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The Trends in Research on the Effects of Biochar on Soil

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Abstract: The present study used bibliometric methods to analyze the literature regarding the biochar effects on soil that are included in the Web of Science Core Collection database and quantified the annual number of publications in the field and distribution of publications. Using CiteSpace as a visual analytic software for the literature, the distribution of the subject categories, author collaborations, institution collaborations, international (regional) collaborations, and cocitation and keyword clustering were analyzed. The results showed the basic characteristics of the literature related to the effects of biochar on soil. Furthermore, the main research powers in this field were identified. Then, we recognized the main intellectual base in the domain of biochar effects on soil. Meanwhile, this paper revealed the research hotspots and trends of this field. Furthermore, focuses of future research in this field are discussed. The present study quantitatively and objectively describes the research status and trends of biochar effects on soil from the bibliometric perspective to promote in-depth research in this field and provide reference information for scholars in the relevant fields to refine their research directions, address specific scientific issues, and help scholars to seek/establish relevant collaborations in their fields of interests.

Keywords: biochar; soil; mapping knowledge domain; CiteSpace; popular research topics; research trends

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1. Introduction

The discovery of Amazonian dark earths—previously known as Indian Black Earth (Terra Preta de Indio)—opened the field of biochar research [1,2]. Biochar is a category of carbon-rich organic materials that are produced by the pyrolysis of biomass raw materials under oxygen-limited conditions [1,3]. Biochar is structurally stable and difficult to decompose by microbes [4,5]. Biochar is an alkaline porous material with a low bulk density, large specific surface area, and strong adsorption ability [6,7].

Biochar addition to soil can cause changes in the soil physical properties, including decreases in the soil bulk density and increases in the porosity, which promotes the formation of aggregates [8] and in turn improves the soil structure [9]. Biochar can also modify the soil chemical properties, e.g., by increasing cation exchange capacity (CEC) [10], and since most biochars are alkaline, they can increase the pH of acidic soils [11]. Since biochar contains a large amount of organic carbon, it can rapidly increase the soil organic carbon content in a short period of time [12]. Biochar can act as an adsorbent reducing nitrogen leaching and increasing nitrogen use efficiency [13]. The porosity and surface area of biochar play an important role in maintaining soil nutrients due to surface binding of both cations and anions to its surfaces [14–17]. The strong NH_4^+ adsorption on biochar [18] can reduce the nitrogen volatilization, which in turn enhances the soil fertility [19] and promotes plant growth and development [20]. Biochar can enhance the soil microbial community structure and enzymatic activity through increasing basal soil respiration and respiration rate per micro-organism [21–24], for example, by enhancing the soil microbial biomass carbon, nitrogen, and phosphorus [25–27] and facilitating the growth of soil bacteria and specifically of certain microbial guilds (e.g., diazotrophs) [28,29]. Biochar can provide a physical niche for growing hyphae, devoid of fungal grazers, thereby promoting soil fungal growth [30]. Given the measured biochar pores size, soil grazers in the size range of collembola and protozoans (>1.6 mm) would be excluded [6]. For example, some arbuscular mycorrhizae increase root colonization sites in the presence of biochar [6,31]. In addition, biochar has potentially synergistic effects on mycorrhizal fungi by increasing their abundance and activity and promoting their permeation and colonization of plant roots [32,33]. The fine structural pores of biochar declined oxygen concentration, thus allowing nitrogenase to work effectively [34]. Furthermore, due to the positive surface charges of biochar, it can adsorb soil heavy metals and organic pollutants [35–37], which contributes to reduce the mobility of heavy metals (Cu and Zn) [38] and other organic soil contaminants (insecticides) [39]. Therefore, biochar research and application in soil improvement have received increasing attention from scholars.

Literature is the main form of representation of scientific research output [40]. After biochar was unified its name in the 1st International Biochar Conference in 2007, much research work has been done regarding the effects of biochar on soil properties, soil carbon fixation and emission reduction, and soil pollution. This resulted in the publication of many studies, including higher-impact review articles related to the biochar effects on soil [6,21,41]. These reviews play an important role in furthering in-depth studies along specific directions in these fields. However, it is also necessary to fully understand the current research progress, popular research topics, and development trends regarding the biochar effects on soil from a wider perspective.

Given the broad range of literature regarding the effects of biochar on soil, systematic and accurate bibliometric methods should be used to conduct a combined quantitative and qualitative review to more precisely and comprehensively assess the biochar effects on soil. CiteSpace—a visual analytic tool—analyzes the relationships between popular frontier research topics on a subject, the evolution of topics, and the determination of the knowledge base [42] and is a currently relatively popular visual data analysis software for scientific research. Therefore, the present study used bibliometric methods to statistically describe and analyze the research findings related to the biochar effects on soil. In combination with CiteSpace, data mining and visual quantitative analysis of the literature was conducted to reveal the knowledge base of the studies on the biochar effects on soil. The current research status and popular trends are identified to aid in explaining the latest research progress and its future trends. This study aims to facilitate more in-depth research on the biochar effects on soil and provide reference information for scholars in the relevant fields to refine the research directions and issues.

2. Material and Methods

2.1. Data Collection

The literature data were obtained from the Science Citation Index Expanded (SCI-E) database in the Web of Science (WOS) Core Collection provided by Clarivate Analytics. The SCI-E database in the WOS Core Collection is the most frequently used database in bibliometric studies [43] and is regarded as the most reputational academic journal system in which the published papers are ensured with rigorous peer review process [44,45]. The data were retrieved on 1 April 2020. In the SCI-E database, the "topic" tag was selected in "Advanced Search" to search for the literature relevant to the research on the biochar effects on soil. The topic was set to "TS = (biochar* AND soil*)", and document type was set to "Article" and "Review". Since biochar was unified its name in 2007, we set the time range from 2007 to 2019. The titles and abstracts of publications obtained from the search were checked to determine their relevance to the biochar effects on soil. Irrelevant literature was excluded from the analysis.

2.2. Methodology

Using the bibliometric data provided by Web of Science, the following metrics were obtained: annual number of publications, number of publications, citation frequency, and average citation frequency per publication in journals. CiteSpace was used to analyze the distribution of the subject categories of publications, coauthorship, institutional collaborations, and international collaborations [46]. In addition, CiteSpace was used to perform cluster analysis of publications and keywords based on the strength of correlation and similarity, which is powerful for illustrating maps [47]. The analysis of the clustering of publications can help identify the knowledge base of the biochar effects on soil. The analysis of the clustering of keywords can reflect the popular research topics and trends in this field.

3. Results and Discussion

3.1. Basic Characteristics of the Literature

3.1.1. Annual Variations in Publications

The annual number of articles published in given research field can reflect the degree of conceptual development and where attention is being directed in that field and is therefore an important indicator of its development and evolution [48]. As of 2019, a total of 5837 publications were retrieved related to the biochar effects on soil. There were 244 publications in this field during 2007–2011, which accounted for 4.18% of all the publications in WOS. During 2012–2015, there were 1490 publications in this field, which accounted for 25.53% of all the publications in WOS. During 2016–2019, there were 4103 publications in this field, which accounted for 70.29% of all the publications in WOS. We separated the entire research stage to three stages of slow growth, steady growth, and rapid growth, corresponding to the distribution of the number of publications in different time periods (Figure 1). Prior to 2011, this research field received limited attention and was in the initial stage. From 2012 to 2015, the theoretical basis was formed as a large body of relevant literature was published, and the development stage was reached. From 2016 to 2019, the research field received a rapidly increasing amount of attention and entered the rapid development stage. This showed that the research field was being given extensive attention by scholars. As the relevant studies continue to develop, research on the biochar effects on soil is expected to be more in-depth and to improve.

