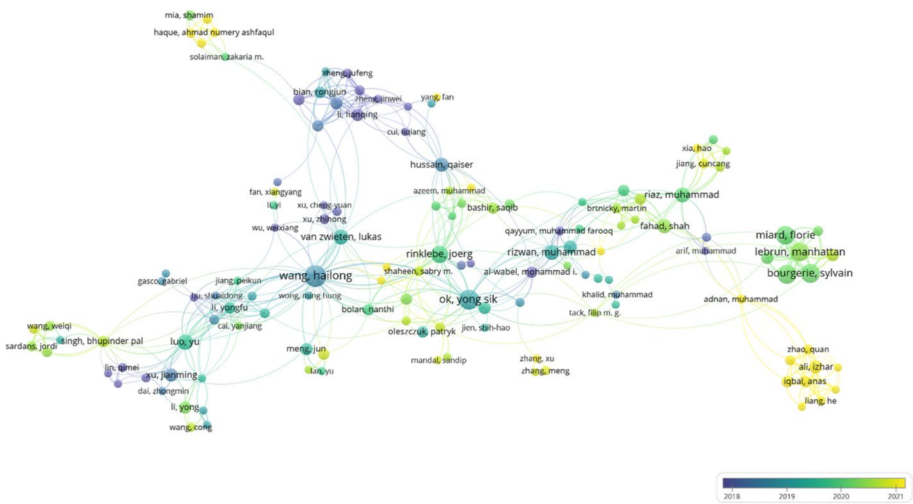

Fig. 4 Network analysis of collaboration between authors of research on the influence of BC on soil physicochemical properties (colour shades indicate the average publication year of the author)

structure, is without a doubt the most well-known and productive author of the group. To research soil physicochemical properties, he has worked on the production of BC with improved properties from various sources (He et al., 2021; Igalavithana et al., 2017).

On the basis of the shade of hue, we discovered that authors, such as Zhao Quan, He Liang, Izhar Ali and Anas Iqbal, are part of the rising research team. Sylvain Bourgerie, Manhattan Lebrun and Florie Miard et al. are also emerging teams and have published more papers than the team of Zhao Quan and He Liang et al. This result is also related to the early start of the study. Interestingly, authors whose backgrounds are comparable in terms of nationality and institution tend to interact more frequently and more comfortably with one another. Nevertheless, building collaborative networks with other active researchers working in the same field is advantageous for researchers. Therefore, collaboration across backgrounds, institutions, nations and multidisciplinary roles should be promoted because such collaborations allow reciprocal learning across various teams and contribute to the diversity and innovation of the subject area (Wu et al., 2020; Yan et al., 2020).

3.4 Network analysis of cooperation between countries

A total of 105 nations have studied the influence of BC on soil physicochemical properties, and we have selected the countries that have contributed more to the publishing of research in this field (Fig. 5a). America and Australia are in second and third positions, respectively, with 193 and 114 papers. Meanwhile, China remains in the lead. For Pakistan (99 articles), Germany (85 articles) and Spain (78 articles), the three rising nations in this field, no remarkable difference was found in the number of publications on the influence of BC on soil physicochemical properties. In addition, East Asia, North America, Oceania and Europe dominated the list of nations with the largest number of publications. Compared with America and China, the remaining nations have a comparatively modest number of publications. For example, Egypt, India and Saudi Arabia have only 63, 57 and 53 publications, respectively.

