Scientometric Analysis and Scientific Trends on Biochar Application as Soil Amendment

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Abstract

A scientometric study on the application of biochar for the amendment of soil was studied to investigate research and developments as well as scientific advances and gaps. A total of 2982 bibliographic records were retrieved from the Web of Science (WoS) database using appropriate sets of keywords, which were analyzed based on the criteria of the authors, publishing journals, citations received, contributing countries, institution, and categories in research and development. Based on these data, progress of research activity was mapped to identify the scientific status, such as current scientific and

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technological trends as well as knowledge gaps. The majority of scientific developments started in the early 2000's and accelerated considerably after 2014. China and the USA are leading countries in the application of biochar for the treatment of soils. Among the active journals, "Plant and Soil" has received the highest number of citations. This study attempts for a comprehensive discussion on the scientific advances as well as the progress made, especially in recent years.

Keywords:

Biochar, Soil amendment, Scientometry, CiteSpace, Web of Science (WoS).

1. Introduction

Biochar is a solid product of biomass thermochemical conversion conducted in the absence of O_2 at temperatures above 250°C (pyrolysis) and with residence times ranging from seconds up to hours or days. Such products have basically a high carbon content and high specific surface area [1–3]. Hence, numerous applications can be expected for such products, especially where the material with high carbon content and/or a vast adsorption is required [4–7]. Biochar is employed for the capture and storage of carbon in the soil to mitigate adverse environmental impacts such as climate change [8]. For specific applications such as soil amendment, innumerable published works are available on the applications of biochar, which bring a number of advantages such as enhancement of soil fertility and improvement of soil properties for agricultural applications [9–11].

The number of published documents clearly emphasizes the potential application of biochar for soil amendment in compliance with the sustainable developmental goals defined by the United Nations (since it is recognized as a climate change mitigator, waste management, and waste as a resource) [12–14]. These aspects can be attributed to the high nutrient content of biochar as well as to its ability to absorb and immobilize toxic heavy metals, especially Cd and Cu from the soil [9,10,15,16]. Also, pH adjustment with biochar is considered an effective way to re-use soils with low pHs such as those from mining activities [9]. These positive effects can result in the enhancement of microbial activity, leading to improved soil fertility [17].

A lot of evidence is available to prove that the application of biochar, produced mainly from animal manure and fish bones, was first practiced in Ancient Amazon as early as 2500 years ago. The product of such practices is called "black earth" ("terra preta" in Portuguese) with a high carbon content. There is some evidence of biochar application in other regions of the word such as in Egypt, Japan, and Greece. Although the Egyptian kilns used historically for the production of biochar are still in use, they are energy consuming, generate a lot of atmospheric emissions and do not offer the potential of by-products (such as bio-oil and syngas) recovery [18].

The present manuscript assesses the current level of scientific and technological development in this field [19]. The scientometric study aims at determining the current trends in this scientific field, which will facilitate to identify deficiencies and areas in which further improvements are required to accelerate the commercialization of biochar for soil applications. An analytical overview of the state-of-art in this field will be highly beneficial to support the sound scientific conclusion on the scientific history, the progress made, previous and current trends in this field, identifying the gaps and potentials for further developments. The present study thus provides a comprehensive scientometric analysis of the global efforts made on the production of biochar for soil applications. The data obtained will support the scientific trends offering an in-depth understanding of the status of science as well as research in this field.

2. Methodology

To proceed with the scientometric study, the database was selected to retrieve the related documents. Among the existing databases including Google Scholar, Scopus, and ISI Web of Science (WoS) core collection, ISI WoS core collection was adopted because it contains the indexed journals, conference proceedings papers, etc., [20–22]. CiteSpace (5.3.R4) with the ability to provide visualized comparisons and also the network analysis [23] was used for the treatment and presentation of results. It must be stated that ISI WoS core collection outputs are compatible with CiteSpace as input raw data [24]. According to pre-literature review, a combination of keywords including "TI=((biochar OR biocarbon OR pyroly* OR biomass product) AND (Soil OR fertili* OR plant OR Grow* OR Compost*)) was used in the advance search mode of ISI WoS core collection. As can be observed, this bibliographic search was combined with a fuzzy string represented as "*", which provides wider ranges of words related to "pyrolysis", "fertilize", "grow", and "compost".