3.1.2. Subject Category Distribution

The literature regarding the biochar effects on soil covers various subject categories in Web of Science. To describe the distributions of the subject categories and more common subject categories, we performed a co-occurrence analysis of the subject categories to identify them in the various developmental stages of the research field [49]. This study selected the top 50 most frequent co-occurring subject categories during 2007–2019 to analyze the characteristics of their developments. Figure 2 shows the high-frequency co-occurrence network map of the subject categories in the field of the biochar effects on soil. Figure 3 shows the frequency and centrality of the top 10 most frequent co-occurring subject categories. The centrality refers to the ratio of the number of shortest paths between two nodes passing through a given node to the number of shortest paths between the two nodes in the network. When the centrality > 0.1, the given node is considered a key node in the network. The studies revealed the importance of the subject categories related to the biochar effects on soil. (1) "Environmental science and ecology" was the largest node as the subject category that received the most attention, with a frequency of 2865, followed by "environmental sciences" (2793), "agriculture" (2092), and "soil science" (1217). These results showed that the scholars in this research field were most concerned with environmental, ecological, agricultural, and soil issues. (2) Among the top 10 high-frequency subject categories, "agriculture" had the highest centrality, suggesting it has a pivotal role in the field of the biochar effects on soil that links different subject categories. The centrality of "chemistry", "science & technology—other topics", and "energy & fuels" followed that of "agriculture". Therefore, agriculture, chemistry, and energy & fuels played key intermediary roles in the network structure of the research field.

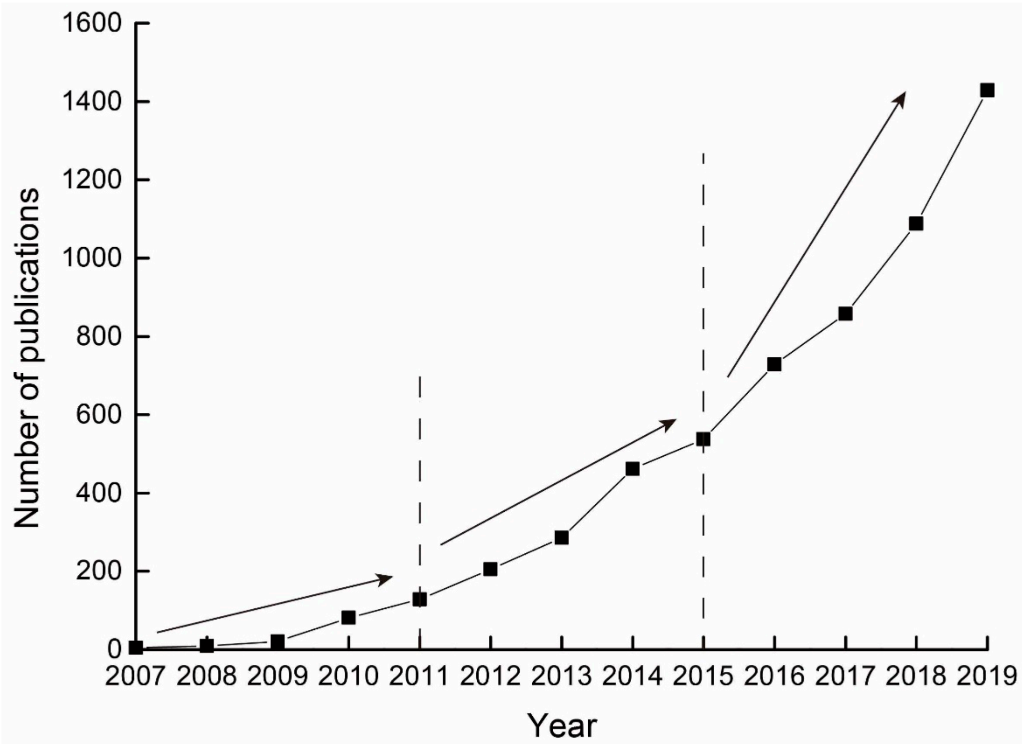

Figure 1. Annual variation in documents on the effects of biochar on soil.

Figure 2. Top 20 co-occurring subject categories during 2007–2019.

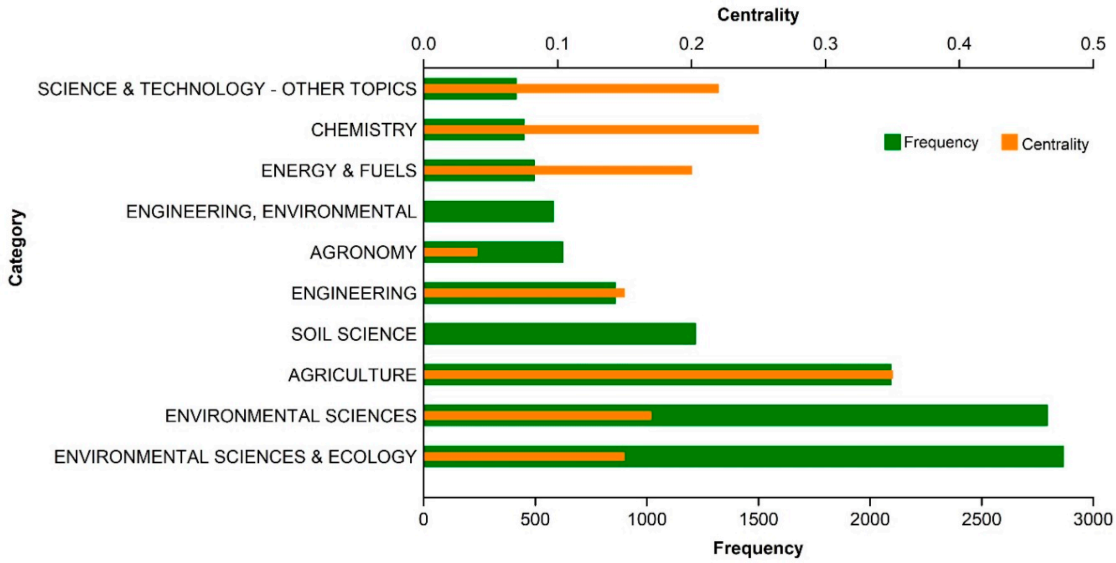

Figure 3. Top 10 most frequently appearing subjects with frequency and centrality.

CiteSpace can recognize subject categories with high rate of change from many subject categories according to the co-occurrence frequency of subject categories during a certain period of time, which is called bursting subject categories. The bursting subject categories are able to reflect the increase of co-occurrence frequency, which are new hot subject categories during one period of time.

There were 11 bursting subject categories (Table 1). "Soil Science" was the earliest hot subject in the field of the biochar effects on soil, which lasted during the whole initial stage of this field. "Agriculture" also appeared in the initial stage, but its duration was relatively short. "Food Science & Technology", "Chemistry, Applied", "Agricultural Engineering", "Biotechnology & Applied Microbiology", "Energy & Fuels", "Economics" and "Business & Economics" appeared in the initial stage and continued into the development stage. Among them, the duration of "Chemistry, Applied" was relatively long, while the durations of "Economics" and "Business & Economics" were relatively short. "Spectroscopy" and "Geochemistry & Geophysics" appeared in the development stage, among which "Spectroscopy" continued into the rapid development stage, indicated that "Spectroscopy" was the most concerned at the present stage.