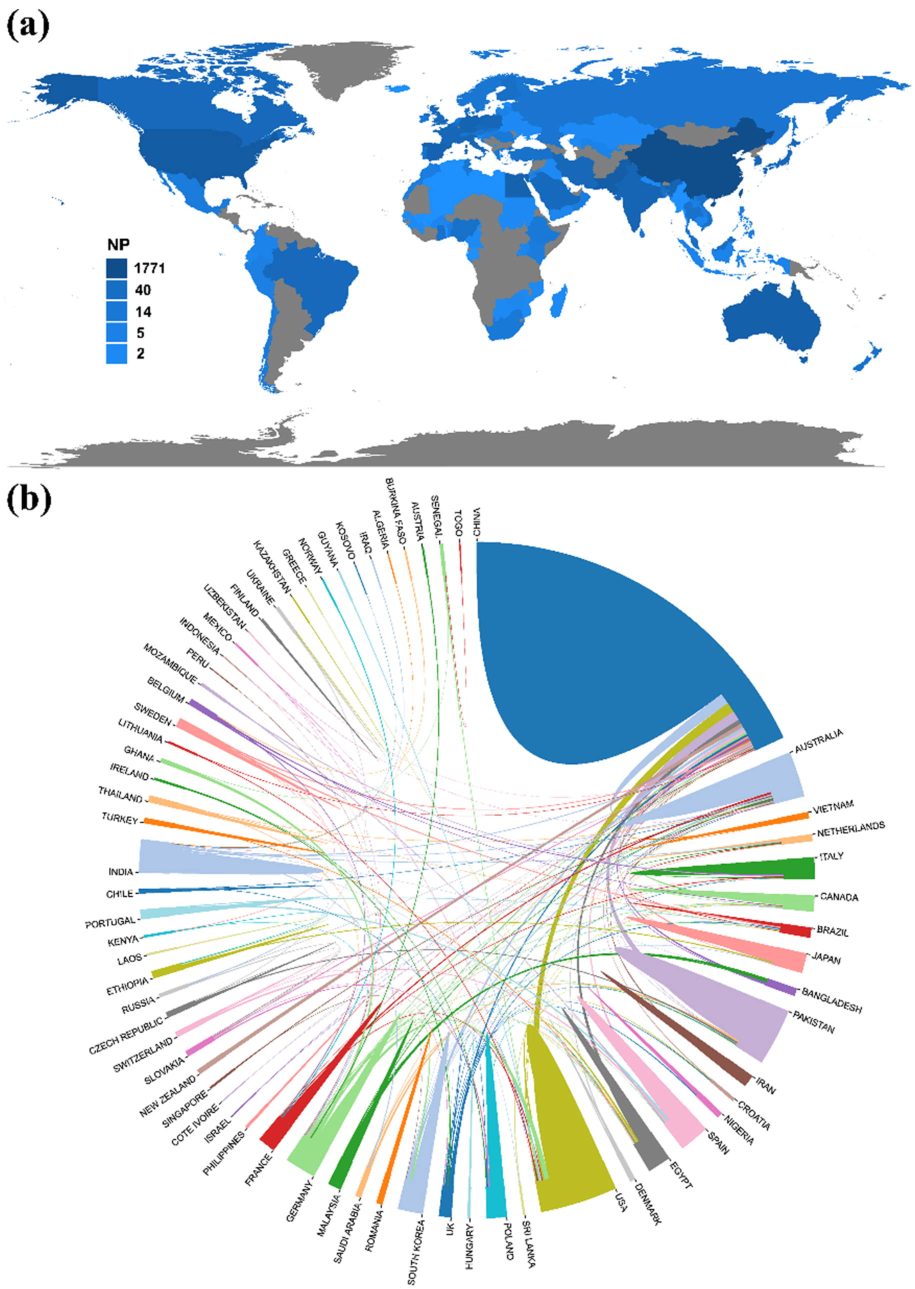

Fig. 5 **a** World map of the number of publications between countries that conduct research on the influence of BC on soil physicochemical properties (NP: number of papers); **b** country cooperation chord chart of research on the influence of BC on soil physicochemical properties

In Fig. 5b, the number of connecting lines, the density of those links and the aggregation that occurs between the nodes all point to the existence of much more intimate cooperation between various nations. Amongst these nodes, China (464), Australia (203), Germany (198) and America (195) all have high values in the TLS indicators, indicating that these countries are at the core of the collaborative network in the field of research on the influence of BC on soil physicochemical properties and that their related research has a considerable impact on this field. In general, the formation of various collaborations amongst various nations and areas continues to be a trend in this field of study. Despite the number of papers published in China being high, the CPP indicator is much lower than that of Australia, America and Germany (Table 2) because certain academic findings are of low quality, which is caused by the publication of duplicate or similar results. Therefore, the quality of research in China can still be improved, and original discovery must be encouraged whilst reducing the amount of repeated research.

3.5 Co-occurrence analysis of the keywords

Research hotspots feature prominently in an area of strong academic interest, typically defined as a cluster of closely connected research issues or subjects that have been studied extensively over a relatively short period (Fu et al., 2013; Xie et al., 2008). Keywords in an article can greatly refine, extract and summarise the article's primary concept, which is the core point of the article, and more visually express the direction and

Table 2 Top 20 countries with high cooperation of research on the influence of BC on soil physicochemical properties

Rank	Country	NP	APY	TC	TL	TLS	CPP
1	China	689	2019.87	17,002	60	464	24.68
2	Australia	114	2018.46	5976	44	203	52.42
3	Germany	85	2018.56	3266	52	198	38.42
4	America	193	2017.84	7889	54	195	40.88
5	Pakistan	99	2019.87	2312	29	163	23.35
6	Saudi Arabia	53	2019.94	2124	31	145	40.08
7	Egypt	63	2020.23	1795	32	133	28.49
8	Korea	40	2019.93	2178	23	115	54.45
9	Spain	78	2018.74	3158	34	98	40.49
10	France	51	2019.56	1082	32	80	21.22
11	England	33	2018.33	1395	34	78	42.27
12	Italy	52	2018.96	2460	28	66	47.31
13	Czech	36	2020.33	435	27	65	12.08
14	Japan	43	2019.80	1347	29	63	31.33
15	Brazil	35	2019.03	684	24	56	19.54
16	India	57	2020.09	1090	34	55	19.12
17	Canada	52	2018.62	1788	23	53	34.38
18	New Zealand	24	2018.83	1286	15	42	53.58
19	Poland	42	2019.66	690	22	41	16.43
20	Belgium	23	2018.96	941	18	36	40.91

NP number of papers, *C* country, *TL* total link, *TLS* total link strength, *TC* total citations, *CPP* citations per paper, *APY* average publication year worth of study results (Tan et al., 2021). Keyword co-occurrence analysis creates the knowledge graph, where the circles at the network's nodes stand in for the terms themselves (de Jong et al., 2015). The co-occurrence of keywords is shown by the appearance of correlation curves between the circular nodes, and the bigger the diameter and area of the circular nodes, the more frequently the term appears in this field (Su & Lee, 2010; Wang et al., 2021).