In this research, English documents published between 2000 and 2020 were collected on 1th April, 2020 and the search was oriented based on the appearance of intended keywords in the titles of the documents. A critical screening on the retrieved bank was performed to guarantee the accuracy of the data collected. Relevant papers were selected into the "marked list" of WoS, which were exported from WoS in the format of "plain text" and were then inserted in CiteSpace (5.3.R4) to be analyzed regarding their specific characteristics. The scientometric criteria, which were taken into consideration in this analysis are: (1) publication type, (2) publication year, (3) contributed countries, (4) keyword, (5) author, (6) cited authors, (7) cited journals, (8) categories, and (9) cited documents. The parameters included in the scientometric analysis of the biochar application for soil amendment are:

a) Betweenness centrality (BC)

This parameter represents specific characteristics of any node located in a network [25]. BC, which accounts to assess links between the nodes (e.g., authors) measures the possibility of fitting any node in the shortest path between the two other nodes. Its relevant value varies between zero and one [26].

b) Citation burst (CB)

The concept of "burst" refers to a frequency of a topic growing acutely as the topic appears and eventually fades after a duration. Citation burst is a tool to measure the increase in the citations received by either a specific author or a document over a certain period of time [27].

c) Sigma

Sigma is a pre-defined parameter in CiteSpace accounted as an integrated measurement of the strength and the characteristics of the nodes including BC and CB, respectively [23].

d) Citation counts (CC)

Citation counts criterion deals with the number of times that a specific document, author, or journal has been citated since its publication date over a certain period of time known as an exposure time. CC includes all the citations received including self-citations. The number of co-authors of any specific document can potentially affect the CC [28].

e) Citation frequency (CF)

Citation frequency is calculated by the division of CC of any publication by its considered exposure time [29].

f) Clustering

Clustering is a technique employed by the CiteSpace that classifies the input data such as keywords and authors of the publications into sub-categories. The strongest cluster, represented as "#0", stands for a category containing elements with the highest level of similarity to one another [21,30].

3. Results

By applying an advanced search in the WoS database using the set of keywords (section 2), a total of 2982 English documents were collected for the period (2000 till the end of 2018). The results achieved by executing the research design are presented according to the selected scientometric parameters mentioned in the Methodology section.

3.1 Publication type analysis

Among the bibliographic documents gathered, research articles shared the highest portion with 86% of all the publications over the studied period. Figure 1 presents the respective results obtained.

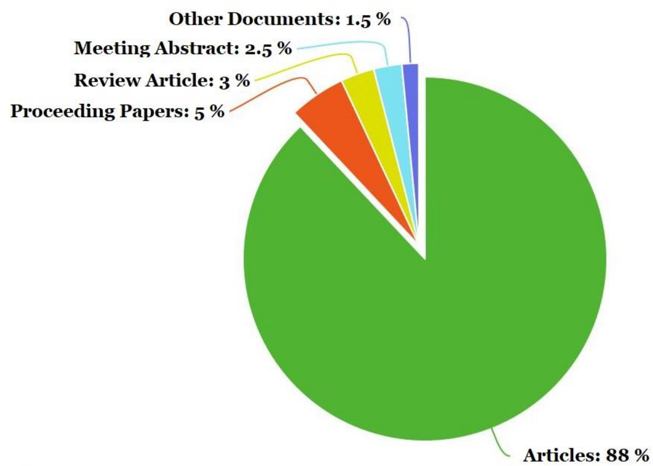

Figure 1. Types of documents published on biochar application in soil amendment.

3.2 Distribution of publications over the years

Distribution of various types of publications over the studied period offers an overview on the progress made in this field. In this regard, total number of published documents on biochar application for soil amendment over the adapted duration, extracted from WoS, was analyzed and the results (Fig. 2 and Table 1) suggest that publication in this field was initiated since the 2000s. However, until 2008, the number of bibliographic documents did not show much significant growth. Afterwards, rapid growth was observed, especially after 2010. The cumulative number of published documents also demonstrate a sigmoidal pattern (R^2=0.99) as illustrated in Fig. 2b. It may be noticed that the number of publications reached a certain point of maturity.