Table 1. Top 11 subject categories with the strongest frequency bursts.

Subject Categories	Strength	Begin	End	2007–2019
Soil Science	13.08	2007	2011	
Agriculture	9.68	2010	2011	
Food Science & Technology	7.36	2010	2013	
Chemistry, Applied	6.87	2010	2014	
Agricultural Engineering	8.18	2011	2014	
Biotechnology & Applied Microbiology	9.04	2011	2013	
Energy & Fuels	17.08	2011	2013	
Economics	3.05	2011	2012	
Business & Economics	3.05	2011	2012	
Spectroscopy	4.23	2012	2016	
Geochemistry & Geophysics	5.14	2013	2014	

Note: The red squares represent the years in which subject categories had frequency bursts, the blue squares represent the years in which subject categories didn't have frequency bursts.

3.1.3. Journal Distribution

Through the statistical analysis of publications in the literature of a certain research field, the major journals in that field can be identified to help scholars select the key journals [50]. This can improve the insights and thought processes of researchers and their ability to evaluate the literature in that field, broaden their academic horizons, expand their research ideas, help them to achieve technological innovations, and promote the development of the relevant research. Furthermore, the identification of major journals can help scholars submit and publish articles and hence illustrate their academic achievements. The citation frequency of publication is an important indicator that measures the recognition of the publication by other scholars and its importance and reflects the degree of attention paid to that publication by other scholars [51]. The impact factor represents the academic influence of the journal in its research field and is an important indicator that measures the level of quality of the journal [52]. The higher the impact factor is, the greater the influence the journal has in its research field.

The top 10 journals with the highest number of publications are shown in Table 2. These journals contained a total of 1801 publications, accounting for 30.85% of all the publications in the literature. The top three journals with the highest number of publications, in descending order, were Science of the Total Environment, Environmental Science and Pollution Research, and Chemosphere. Environmental Science & Technology, Chemosphere, Soil Biology & Biochemistry, and Bioresource Technology were cited for more than 9000 times each and had relatively high citation frequencies. The top three journals with the highest average citation frequency per publication, in descending order, were Environmental Science & Technology, Soil Biology & Biochemistry, and Bioresource Technology. There were seven journals whose impact factor was greater than five, which, in descending order, were Environmental Science & Technology, Bioresource Technology, Environmental Pollution, Science of the Total Environment, Soil Biology & Biochemistry, Chemosphere and Journal of Environmental Management. Based on the comprehensive analysis of the above results, in the research field of the biochar effects on soil, publications in Environmental Science & Technology, Soil Biology & Biochemistry, and Bioresource Technology had higher levels of quality, academic value, and influence and were thus the top journals in the field.

Table 2. Top 10 journals based on number of documents.

Journal	Number of Documents	Percentage of Total Literature/ %/5837	Total Citation Frequency	Average Citation Frequency per Paper	Impact Factor
Science of the Total Environment	367	6.29%	7302	19.9	6.551
Environmental Science and Pollution Research	281	4.81%	3627	12.91	3.056
Chemosphere	268	4.59%	11,342	42.32	5.778
Journal of Environmental Management	153	2.62%	3138	20.51	5.647
Bioresource Technology	134	2.3%	9229	68.87	7.539
Journal of Soils and Sediments	132	2.26%	2897	21.95	2.763
Geoderma	122	2.09%	4878	39.98	4.848
Environmental Science & Technology	120	2.06%	11,427	95.23	7.864
Environmental Pollution	117	2%	4662	39.85	6.792
Soil Biology & Biochemistry	107	1.83%	9807	91.65	5.795

Note: The impact factors were obtained from Journal Citation Reports, 2019; retrieval date: 27 August 2020.

3.2. Research Power Analysis

3.2.1. Author Distribution and Collaboration

Through the analysis of the author distribution in the research field of the biochar effects on soil, the main scholars in the field can be identified to provide a better overview of research, thereby promoting academic exchange and cooperation and research development [53]. Table 3 shows the top 10 authors with the highest number of publications, and Yong Sik Ok, Johannes Lehmann, and Stephen Joseph ranked in the top three. In addition, the citation frequency and centrality of these authors were both ranked in the top three. In particular, the average citation frequencies per publication of Johannes Lehmann and Stephen Joseph were among the top three. The centrality of the nodes in the coauthorship network can reveal how critical and influential a specific author is in developing the knowledge in the research field and reflect the importance of that author in the network structure [54]. Therefore, Johannes Lehmann, Stephen Joseph, and Yong Sik Ok, who had large numbers of publications, citation frequency, and centrality > 0.1, were the core authors in the research field of the biochar effects on soil. In particular, Johannes Lehmann and Stephen Joseph had a higher average citation frequency per publication and thus were core authors with great influence in the field.

Table 3. Top 10 authors based on number of documents.

Author	Number of Documents	Total Citation Frequency	Average Citation Frequency per Paper	Centrality
Yong Sik Ok	166	8101	48.8	0.11
Johannes Lehmann	86	11,264	130.98	0.16
Stephen Joseph	61	5829	95.56	0.12
Daniel C. W. Tsang	59	1888	32	0.04
Hailong Wang	56	2508	44.79	0.07
Genxing Pan	55	3313	60.24	0.04
Lukas Van Zwieten	53	5059	95.45	0.03
Baoshan Xing	52	2412	46.38	0.06
Muhammad Rizwan	52	1127	21.67	0.01
Bin Gao	49	5344	109.06	0.06

Coauthorship maps can visually show the key authors leading a specific research field. Through the analysis of the coauthorship map, closely cooperating groups of scholars can be revealed to study the team effects of academic research. As shown in Figure 4, there were three closely cooperating research teams in the field. The research team with Yong Sik Ok as the core and comprising Daniel C. W. Tsang, Muhammad Rizwan, Hailong Wang, etc. mainly studied the fixation and adsorption mechanisms of heavy metals in soil by biochar [41,55,56]. The research team with Johannes Lehmann as the core and comprising Gerard Cornelissen, Patryk Oleszczuk, etc. mainly studied the biochar effects on soil fertility, carbon sequestration, and adsorption of polycyclic aromatic hydrocarbons and other organic pollutants [57–59]. The research team with Stephen Joseph as the core and comprising Genxing Pan, Lianqing Li, and Lukas Van Zwieten mainly studied the biochar effects on crop growth and yield and adsorption of heavy metals in agricultural fields and the mechanisms of greenhouse gas emission reduction by biochar [60–63]. As seen from the coauthorship network, the authors in the research field of the biochar effects on soil were closely linked with frequent communications among them.