Figure 6a reveals that BC (713), amendment (160), physicochemical properties (141), crop yield (98), heavy metals (84), microbial community (67), soil (67), soil fertility (65), pyrolysis (63) and carbon sequestration (62) were the top 10 terms with more than 50 co-occurrences. These ten keywords accounted for 30.56% of the total number of occurrences. The keyword knowledge map of the entire BC field is centred on the three crucial words (BC, amendment and physicochemical properties), which are located in the central portion of the network, surrounded by other circular nodes of varying sizes, forming a radiating pattern from the centre outwards. To display the high-frequency keywords, the threshold value was adjusted to 6, and 127 high-frequency keywords were acquired. The grouping of terms in different hues in the network indicates that these high-frequency keywords serve as a form of linking hub to join various low-frequency keywords, which collectively represent the hottest frontier research subjects in the BC field during the previous 12 years (Wu et al., 2021).

These keywords may be separated into four distinct clusters. The red cluster is related to physicochemical properties, heavy metals and microbial communities. The high-frequency keywords included BC, amendments, physicochemical properties, heavy metals, microbial communities, soil, compost and soil quality. The application of BC in the soil can improve the physicochemical properties of soil, enhance the activity of the microbial community, immobilise heavy metals and thus remediate the soil. Calcan et al. (2022) found that BC led to an increase in conductivity, pH, soluble and available nutrients and reduced soil bulk density (SBD), which improved plant root development and enhanced water and nutrient uptake (Calcan et al., 2022). The yellow clusters represent the link between the carbon sequestration and climate change mitigation effects of BC. High-frequency keywords include carbon sequestration, GHG, N_2O, paddy soils, pyrolysis temperature, agriculture, CO_2, climate change and soil microbial biomass. BC performed well in reducing GHG emissions. Additionally, BC stays in the soil for hundreds to thousands of years, showing great carbon sequestration potential. Shin et al. (2021) found that the application of BC can contribute to sustainable agriculture by mitigating GHG emissions, enhancing ecosystem carbon sinks and improving the efficiency of nitrogen use. The keywords in the blue cluster are related to crop yield, enzyme activity and fertilisation. High-frequency keywords include crop yield, soil organic matter (SOM), enzyme activity, fertilisation, nutrients, phosphorus, nitrogen and soil health. BC is important for the nutrient cycling of N, P and K and soil health. Liu et al. (2015) discovered that BC plays a critical role in enhancing soil carbon storage, improving soil quality and increasing crop yields; has the potential to influence soil nutrient cycling directly or indirectly; and has a profound impact on soil nutrient leaching (Liu et al., 2015). The green cluster focuses on pyrolysis, different types of BC and soil organic carbon (SOC). High-frequency keywords included soil fertility, pyrolysis, pH, plant growth, SOC, organic amendments, charcoal and black carbon. According to the meta-analysis, different types of BC are one of the factors that influence the priming effect of BC on the various soil carbon components. Liu et al., (2016a, 2016b) found that BC amendment resulted in a remarkable increase in SOC and MBC contents. Soil properties, land use types, agricultural practices and BC characteristics should be considered when assessing the actual potential of BC to mitigate climate change Liu et al. (2016a).