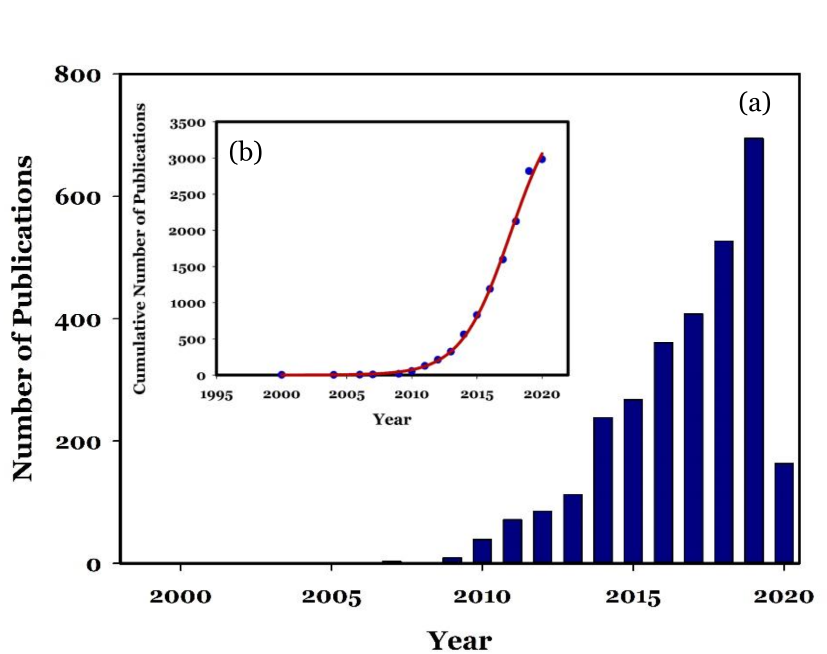

Figure 2. The number of published documents on the application of biochar for soil amendment (a) and cumulative number of publications indicating sigmoidal pattern of growth with and without curve fitting (b).

Table 1. Distribution of publications indexed in WoS on the application of biochar for soil amendment.

Number	Year	Publication (No.)	Contribution (%)
1	2020	163	5.47
2	2019	695	23.31
3	2018	527	17.67
4	2017	408	13.68
5	2016	361	12.11
6	2015	267	8.95

7	2014	238	7.98
8	2013	112	3.76
9	2012	85	2.85
10	2011	71	2.38
11	2010	39	1.31
12	2009	9	0.30
13	2007	3	0.10
14	2006	1	0.03
15	2004	1	0.03
16	2000	1	0.03

3.3 Contributing countries analysis

The most contributing countries in the publication of scientific documents in this field were recognized from the analysis of the WoS database. As can be realized from Fig. 3, China (with 763 documents) is the highest contributing country. Then USA and Australia with significant differences to China occupied the next places among the leading countries with 404 and 217 documents, respectively. However, there is no significant difference among the three upcoming countries including Germany (147 documents), Spain (132 documents), and South Korea (114 documents) in terms of their publications on biochar application to improve the soil physicochemical properties.