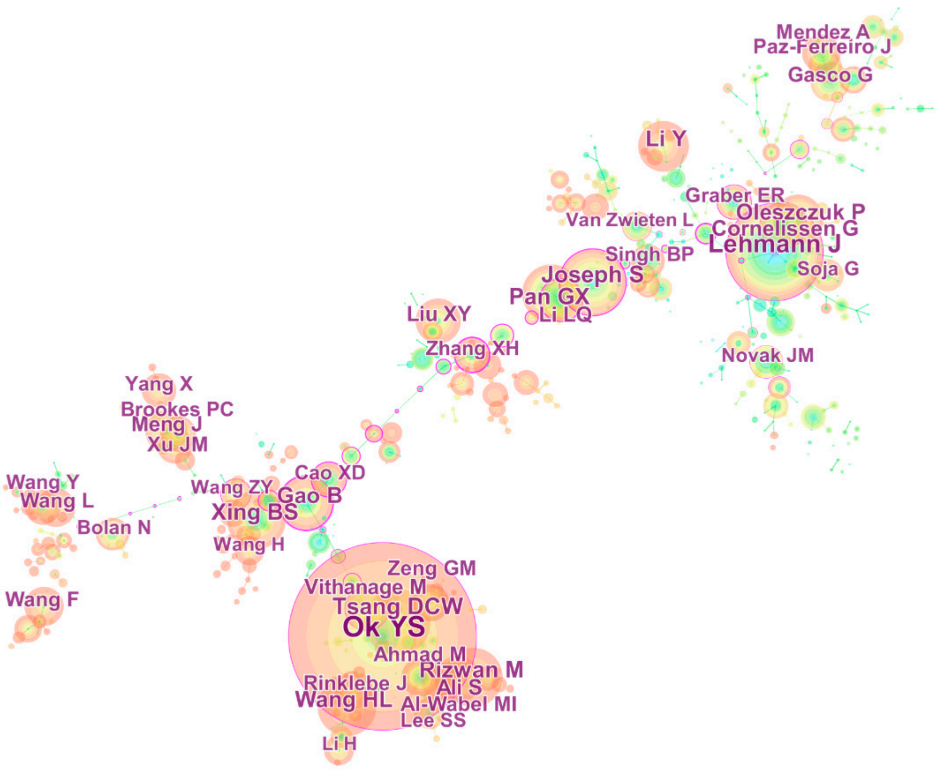

Figure 4. Coauthorship network.

3.2.2. Institutional Distribution and Collaboration

Through analysis of the institutional distribution, the level of academic support and recognition of the research field can be better understood, which benefits cross-institutional exchange and collaboration [64]. As provided by bibliometric databases, the number of publications, citation frequency, and average citation frequency per publication of each institution reflect its overall research capability and academic influence. As shown in Table 4, the top three institutions with the highest number of publications were the Chinese Academy of Sciences, Zhejiang University, and Nanjing Agricultural University. The top three institutions with the highest citation frequency were the Chinese Academy of Sciences, Cornell University, and the University of Florida. The top three institutions with the highest average citation frequency per publication were Cornell University, the University of Florida, and Kangwon National University. The institutions with centrality greater than 0.1 included the Chinese Academy of Sciences, Cornell University, Kangwon National University, and the United States Department of Agriculture-Agricultural Research Service. These four institutions were the core institutions in the research field of the biochar effects on soil. Among them, Cornell University and Kangwon National University had important influence on the field given their higher average citation frequency per publication. Among the institutions shown in the map (Figure 5), universities and colleges contributed a greater number of publications. The Chinese Academy of Sciences, United States Department of Agriculture-Agricultural Research Service, etc. had more publications and greater influence than most universities and colleges.

Table 4. Top 10 institutions based on number of documents.

Institution	Number of Documents	Total Citation Frequency	Average Citation Frequency per Paper	Centrality
Chinese Academy of Sciences	505	12,330	24.42	0.22
Zhejiang University	195	6427	32.96	0.02
Nanjing Agricultural University	157	5510	35.1	0.05
United States Department of Agriculture-Agricultural Research Service	132	5586	42.32	0.11
Kangwon National University	118	7279	61.69	0.13
University of Florida	116	8848	76.28	0.09
Cornell University	106	11,675	110.14	0.17
University of Agriculture Faisalabad	96	2236	23.29	0.03
Northwest A&F University	89	1385	15.56	0.02
Chinese Academy of Agricultural Sciences	82	1149	14.01	0.05

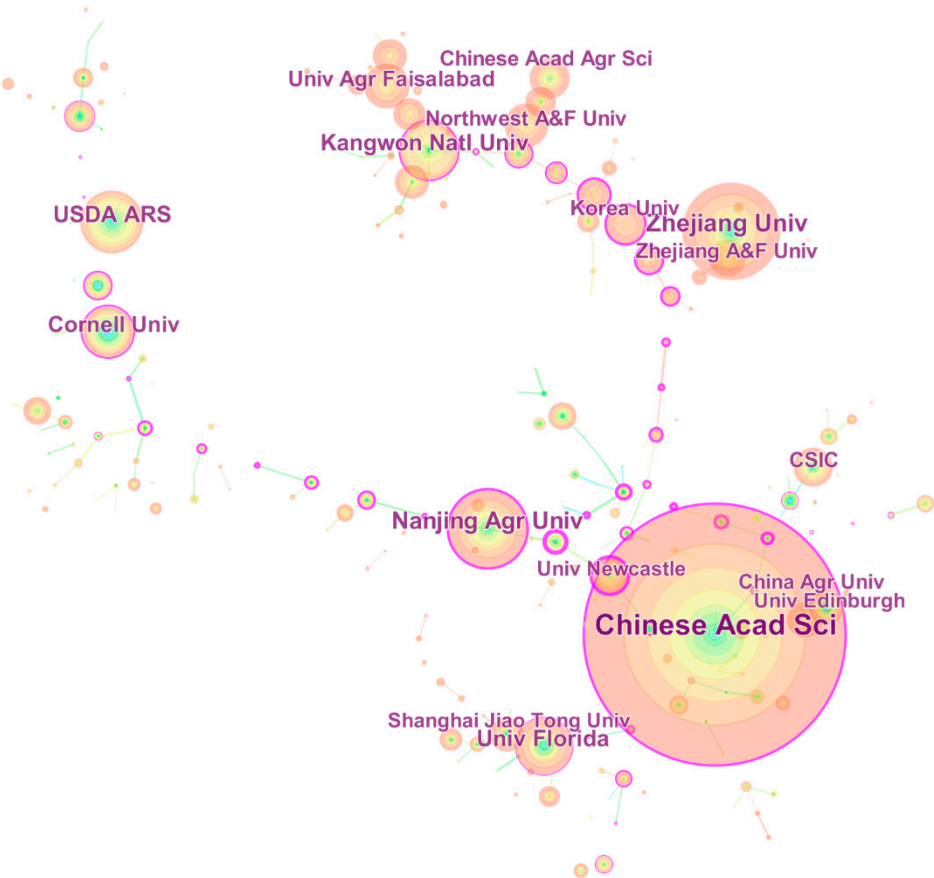

Figure 5. The network of coauthors' institutions.

3.2.3. International (Regional) Distribution and Collaboration

Through analysis of the publications contributed by different countries or regions, the level of attention and influence of these countries and regions on the research field can be reflected [65]. In the SCI-E database in the WOS Core Collection, the number of publications, citation frequency, and average citation frequency per publication are important indicators of the international academic status, level of basic scientific research, strength of technological innovation, and literature quality. To a certain extent, these indicators reflect the overall research strength and academic influence of these countries (regions). As shown in Table 5, both China and the United States had more than 1200 publications.