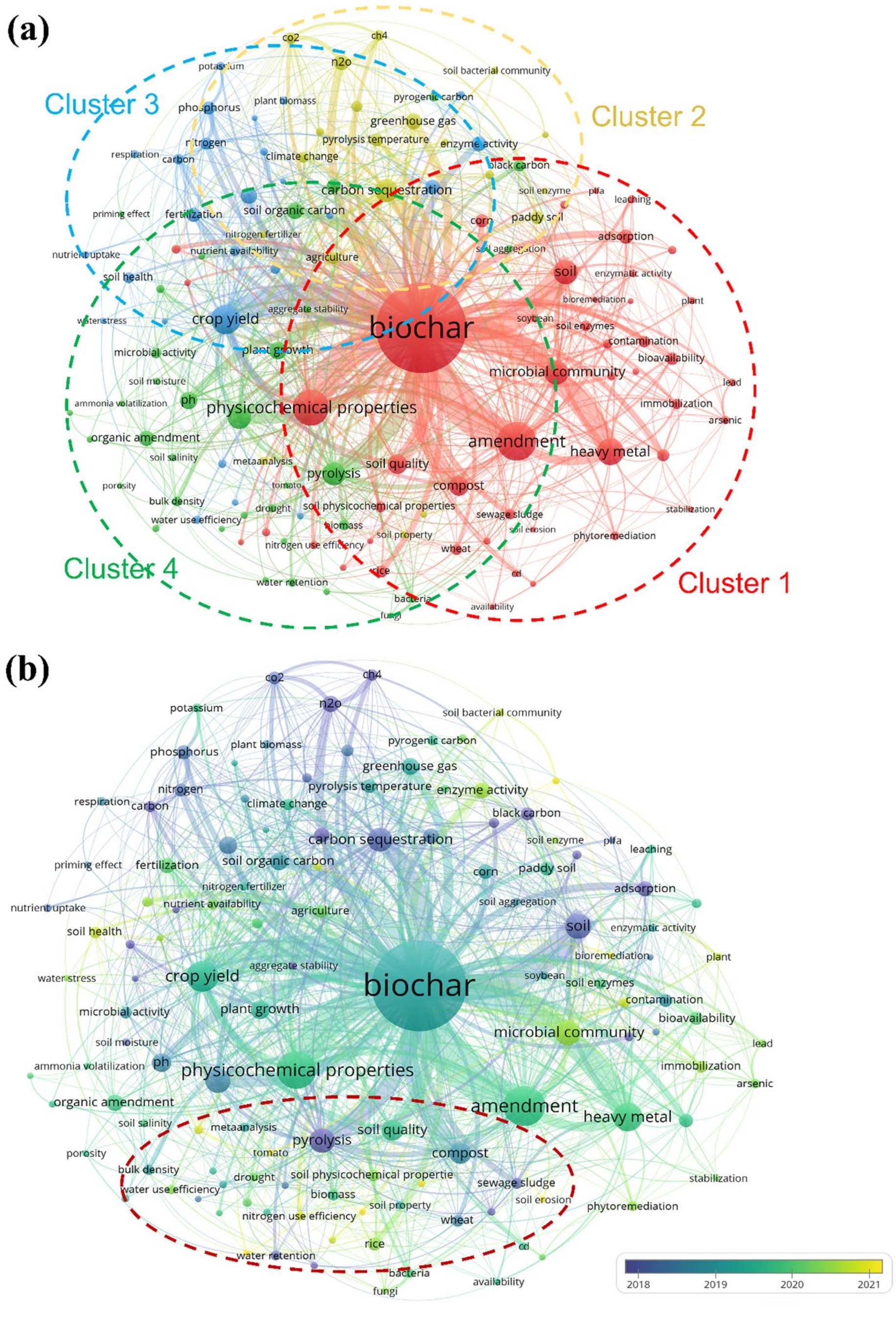

Fig. 6 **a** Cluster analysis of the keyword co-occurrence of research on the influence of BC on soil physicochemical properties; **b** publication time diagram of the keyword co-occurrence of research on the influence of BC on soil physicochemical properties (colour shades indicate the average publication year of the keywords)

The light-coloured keywords in Fig. 6b are all the research hotspots in recent years. They mainly include organic fertiliser, crop growth, nitrogen use efficiency, chemical fertiliser, waste management, soil erosion, soil health, salinity, bioremediation, soil physicochemical properties and soil bacterial community. Therefore, future research in this field can be summarised in these three directions: (1) effects of BC mixed with organic and chemical fertilisers on crop growth and nitrogen use efficiency; (2) response to a series of soil health problems, such as soil erosion and salinisation by waste management, to produce BC for bioremediation; and (3) study the effects of BC on soil physicochemical properties from the perspective and mechanism of soil bacterial communities and other microorganisms.

3.6 Network analysis of paper citations

The findings of the available literature on the influence of BC on soil physicochemical properties are presented in Table 3. This analysis was conducted using a literature citation network. By combining Table 3 with Fig. 7, we can deduce that "A quantitative review of the effects of BC application to soils on crop productivity using meta-analysis" (Jeffery et al., 2011), "Influence of Pyrolysis Temperature on BC Property and Function as a Heavy Metal Sorbent in Soil" (Uchimiya et al., 2011), and "Effect of BC amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China" (Zhang et al., 2010) are the most important pieces of published research in this field. In the top 10 most highly cited publications, reviews made up 40% of the total. These reviews often cover fundamental or topical concerns of the influence of BC on soil physicochemical properties. They are detailed, with thorough analysis and strong conclusions, and they tend to address either fundamental or topical issues.

In addition, seven of the top 10 most highly cited papers were concentrated in the early research phase (2010–2015), suggesting that these papers contributed to the development of theories, concepts and methods and provided fundamental ideas for the development of the BC field. Notably, three more studies dealt with microbes, heavy metals and GHG emissions. This finding indicates that contemporary research on the influence of BC on soil physicochemical properties has been undertaken in conjunction with these elements. In bibliometric analysis, two important assessment metrics are known as the impact factor and the H-index. The importance of the impact factor as a measure of the academic level of researchers, the quality of publications and the influence of journals cannot be overstated. The H-index can precisely quantify the academic accomplishments of various authors in a certain subject and accurately indicate the strength of a country in a particular topic. Thus, the academic impact is larger when the H-index is higher. We conducted research and concluded that the most influential journals in this field are Environment International, Journal of Hazardous Materials, Environmental Science and Technology and Environmental Pollution, which correspond to the top 10 published research articles in the field.