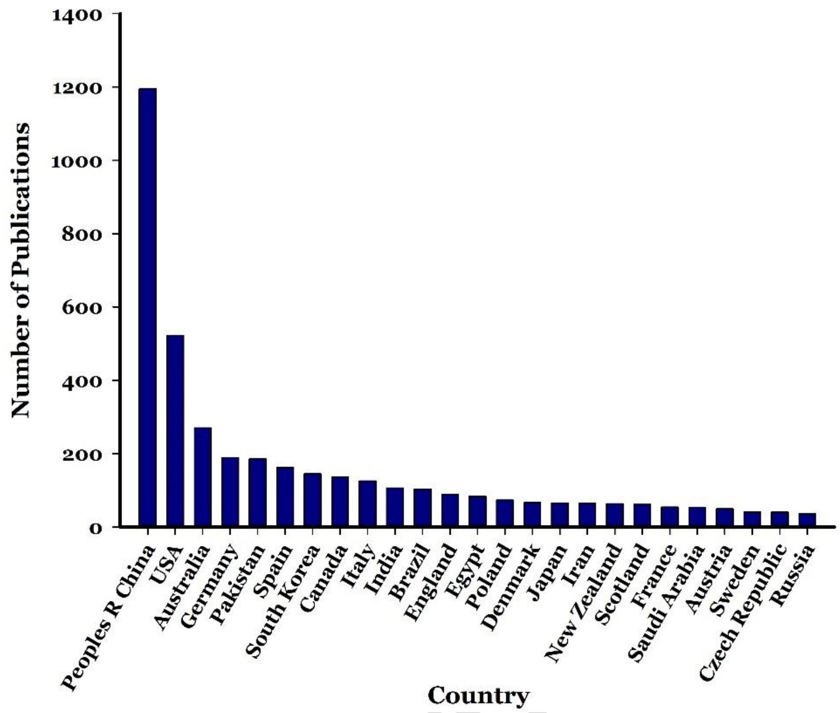

Figure 3. Contributions of various countries worldwide in the production of scientific documents on the application of biochar for the amendment of soils.

Table 2. Contributing countries in terms of publications on biochar application for soil amendment.

Rating	Country	Count (No.)	Contribution (%)
1	China	1195	40.07
2	USA	522	17.51
3	Australia	270	9.05
4	Germany	189	6.34
5	Pakistan	185	6.20

6	Spain	162	5.43
7	South Korea	145	4.86
8	Canada	136	4.56
9	Italy	125	4.19
10	India	106	3.55

3.4 Keyword analysis

Co-occurring of the collected keywords appearing in the documents was analyzed using the CiteSpace. As can be observed, keywords including “biochar”, “black carbon”, and “charcoal” have appeared most frequently (in number of 1081, 468, and 450, respectively) among all the applied keywords to represent the documents published on the application of biochar for soil treatment. “Amendment”, “carbon”, and “soil” are the up-coming keywords from the frequent perspective, in number of 411, 332, and 270, respectively, which demonstrates the focus of studies in this field. The keywords including “biochar” and “black carbon” have the highest centrality strengths among others. In terms of burst strength, “Charcoal” received the highest score. Figure 4 and Table 3 show the results provided by CiteSpace with the minimized overlap.

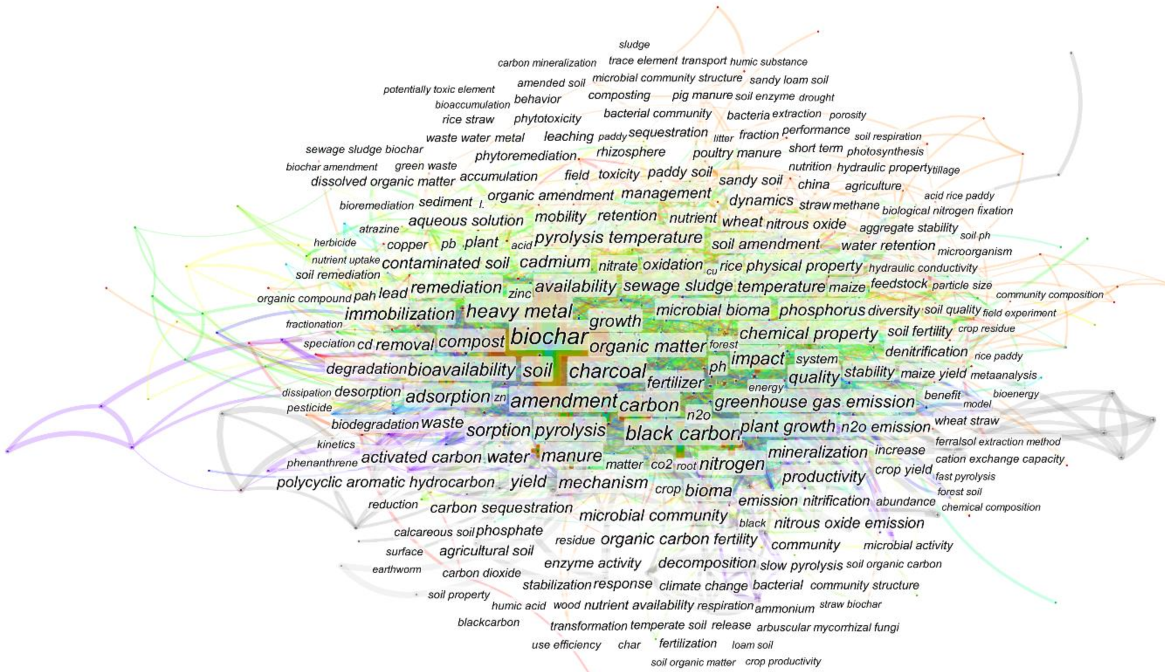

Figure 4. A schematic representation of co-occurring analysis of keywords appeared in scientific documents published on the application of biochar for soil treatment. In this figure, centrality was neglected to represent clear illustration. The figure containing the exact centrality is provided in the supplementary information.