These two countries were therefore hotspots in the field of the biochar effects on soil. Moreover, China ranked first in the world, accounting for 38.7% of the publications. Half of the top institutions with the highest number of publications were research institutions in China (Table 4), indicating that more attention was given to this research field in China than in other countries. Among the top 10 funding agencies based on number of documents, six funding agencies were from China, and the number of documents funded by the top-ranked NSFC (National Natural Science Foundation of China) accounted for 23.8% of total documents (Table 6). In summary, this research field was relatively more active in China than in other countries. The citation frequency was highest in the United States, followed by China, Australia, and Germany, indicating that these four countries had high academic influence, level of research, and literature quality. The centralities of Germany and Australia were both greater than 0.1, suggesting that these two countries contributed more to international exchange in the field and were more active in international collaboration than other countries (Figure 6).

Table 5. Top 10 countries or regions based on number of documents.

Country	Number of Documents	Total Citation Frequency	Average Citation Frequency per Paper	Centrality
People's Republic of China	2259	54,054	23.93	0.03
United States of America	1232	56,742	46.06	0.05
Australia	532	26,053	48.97	0.12
Germany	424	15,700	37.03	0.27
Pakistan	309	7209	23.33	0.02
Spain	296	10,382	35.07	0.08
South Korea	294	10,882	37.01	0.04
Canada	260	8102	31.16	0.04
Italy	240	7223	30.1	0.04
Brazil	214	3167	14.8	0.01

Table 6. Top 10 funding agencies based on number of documents.

Funding Agencies	Record Count	% of 5837
National Natural Science Foundation of China NSFC	1389	23.80%
Fundamental Research Funds for The Central Universities	187	3.20%
National Key Research and Development Program of China	183	3.14%
National Science Foundation NSF	162	2.78%
National Basic Research Program of China	150	2.57%
United States Department of Agriculture USDA	117	2.00%
Chinese Academy of Sciences	114	1.95%
European Union EU	104	1.78%
China Scholarship Council	97	1.66%
Natural Sciences and Engineering Research Council of Canada	96	1.64%

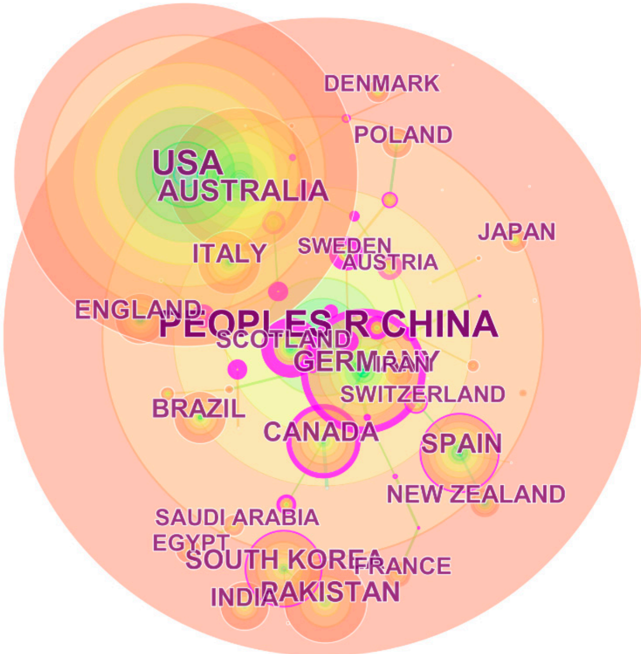

Figure 6. The network of coauthor countries.

3.3. Intellectual Base Recognition

3.3.1. Reference Cocitation Network

To understand the clustering of the representative literature, we constructed a cocitation network that comprised 127,908 publications. It should be noted that these 127,908 papers are the references cited in the 5837 publications mentioned above. In this constructed network, the Q value of the modularity was 0.9022 (Q > 0.3 generally indicates a significant clustering structure). Therefore, we concluded that the clustering effect was highly significant. However, the mean silhouette value was relatively low at 0.3195, mainly due to the many small clusters. In terms of the clustering contour values, the main clusters concerned had significantly higher silhouette values that were greater than 0.5 (a cluster with a silhouette > 0.5 is considered reasonable) and indicated higher grouping quality.

As shown in Figure 7, there were 10 key cocitation clusters in the network, which were labeled by titles. The details of these 10 clusters are summarized in Table 7. The clusters in the earliest stage mainly included #6 (labeled as land use) and #7 (charcoal). The clusters in the initial stage mainly included #1 (emission), #2 (laboratory produced biochar), #3 (nitrous oxide emission), #4 (particulate matter), and #5 and #9 (mineralization). The clusters in the development stage mainly included #0 (pyrolysis temperature) and #8 (denitrification).

Cluster #6 had 19 members and a silhouette value of 0.789. Analysis of the cluster showed that it focused on the effects of biochar as a soil amendment on soil physical and chemical properties and crop yield [66]. The most cited reference in the cluster was "Agronomic values of greenwaste biochar as a soil amendment". Cluster #7 had 18 members and a silhouette value of 0.59. This cluster focused on how biochar enhanced soil cation exchange capacity [67]. The most cited reference in the cluster was "Black carbon increases cation exchange capacity in soils". In addition, within cluster #7, the publication "Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil" ranked third in centrality (0.77) and effectively connected the clustering structures in the earliest and initial stages [68].

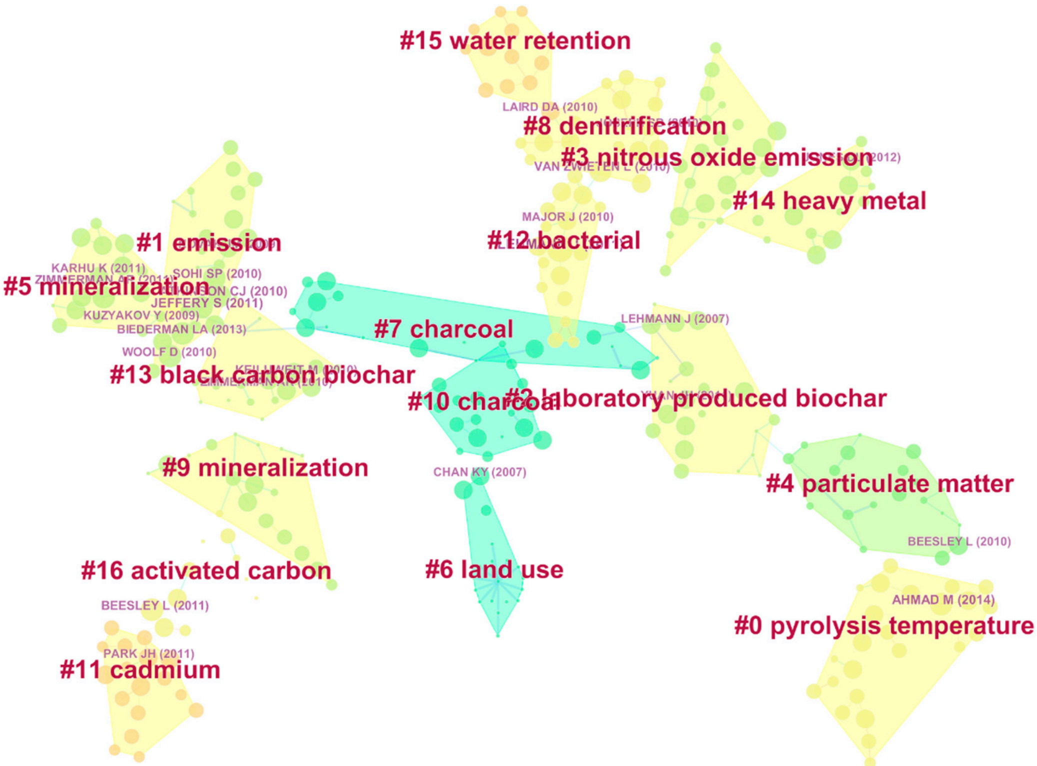

Figure 7. Cluster visualization based on the document cocitation network.