3.7 Network analysis of journal cocitations

Journals are the most essential source, as well as the most crucial indication of scientific outcomes (Muhuri et al., 2018). The journal cocitation network provides an opportunity to ascertain the concentration and the diffusion of research within the field (Shi et al., 2021). All the outcomes of the study performed on BC from the year 2010 to 2022 were published in 410 different journals (Fig. 8). Table 4 shows a list of the top 10 journals

Table 3 Top 10 papers with high citations of research on the influence of BC on soil physicochemical properties

Rank	Title	FA	PY	Journal	IF	HI	TC	TL
1	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis	Simon Jeffery	2011	Agriculture Ecosystems and Environment	7.089	26	1339	227
2	Influence of Pyrolysis Temperature on Biochar Property and Function as a Heavy Metal Sorbent in Soil	Minori Uchimiya	2011	Journal of Agricultural and Food Chemistry	6.048	35	538	27
3	Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China	Zhang Afeng	2010	Agriculture Ecosystems and Environment	7.089	26	508	74
4	Biochar induced soil microbial community change: Implications for biogeochemical cycling of carbon, nitrogen and phosphorus	Craig Anderson	2011	Pedobiologia	3.179	17	498	74
5	Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs	Joan J. Manya	2012	Environmental Science and Technology	12.154	21	484	25
6	Effects and mechanisms of biochar–microbe interactions in soil improvement and pollution remediation: A review	Zhu Xiaomin	2017	Environmental Pollution	10.366	16	409	76
7	Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China	Peng Xinhua	2011	Soil and Tillage Research	7.829	34	404	77
8	Immobilization of Cu(II), Pb(II) and Cd(II) by the addition of rice straw derived biochar to a simulated polluted Ultisol	Jiang Jun	2012	Journal of Hazardous Materials	12.984	21	377	35
9	Soil amendments for immobilization of potentially toxic elements in contaminated soils: A critical review	Kumuduni Niroshika Palansooriya	2020	Environment International	13.238	14	367	26
10	Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil	Getachew Agegnehu	2016	Science of the Total Environment	10.237	23	350	78

FA first author, *PY* publication year, *C* country, *IF* impact factor, *HI* H-index, *TC* total citations, *TL* total link

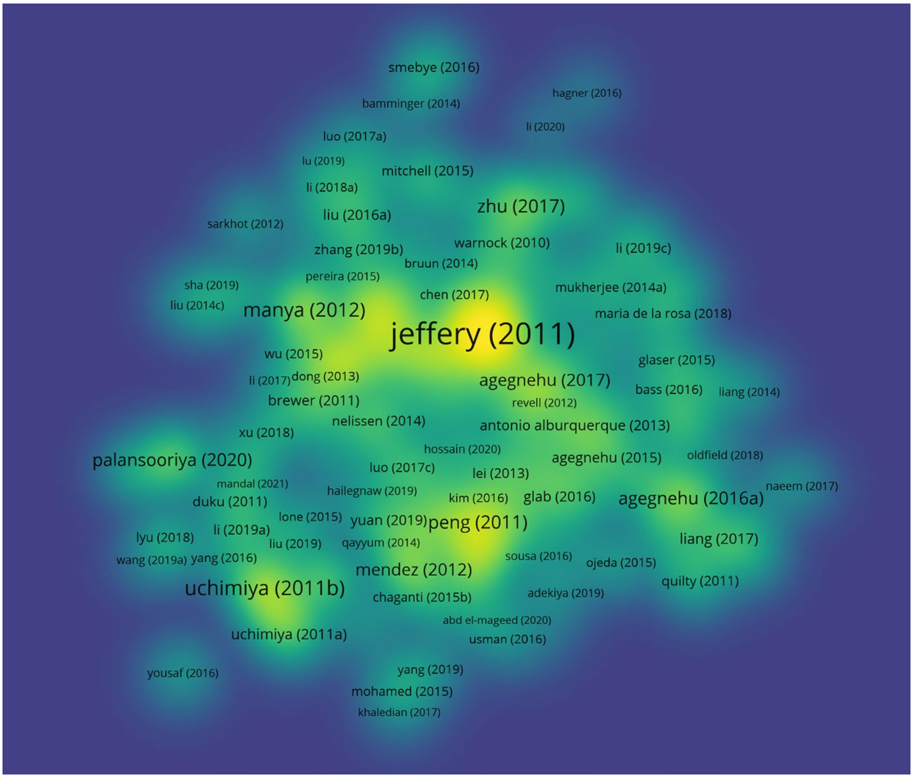

Fig. 7 Network analysis of the paper citations of the influence of BC on soil physicochemical properties

that publish research on the influence of BC on soil physicochemical properties based on the TLS ranking. The large number of papers published in the top five journals (i.e. Science of the Total Environment, Soil Biology and Biochemistry, Chemosphere, Bioresource Technology and Plant and Soil) provides additional evidence of the significance of BC in affecting the physicochemical properties of soil.