Table 3. Output of keywords co-occurring analysis and respective parameters of scientometric analysis. These keywords are most widely used to represent scientific documents published so far on the application of biochar for soil amendment.

Rank	Keyword	Sigma	Centrality	Burst	Frequency
1	Biochar	1	0	-	1520
2	Amendment	1	0	-	569
3	Black Carbon	1	0	52.14	566
4	Charcoal	1	0	63.02	523

5	Carbon	1	0	-	470
6	Soil	1	0	2.83	368
7	Heavy Metal	1	0	-	362
8	Organic Matter	1	0	1.35	335
9	Impact	1	0	-	323
10	Pyrolysis	1	0	0.96	319
11	Nitrogen	1	0	-	316
12	Bioavailability	1	0	1.26	314
13	Sorption	1	0	2.63	306
14	Adsorption	1	0	1.01	276
15	Manure	1	0	3.24	246
16	Growth	1	0	-	236
17	Water	1	0	-	231
18	Bioma	1	0	2.18	222
19	Yield	1	0	1.21	217
20	Availability	1	0	-	197
21	Compost	1	0	-	190
22	Chemical Property	1	0	1.23	190
23	Greenhouse Gas Emission	1	0	-	188
24	Immobilization	1	0	-	183
25	Cadmium	1	0	-	182

Figure 5 is designed to demonstrate the trends in the evolution of keywords introduced by the authors to represent their scientific publications on the production and application of biochar for soil amendment activities.