Table 7. Top 10 cocitation clusters based on frequency.

Cluster ID	Size	Silhouette	Mean Cited Year	Label (LLR)
0	25	0.64	2012	pyrolysis temperature
1	23	0.522	2009	emission
2	22	0.602	2008	laboratory produced biochar
3	21	0.648	2010	nitrous oxide emission
4	20	0.548	2007	particulate matter
5	20	0.573	2009	mineralization
6	19	0.789	2005	land use
7	18	0.59	2005	charcoal
8	18	0.556	2012	denitrification
9	18	0.591	2009	mineralization

Note: LLR, extraction algorithm of cluster label based on log-likelihood rate.

Cluster #1 had 23 members and a silhouette value of 0.522. This cluster focused on how biochar enhanced crop productivity and carbon sequestration and reduced emissions [69]. The most cited reference in the cluster was "A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis". Cluster #2 had 22 members and a silhouette value of 0.602. This cluster focused on the differences in the characteristics of char produced by different raw materials and pyrolysis temperatures [70]. The most cited reference in the cluster was "The forms of alkalis in the biochar produced from crop residues at different temperatures". Cluster #3 had 21 members and a silhouette value of 0.648. This cluster focused on the differences in the biochar effects on crop yield and nitrous oxide emissions [71]. The most cited reference in the cluster was "Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China". Cluster #4 had 20 members and a silhouette value of 0.548. This cluster focused on the adsorption of inorganic and organic pollutants on biochar [72]. The most cited reference in the cluster was "Effects of biochar and green waste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil". Cluster #5 had

20 members and a silhouette value of 0.573. This cluster focused on the adsorption of soil organic matter on biochar and the mechanisms of carbon sequestration by biochar [73]. The most cited reference in the cluster was "Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils". Cluster #9 had 18 members and a silhouette value of 0.591. This cluster focused on the biochar effects on the soil carbon cycle [74]. The most cited reference in the cluster was "Fate of soil-applied black carbon: downward migration, leaching and soil respiration". In addition, within cluster #4, the publication "Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: Mechanisms and consequences for distribution, bioaccumulation, and biodegradation" ranked first in centrality (0.37) and effectively connected clustering structures in the initial and development stages [75].

Cluster #0 was the largest cluster and had 25 members and a silhouette value of 0.64. This cluster focused on the adsorption of soil and wastewater pollutants on biochar [41]. The most cited reference in the cluster was "Biochar as a sorbent for contaminant management in soil and water: A review". Cluster #8 had 18 members and a silhouette value of 0.556. This cluster focused on the biochar effects on soil fertility, nutrient uptake by crops, and crop yield [11]. The most cited reference in the cluster was "Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility".

In summary, the research field of the biochar effects on soil is multifaceted and includes the improvement in soil physical and chemical properties by biochar, biochar effects on crop growth and yield, carbon sequestration and emissions, and adsorption of soil pollutants. In the early stage, scholars focused on the biochar effects on soil physical and chemical properties and crop yield. Since the development stage, with more attention given to environmental problems, scholars began to shift their focus to the adsorption of soil pollutants on biochar and biochar effects on carbon sequestration and emissions. Furthermore, scholars emphasized the adsorption mechanisms of pollutants on biochar and the mechanisms of carbon sequestration and emission reduction by biochar. In recent years, more attention has been given to the environmental benefits of biochar. Therefore, new discovery trends appear to be centered on the remediation of soil pollution by biochar and carbon sequestration and emission reduction by biochar.

3.3.2. Landmark References

Based on the cocitation analysis, the key publications in the related fields can be easily identified. The top 10 publications with the most citations in the field of the biochar effects on soil according to the cocitation network analysis are listed in Table 8. The listed publications are not the most cited studies in Web of Science but rather are the most cited among the 127,908 publications obtained in this study.

Among the top 10 publications, one was related to soil organisms, four were related to the improvement of soil fertility and crop growth, two were related to the remediation of soil pollution, two were related to soil nitrogen fixation and emission reduction, and one was an analysis of biochar characteristics and structure. Obviously, Lehmann et al. (2011) was the most cited publication, with a citation frequency of 1206. This publication summarized the research progress of the biochar effects on soil biology from three aspects following as: (a) the improvement of soil habitats; (b) the responses of soil organisms to biochar; (c) the management and risks of biochar application to soil. Targeting the responses of soil organisms to biochar, the publication described the research progress regarding biochar effects on soil microbes in detail from the perspectives of soil microbial diversity, community structure, and functional ecology. It gave an overview of the influences of biochar on earthworms, nematodes, microarthropods, and plant roots and proposes that future biochar research should provide systematic reviews of different types of biochar and basic experimental operations to clarify the mechanisms of interactions between biochar and soil organisms [21].

Table 8. Top 10 cited references based on frequency.

Frequency	Author	Title	Source	Year	Burst	Centrality	Cluster ID
1206	Lehmann et al.	Biochar effects on soil biota—A review	Soil Biology & Biochemistry	2011		0.09	12
648	Jeffery et al.	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis	Agriculture, Ecosystems & Environment	2011		0.06	1
645	Ahmad et al.	Biochar as a sorbent for contaminant management in soil and water: A review	Chemosphere	2014	68.75	0.07	0
565	Atkinson et al.	Potential mechanisms for achieving agricultural benefits from biochar	Plant and Soil	2010		0	1
505	Sohi et al.	A review of biochar and its use and function in soil	Advances in Agronomy	2010		0.14	1
490	Zimmerman et al.	Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	Soil Biology & Biochemistry	2011		0.07	5
484	Van Zwieten et al.	Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	Plant and Soil	2010		0.32	8
474	Beesley. et al.	A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils	Environmental Pollution	2011		0	16
472	Keiluweit et al.	Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	Environmental Science & Technology	2010		0.03	13
426	Woolf et al.	Sustainable biochar to mitigate global climate change	Nature Communications	2010		0.01	1

The publications with citation bursts reflect the growth of the citation frequency in a certain period. The bigger the burst is, the more rapid the growth of citation frequency [76]. Among the top 10 highly cited references based on frequency, Ahmad et al. (2014) had a burst value of 68.75 (Table 8). This article summarized the research progress of the mechanisms of adsorption of organic and inorganic pollutants in soil and water on biochar. It pointed out how the adsorption performance of biochar was affected by the pyrolysis conditions and raw material types of biochar and proposed that given the complexity of soil systems, long-term field experiments would be needed to study the mechanisms of adsorption of soil pollutants on biochar [41].

Van Zwieten et al. (2010) and Sohi et al. (2010) played key intermediary roles in the network structure of the knowledge domain because of their centrality > 0.1 (Table 8). Through an indoor pot experiment, Van Zwieten et al. (2010) observed the effects of biochar on soil physicochemical characteristics, soil fertility, crop nutrient absorption, and growth. This paper stated that the effects of biochar application need to be further studied for different soil types and crops [11]. Sohi et al. (2010) provided a review of the application and functions of biochar in soil from the aspects of the biochar effects on the soil carbon cycle, basic properties of biochar, and biochar application in agriculture. It revealed the emphasis and challenges of future biochar research, including the mechanisms of how biochar influences the soil and agroecosystem, the cost effectiveness and environmental risks of biochar application to soil, the simulation test abilities of soil-biochar systems, and the research on the formulation of biochar application standards to soil [77].