The analysis of journal cocitations reveals that several journals have a higher level of cocitation intensity. Soil Biology and Biochemistry have a larger number of cocitations than Science of the Total Environment, suggesting that papers published in Soil Biology and Biochemistry have a slightly better chance of being referenced. The greatest correlation between Science of the Total Environment and Chemosphere implies that these two journals are strongly connected. The connections that are shown in journal cocitations are often changing or preliminary (Muessigmann et al., 2020). In the future, research should examine the effects of BC on soil physicochemical properties using an approach that is comprehensive and based on publications that have had numerous citations and have been published in mainstream journals (Guo et al., 2019). According to the findings that we obtained from the COPP indicator, in the field of BC, articles that were published in Bioresource Technology, Environmental Science and Technology, Soil Biology and Biochemistry and Plant and Soil are more likely to be cited by

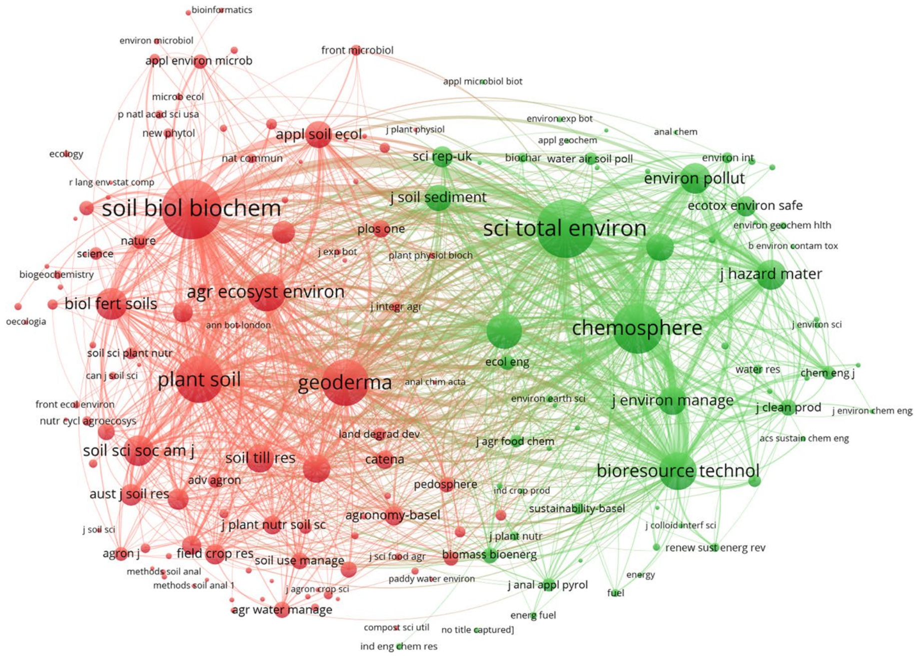

Fig. 8 Network analysis of the journal cocitations of research on the influence of BC on soil physicochemical properties

Table 4 Top 10 journals with high cocitations of research on the influence of BC on soil physicochemical properties

Rank	Journal	IF	NP	TL	TLS	TCO	COPP
1	Science of the Total Environment	10.237	109	999	335,778	4077	37.40
2	Soil Biology and Biochemistry	9.956	12	996	281,773	4233	352.75
3	Chemosphere	8.520	51	999	272,797	3238	63.49
4	Bioresource Technology	11.139	1	997	235,174	2066	2066.00
5	Plant and Soil	5.440	12	999	211,008	2942	245.17
6	Geoderma	7.444	42	999	206,753	2885	68.69
7	Environmental Science and Technology	12.154	4	993	157,821	1831	457.75
8	Agriculture Ecosystems and Environment	7.089	22	997	149,904	2093	95.14
9	Journal of Hazardous Materials	12.984	15	992	126,278	1432	95.47
10	Journal of Environmental Management	8.549	29	992	124,059	1299	44.79

NP number of papers, *IF* impact factor, *TCO* total cocitations, *TL* total link, *TLS* total link strength, *COPP* cocitations per paper

one another. This finding suggests that these journals are influential, highly recognised and interrelated. In general, the information presented in these journals offers a measurement of the progress of research on the influence of BC on soil physicochemical properties.