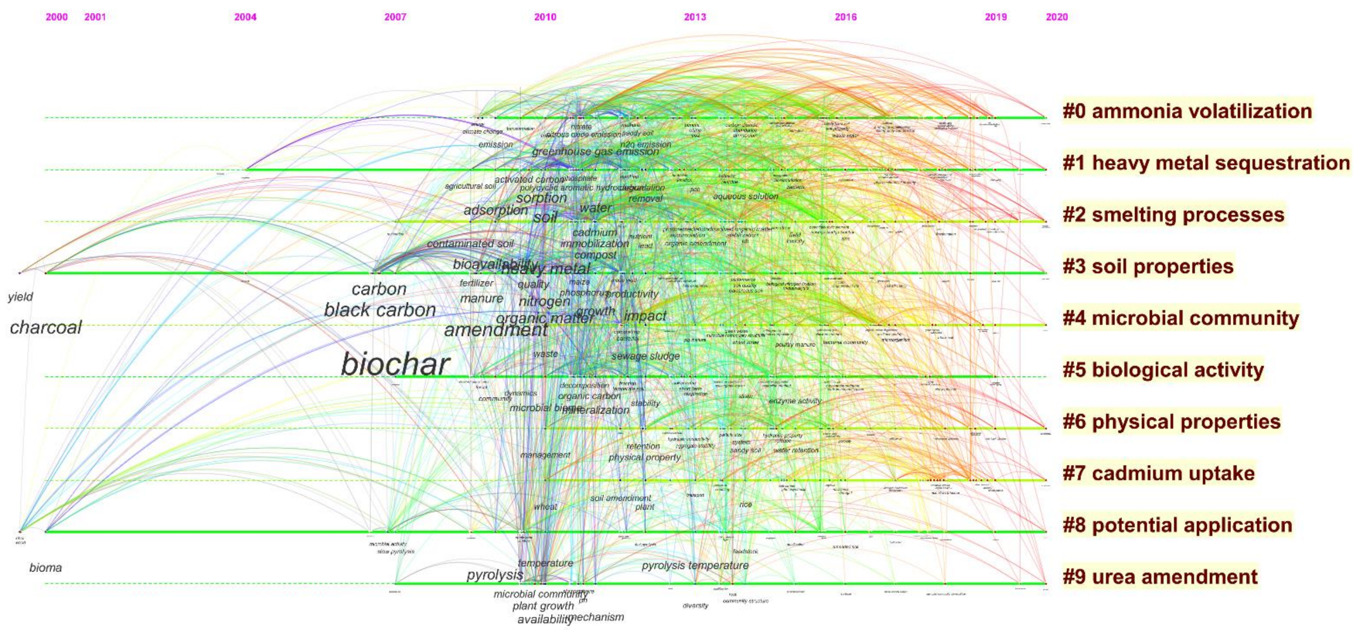

Figure 5. Appearance of time-line of keywords applied to represent the scientific documents published on the application of biochar for amendment of soil.

From Fig. 5, it is observed that most frequent keywords, "biochar", "black carbon", and "charcoal" have appeared simultaneously in 2009. Hence, this year is considered as the main milestone in the scientific knowledge in this field. Also, it can be concluded that most of the keywords have been applied for the first time before 2013, but only a limited number of them have appeared after this date.

3.5 Authors analysis

"Authors" represent the contribution of authors of scientific publications on biochar application for soil treatment and results of this analysis are provided in Fig. 6 and in Table 4. The nodes stand for contributing authors in this field, while the links represnt their cooperations. Also, the fonts representing the names of authors are to visualize their extent of contributions. The bigger the utilized font, the more contributions author had. As can be observed in Fig. 6, “Yong sik Ok”, shown as OK YS, with 68 documents from South Korea, “Van Zwieten” with 31 documents from Australia, and “Pang GX” with 27 documents from China contributed as the leading authors in this field. Of these, Yong sik Ok is currently recognized as the most active author who worked in various diciplines of biochar preparation with enhanced properties [31] from various sources [32] for different applications such as adsorption of hazardous materials from air [33], soil [31], aqueous media [32,34], and on agricultural applications [35], etc. However, the present work is limited to soil applications only.