3.4. Popular Research Areas and Trends

3.4.1. Keyword Clustering Analysis

Keywords are the core and the essence of the literature and provide an overview of and indicate the prominent research topics in the subject area [78]. Keyword clustering maps drawn using CiteSpace can reflect the correlations between keywords. A keyword clustering analysis was performed for the literature, resulting in a total of 11 clusters in the constructed map (Figure 8). The clustering structure was significant, with modularity Q = 0.8455. Apart from cluster #10, the silhouette values of all other clusters were at least 0.5. The structures of the 10 clusters (#0 to #9) were reasonable (Table 9). Among them, cluster #0 was labeled "mixture" and focused on the research on the biochar effects on soil organisms, soil carbon sequestration, and emissions. Cluster #1 was labeled "feedstock" and focused on the research on the characteristics of biochar formed by different raw materials and under different pyrolysis temperatures and the adsorption of soil polycyclic aromatic hydrocarbons on and bioavailability of biochar. Cluster #2 was labeled "accumulation" and focused on the research on the biochar effects on the adsorption and fixation of heavy metals, such as cadmium, in farmland soil and wastewater. Cluster #3 was labeled "mineralization" and focused on the research on the biochar effects on soil temperature, nitrogen, and phosphorus nutrients and the yields of crops such as wheat. Cluster #4 was labeled "oxidation" and focused on the research on the effects of pyrolysis conditions on biochar properties and application of biochar to improve soil. Cluster #5 was labeled "ponderosa pine" and focused on the research on the production of biochar using agricultural and forestry wastes and biochar effects on soil microbial properties and greenhouse gas emissions. Cluster #6 was labeled "charcoal" and focused on the research on the biochar effects on soil organic matter and plant growth. Cluster #7 was labeled "sustainable agriculture" and focused on the research on biochar applications in agriculture. Cluster #8 was labeled "carbon" and focused on the research on the biochar effects on soil fertility and crop yield and quality. Cluster #9 was labeled "organic carbon" and focused on the research on the biochar effects on soil organic carbon and nitrogen mineralization and microbial community structure.

3.4.2. Keyword Burst Analysis

A keyword burst describes the event when a keyword increases sharply in frequency [79]. Table 10 lists the keywords with the strongest citation bursts in different periods and shows the research topics in the field of the biochar effects on soil and their changes. Table 10 shows the time of first appearance of each keyword and its duration, which reflects the persistence of the influence of keywords in the research field. In addition, the blue lines indicate the entire study period (2007–2019), whereas the red lines indicate the duration of citation bursts [80]. Moreover, to more accurately explore the research topics of the biochar effects on soil and the pattern of their development from 2007 to 2019, we divided the study period into three parts based on the annual distribution of the number of publications, which were the initial stage (2007–2011), development stage (2012–2015), and rapid development stage (2016–2019).

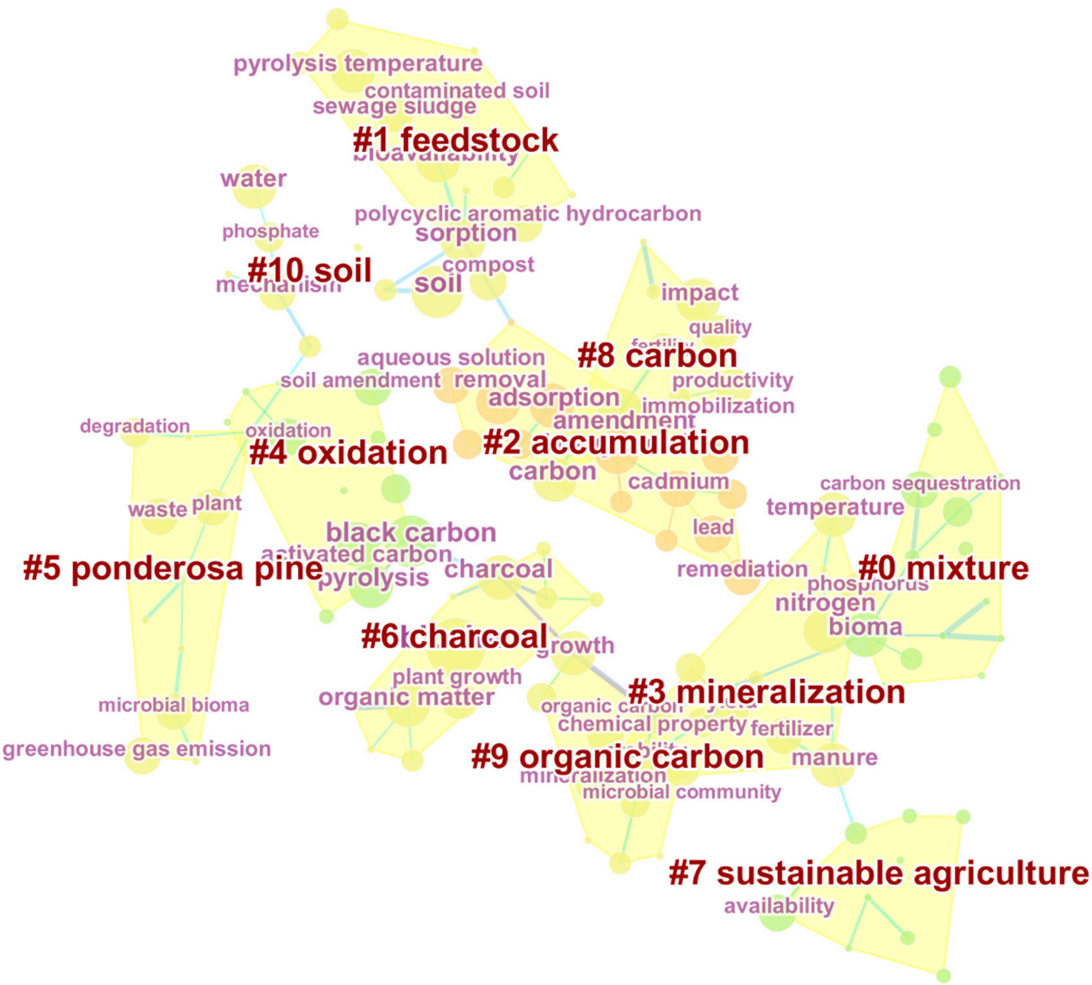

Figure 8. The keyword clustering knowledge map of the documents.

Table 9. Top 10 keyword clusters based on frequency.

Cluster ID	Size	Silhouette	Mean Cited Year	Label (LLR)
0	14	0.626	2009	mixture
1	14	0.524	2011	feedstock
2	14	0.643	2012	accumulation
3	14	0.67	2009	mineralization
4	12	0.5	2009	oxidation
5	12	0.75	2010	ponderosa pine
6	11	0.501	2009	charcoal
7	10	0.6	2011	sustainable agriculture
8	10	0.574	2009	carbon
9	9	0.522	2009	organic carbon

Table 10. Keywords with the strongest citation bursts in different periods.