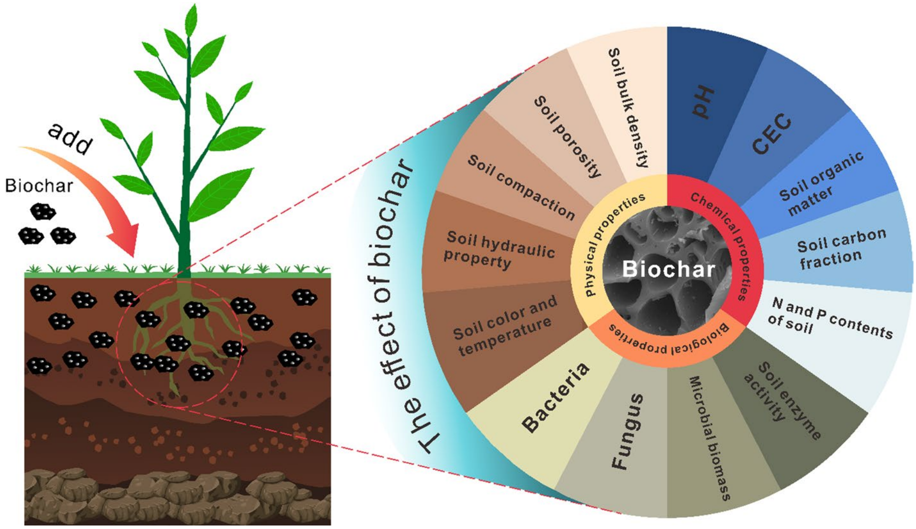

Fig. 9 BC application has a considerable effect on soil properties

3.8 Effects of BC application on soil properties

3.8.1 Soil physical properties

The application of BC has a favourable influence on soil physical properties (Fig. 9), which is strongly connected to the type of BC and soil, BC particle size and application amount. Soil bulk density is an important measure of soil physical qualities and is strongly related to soil compaction. Low SBD improves soil structure, promotes nutrient release and uptake and effectively minimises soil compaction. According to one study, the incorporation of BC into soil dramatically decreased SBD, increased overall porosity and promoted soil aggregation (Laird et al., 2010; Qin et al., 2016). Moreover, the application of BC successfully enhanced the soil pore structure. Soil pore space provides soil organisms with oxygen and space and regulates the conversion, retention and use of water. The pore connectivity and particle size of BC have a great influence on the soil pore structure. BC is porous and has a large specific surface area, which promotes the activity of microorganisms in soil pores, as well as the growth of plant roots. According to previous studies, the application of BC alters the pore distribution of the soil by reorganising the porosity of the soil (Rasa et al., 2018). Given that BC is black, its addition darkens the soil, which increases soil warmth, promotes seedling emergence and increases crop production (Öz, 2018). The use of BC affects the soil's surface reflectance and thermal conductivity, hence altering soil temperature. According to one study, BC may adjust soil temperature at a 5 cm depth (Zhang et al., 2013).

The principal soil hydraulic parameters are saturated hydraulic conductivity and saturated hydraulic conductivity. The large specific surface area and high porosity of BC improve the soil water holding capacity and alter the residence duration and flow pattern of water through the soil (Abrol et al., 2016). BC has been demonstrated to boost soil water holding capacity in the field. Consequently, BC can be utilised as an environmentally beneficial ingredient to enhance soil water retention by adjusting application rates. Additionally, the application of BC affects the water retention and mechanical strength of the soil. Larger pore sizes can improve the capacity of BC to retain water. Consequently, BC can increase the hydraulic conductivity of soil water, particularly when added to sandy soils. BC greatly enhances the saturated hydraulic conductivity of several soil textures (Trifunovic et al., 2018); however, certain values decrease or show no effect (Devereux et al., 2012), resulting in various effects that may be influenced by soil type, BC type and application rate.

3.8.2 Soil chemical properties

The application of BC also promotes soil chemical activity (Fig. 9). BC controls the soil's pH and enhances the saturation of bases (Masud et al., 2014). According to previous studies, the application of BC to acidic soils increased the soil pH to different degrees (Hossain et al., 2010; Nielsen et al., 2018). Therefore, the application of BC to alkaline crops and acidic soils is beneficial for their improvement. Furthermore, surface BC is abundant in functional groups. BC application can considerably affect soil cation exchange capacity (CEC) levels. CEC is utilised to evaluate a soil's capacity to acquire, hold and transfer cations. High CEC soils have a greater propensity to absorb Ca^{2+}, Mg^{2+} and NH_4^+, which may improve the usage of soil nutrient ions and reduce the leaching of nutrients (Yuan et al., 2011). According to previous studies, the application of BC greatly boosts the total soil charge and CEC (Chintala et al., 2014).

BC application enhances SOM content. The soil environment is essential for crop growth, and the application of BC may boost soil fertility, the efficacy of soil fertilisers and the nutrient absorption efficiency of plants (Schmidt et al., 2014). According to many studies, the degree to which BC enriches SOM depends on the BC's stability and the amount supplied (Wang et al., 2005; Zygourakis, 2017). A rise in the SOM content can influence crop yield. In addition, the increased soil microbial population increases the soil's specific surface area and porosity, thereby improving the carbon and nitrogen cycle process by allowing plant roots to absorb nutritional ions from the soil. As an inert carbon source, BC can be sequestered in the soil for a long period and act as a GHG reduction material; it can remain in the soil for up to 100 years (Fang et al., 2014). It is generated from agricultural waste and has widespread agricultural applications. The application of BC to soil modifies the cycling and transformation of nitrogen, hence enhancing the efficiency of nitrogen in the soil and decreasing its leaching. Sika and Hardie (2014) discovered that plants can utilise ammonium N adsorbed by BC, hence decreasing N losses and enhancing N usage. After adding BC, Harter et al. (2014) discovered an increase in soil microbial N concentration. This result shows that microorganisms absorb nitrate N as organic N and that BC and soil minerals readily adsorb organic N. Nevertheless, several studies have demonstrated that pH has a substantial effect on the effect of BC on soil ammonium nitrogen. The application of BC did not decrease nitrate leaching but rather increased its losses (Cao et al., 2017). Consequently, the addition of BC influences the transformation of N in soil on the basis of the temperature of BC preparation, the amount added and the soil pH.