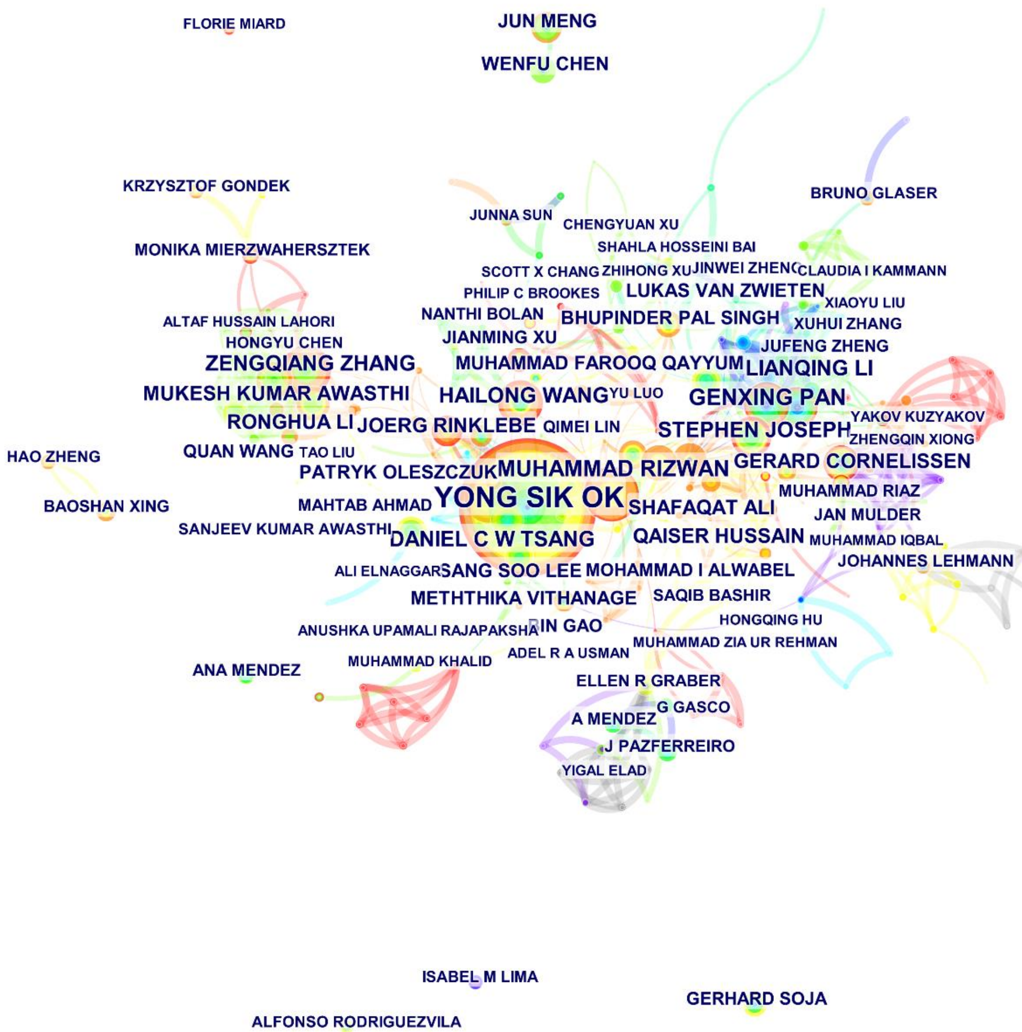

Figure 6. A scheme to illustrate the authors contributed in scientific publications on the application of biochar for soil amendment. This figure is produced with minimum overlaps. The figure containing the exact centrality is provided in the supplementary information. This analysis was performed considering all the authorship team members.

Table 4. List of contributing authors in the application of biochar for soil amendment including detailed information and their respective countries.

Rating	Author	Count (No.)	Contribution (%)
1	Yong Sik OK	78	2.62
2	Muhammad Rizwan	31	1.04
3	Genxing Pan	29	0.97
4	Zengqiang Zhang	27	0.91
5	Hailong Wang	27	0.91
6	Daniel C W Tsang	27	0.91
7	Lianqing Li	24	0.80
8	Stephen Joseph	24	0.80
9	Gerard Cornelissen	22	0.74
10	Mukesh Kumar Awasthi	20	0.67
11	Shafaqat Ali	20	0.67
12	Qaiser Hussain	19	0.64
13	Ronghua Li	19	0.64
14	Ioerg Rinklebe	19	0.64
15	Jun Meng	18	0.60
16	Patryk Oleszczuk	18	0.60
17	Sang Soo Lee	18	0.60
18	Bhupinder Pal Singh	17	0.57
19	Lukas Van Zwieten	16	0.54
20	Meththika Vithanage	16	0.54

3.6 Cited authors analysis

"Cited authors" analysis was performed by using scientometric parameters introduced in the methodology section including CC, CB, centrality, sigma, and clustering. Regarding the CC analysis, Lehmann J (cluster#3), Glaser B (cluster#1), and Spokas KA (cluster#0) with the frequencies of 1398, 579, and 545, respectively are considered as the highlighted authors. With regard to CB analysis, Ahmad M (2015, cluster #6), Yanai Y (2010, cluster#0), and Wang J (2017, cluster#0) have the highest burst strengths of 26.83, 26.74, and 25.61, respectively. For the centrality, Lehmann J (cluster#3), Major J (cluster#1), and Zimmerman AR (cluster#0) have the highest respective centralities of 0.45, 0.16, and 0.13 among all the authors published in this field. With regard to sigma analysis, Schmidt (cluster#3), Ahmad M (cluster#6), and Yu XY (cluster#3) received the highest sigma of 4.48, 3.64, and 3.62, respectively among others. Figure 7 and Table 5 show the respective data as an output of CiteSpace. It is worthy to mention that "Yong sik Ok" is identified as a highly cited author for the aplication of biochar for various applications [36–51].

In addition, the analysis of clustering with the top seven clusters according to their size of the cited authors is shown in Fig. 8. This clustering analysis was implemented over the cited author analysis demonstrating the main focus of research for the most cited authors. The first three largest clusters of keywords are represented as follows. The cluster#0, entitled as "potential mechanism", with cluster strength of 1.6 was formed in 2012, and contains 28 members. The most active citer in this cluster is "XU, G" (2012, for the document entitled "Recent advances in biochar application in agricultural soils: benefits and environmental implications" published in the journal of "Clean – Soil Air Water") [51]. The cluster#1, entitled as "nutrient status", has the cluster strength of 0.77 and was arranged in 2011, containing 25 members.