Period	Keywords	Strength	Begin	End	2007–2019
2007–2011	charcoal	3.28	2007	2008	
	char	2.39	2008	2009	
	soil organic matter	2.29	2008	2009	
	fraction	3.45	2008	2009	
2012–2015	gasification	6.25	2012	2013	
	wood	6.25	2012	2013	
	matter	7.65	2012	2013	
	sediment	6.95	2012	2013	
	waste	2.57	2013	2015	
	management	6.18	2013	2015	
	decomposition	2.41	2013	2015	
	retention	6.37	2013	2015	
	aqueous solution	5.98	2013	2015	
2016–2019	chemical property	10.70	2016	2017	
	carbon sequestration	19.82	2016	2017	
	waste water	16.78	2017	2019	
	microbial biome	14.67	2017	2019	

Note: The red squares represent the years in which keywords had citation bursts, the blue squares represent the years in which keywords didn't have citation bursts.

Initial Stage (2007–2011)

There were four keyword bursts in this stage, which was a relatively low number and indicated a small number of research topics. The analysis of keywords with strong citation bursts in this period showed that as biochar research was still in the initial stage, the definitions of biochar were not yet unified, and biochar was called "charcoal" and "char". After biochar was given its name in the 1st International Biochar Conference in 2007, biochar research began to receive international attention. In addition, based on the strong citation bursts of the keywords "fraction" and "soil organic matter", research in this stage focused on the compositional analysis of biochar and biochar effects on soil organic matter.

Development Stage (2012–2015)

There were nine keyword bursts in this stage, which was a relatively high number and indicated a wider range of topics. The analysis of keywords with strong citation bursts in this period suggested a focus on the effects of the raw material type and pyrolysis and vaporization conditions on the biochar structure and properties, mechanisms by which biochar promotes the decomposition of soil organic matter, biochar application in environmental management, and adsorption and fixation of inorganic/organic pollutants in soil, aqueous solution, and sediments on biochar.

Rapid Development Stage (2016–2019)

There were four keyword bursts in this stage, indicating that research topics were relatively concentrated. The analysis of keywords with strong citation bursts in this period suggested that the research focused on the biochar improvements of soil chemical properties, biochar effects on carbon sequestration and emissions, adsorption of inorganic/organic pollutants in wastewater on biochar, and biochar effects on soil microbial biomasses. Among them, the citation burst of "carbon sequestration" was the strongest, indicating that the research on the biochar effects on carbon sequestration and emissions was the most popular research topic in this stage.

4. Conclusions

Through the visual analysis and processing of a large amount of literature data using CiteSpace, possible knowledge networks within literature can be thoroughly analyzed to explore hidden data patterns [47]. The findings of this study are based on objective data analysis that was not subjectively influenced and was thus stable and reliable. Therefore, the study findings are convincing and can indicate popular research topics, development trends, and research frontiers in the field of the biochar effects on soil.

The annual number of publications on the biochar effects on soil exhibited a significant increasing trend that could be divided into the three stages of slow growth, steady growth, and rapid growth. In the recent decade, the research topics have been constantly changing, expanding, and continuing to become more in-depth. Research on the biochar effects on soil involves many disciplines; this research is of great significance in various fields, such as climate change mitigation, soil improvement, energy production, and agricultural and forestry waste management. Due to the relatively high quality, academic value, and influence of publications therein, *Environmental Science & Technology*, *Soil Biology & Biochemistry*, and *Bioresource Technology* were the top journals in WOS in the research field of the biochar effects on soil.

Johannes Lehmann, Stephen Joseph, and Yong Sik Ok were the core authors in this research field and played a critical role in promoting the development and expansion of the field. The Chinese Academy of Sciences was the institution with the highest number of publications and citation frequency and had an important position in the research field of the biochar effects on soil, although its average citation frequency per publication was relatively low. The average citation frequency per publication was relatively high for Cornell University, indicating the higher academic value and influence of these publications. The Chinese Academy of Sciences, Cornell University, Kangwon National University, and United States Department of Agriculture-Agricultural Research Service were the core institutions in the research field and more actively collaborated with other institutions. China had the highest number of publications. Australia, United States, Germany, and South Korea had relatively high academic influence, research level, and literature quality in the research field. Furthermore, Germany and Australia were more active in collaborating with other countries in the domain.

Based on reference cocitation clustering analysis, the main intellectual base in the domain of biochar effects on soil could be summarized with indexing terms as: (a) pyrolysis temperature; (b) emission; (c) laboratory produced biochar; (d) nitrous oxide emission; (e) particulate matter; (f) mineralization; (g) land use; (h) charcoal; (i) denitrification; (j) mineralization. In the process of biochar effects on soil research knowledge evolution, Lehmann et al. (2011), Ahmad et al. (2014), Van Zwieten et al. (2010), and Sohi et al. (2010) played key roles and are the most important pieces of the intellectual base in the field.

Based on keyword co-occurring clustering analysis, the main research hotspots in the domain of biochar effects on soil could be summarized with indexing terms as: (a) mixture; (b) feedstock; (c) accumulation; (d) mineralization; (e) oxidation; (f) ponderosa pine; (g) charcoal; (h) sustainable agriculture; (i) carbon; (j) organic carbon. By analyzing the keyword bursts in different stages, we showed the changes in the research trends in the field of the biochar effects on soil. In the initial stage (2007–2011), the compositional analysis of biochar and the biochar effects on soil organic matter were topics of interest. In the development stage (2012–2015), the effects of raw material types and pyrolysis and vaporization conditions on the biochar structure and properties, mechanisms by which biochar promotes the decomposition of soil organic matter, biochar application in environmental management, and adsorption and fixation of inorganic/organic pollutants in soil, aqueous solution, and sediments on biochar were popular topics. In the rapid development stage (2016–2019), biochar improvements in soil chemical properties, biochar effects on carbon sequestration and emission reduction, adsorption of inorganic/organic pollutants in wastewater on biochar, and biochar effects on soil microbial biomass were the most studied topics. From this information and the cocitation clustering analysis, we suggest that studies on biochar use in ecological and environmental management applications, such as the reduction in greenhouse gas emissions, soil improvement and vegetation restoration, soil and water conservation, and restoration of contaminated soil will be the focus of future research.

The raw materials of biochar are easy to obtain, and biochar is easy to produce. As an ancient and novel functional material, it has clear advantages in improving soil physico-chemical properties, remedying soil pollution, sequestering carbon, and mitigating soil greenhouse gas emissions. At present, the research on biochar effects on soil is in the rapid development stage. As a young and active research field, given the functional complexity of biochar, it is still necessary to conduct in-depth studies of the mechanisms by which biochar affects soil. This includes those that employ molecular biological methods, such as high-throughput sequencing, to study the biochar effects on soil microbes [81]. The effects of the long-term, continuous application of biochar on soil remain to be studied. The preparation condition is critical to exert the utility of biochar, including feedstock, pyrolysis temperature, and modification [82,83]. Meanwhile, the effects of biochar application on soil also depends on soil types [84,85]. Thus, determining the appropriate application of biochar for a given soil type requires further studies. In addition, the environmental risks of biochar need to be evaluated [77]. In the future, long-term field experiments should be established to allow in-depth analysis of the mechanisms by which biochar affects soil. These studies will provide the theoretical basis for the large-scale promotion and application of biochar and facilitate the use of agricultural and forestry wastes, such as crop straw, and the sustainable development of the environment.

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