3.8.3 Soil biological properties

Soil microorganisms are sensitive to environmental changes and can serve as an early indicator of changes in ecosystem function, providing a solid foundation for soil attributes. Therefore, the influence of BC on soil physicochemical qualities affects soil biological properties either directly or indirectly (Fig. 9). BC's porous structure provides a living room for microorganisms. Bacteria can be adsorbed on the surface of BC so that it is not affected too much by soil leaching, thus boosting the number of soil bacteria (Gao et al., 2017). Specifically, the increased activity of nitrogen-fixing bacteria promotes the chemical activity of soil. The surface of BC includes carbon and nitrogen sources that assist bacterial breakdown. According to previous studies, BC dramatically enhanced the population and nitrogen-fixing ability of nitrogen-fixing bacteria (Kim et al., 2007).

The porosity and surface characteristics of BC are conducive to the colonisation and activity of rhizosphere fungi (Aggangan et al., 2019). The retention capacity of BC for fungi may be determined to a large extent by its surface porosity. According to Verma and Reddy (2020), BC greatly boosted the biomass of soil fungi. Steinbeiss et al. (2009) reported that the application of BC might considerably improve fungal colonisation. Nonetheless, many investigations have observed that BC addition lowers the fungal population because BC exhibits variable physicochemical features and has varying effects on soil ecosystem processes due to variances in source materials, processing conditions and thermal cracking (Nie et al., 2018).

The extinction of soil microorganisms enhances the soil's physicochemical impacts, whereas changes in the soil microenvironment influence the proliferation of microorganisms (Lehmann et al., 2011). Microorganisms in the soil may convert charcoal to humus carbon. The application of BC dramatically alters the structural composition of soil microorganisms because the BC surface contains a portion of soluble carbon and nitrogen sources that promote microbial activity (Zhang et al., 2014). In addition, the porosity and surface characteristics of BC may retain water and nutrients and provide a habitat for microbes to thrive (Quilliam et al., 2013). Several studies have demonstrated an increase in soil microbial load following the application of various BCs (Ge et al., 2019; Silva et al., 2020). Nevertheless, Dempster et al. (2012) discovered that excessive BC application may threaten the abundance and composition of microbial communities.

Soil enzyme activity often represents the intensity and direction of many biochemical activities, and its changes have a strong influence on biogeochemical processes (Jiang et al., 2021). Turner et al. (2002) discovered that the application of BC boosted the activity and quantity of soil enzymes. According to Sakin et al. (2021), the addition of BC considerably boosted soil enzyme activity. This finding indicates that the application of BC altered enzyme reactions in the soil, resulting in variable alterations in enzyme activity across soils. This result was correlated with the amount of BC supplied, and distinct microbial communities induced distinct alterations in enzyme activity.

4 Conclusions

Currently, the effects of BC on the physicochemical and biological properties of soil as an environmentally friendly soil amendment have attracted much attention. Between the years 2010 and 2022, a total of 1448 papers were obtained for studies on the influence of BC on soil physicochemical properties. Research increased rapidly after 2015, and the field reached a relatively mature level by 2022. The author with the most published papers is Wang Hailong, and the author with the most citations and the highest H-index is Yong Sik Ok, making him the most well-known and productive author in the field. The top three institutions with the most published papers are the Chinese Academy of Sciences, the Chinese Academy of Agricultural Sciences and the University of Chinese Academy of Sciences. However, in terms of CPP indicators, the leading institutions are Newcastle University, Korea University, Kafrelsheikh

University, Sejong University, King Abdulaziz University and the University of Wuppertal. In addition, America and China are the two countries that published the most articles. Regarding CPP indicators, Australia, America and Germany rank in the top three. China ranks much lower than them in terms of academic influence.

Keywords can be separated into four distinct clusters: (1) physicochemical properties, heavy metals and microbial communities; (2) carbon sequestration and climate change mitigation effect; (3) crop yield, enzyme activity and fertilisation; and (4) pyrolysis, different types of BC and SOC. This categorisation suggests that the current research hotspots in the BC field must focus not only on this aspect of soil physicochemical properties independently but also in combination with heavy metals, microbial communities and carbon sequestration aspects. According to the number of published articles, journals, such as Science of the Total Environment, Agronomy, Chemosphere, Journal of Soils and Sediments, Environmental Science and Pollution Research, are in the top five. The greatest correlation between Science of the Total Environment and Chemosphere implies that these two journals are strongly connected. Articles that were published in Bioresource Technology, Environmental Science and Technology, Soil Biology and Biochemistry and Plant and Soil are more likely to be cited by one another. Given that the BC field is in a period of rapid development, future research should be based on highly cited papers in mainstream journals, combine various research methods and perspectives and actively explore the following: (1) the effects of BC mixed with organic and chemical fertilisers on crop growth and nitrogen use efficiency; (2) the response to a series of soil health problems, such as soil erosion and salinisation by waste management, to produce BC for bioremediation; and (3) the effects of BC on soil physicochemical properties from the perspective and mechanism of soil bacterial communities and other microorganisms.

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Author contributions TZ, JC and CL were involved in study conception and design. TZ and CL were involved in acquisition of data. TZ and JC analysed and interpreted the data. TZ drafted the manuscript. TZ, HC, YT, WG, XL, HL, CL and JC were involved in critical revision.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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