The cluster#2 with similar title to the cluster#0, with the cluster strength of 0.68 has 20 members. It can further be stated that the potential mechanisms involved in the application of biochar for soil amendment have gained most attention by the authors and other aspects such as nutrient status (cluster#1), (biochar to soil) molar ratio (clusters#3 and 4), and soil (properties) (cluster#5) have received the next importance by the most cited authors. Similarity in the title of these two clusters represents the fact that the potential mechanism involved in biochar application is currently a hot topic in the literature [52]. Thus, clustering analysis (Fig.8) was performed on the cited author scheme using centrality criterion presented in the supplementary information. It is observed from Fig.8 that the largest clusters (represented as cluster#0, and cluster#1), are located in the semi-center of the graph illustrating their high significances. In addition, the most active citer in both cluster#1 and 2 is "Atkinson, CJ" (2010, for the document entitled "Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review" published in the journal of "Plant and Soil")[53].

Figure 7. A schematic illustration demonstrating the most cited authors publishing scientific documents on biochar application for soil amendment. Graph is with the minimized overlaps. The figure containing the exact centrality has been provided in supplementary information.

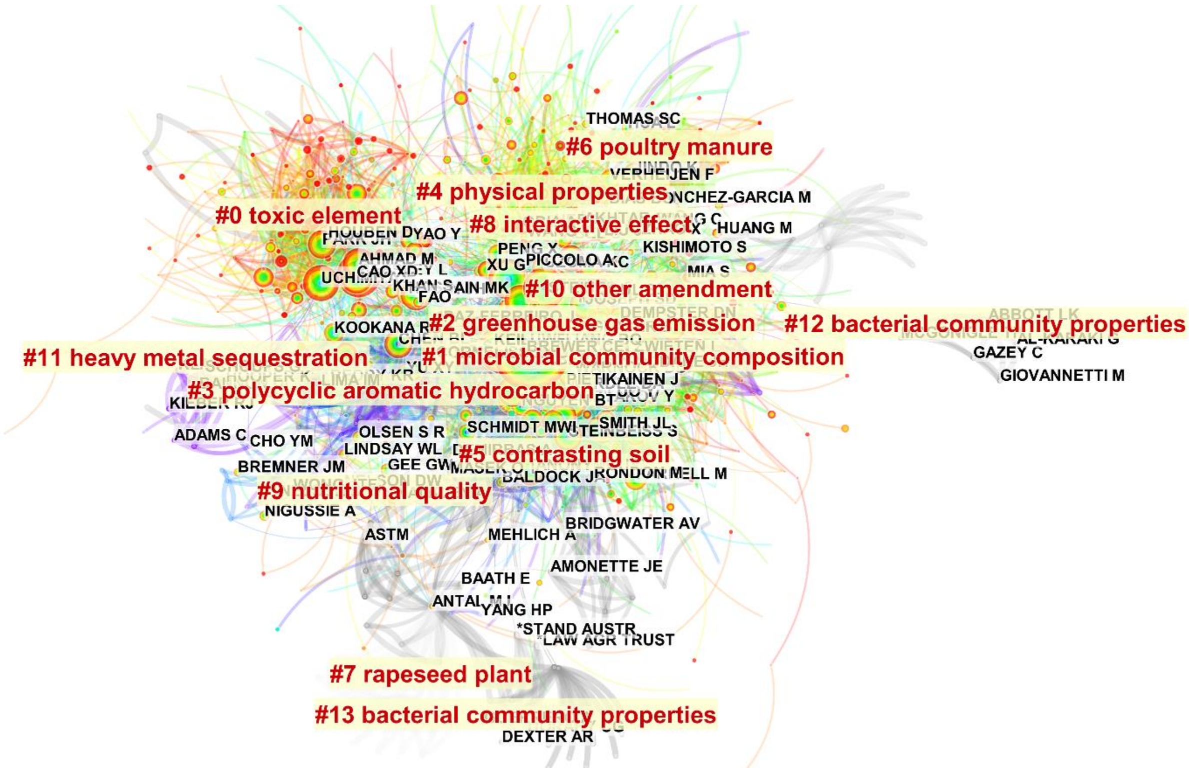

Figure 8. Clustering of cited authors on the application of biochar for the treatment of soils extracted using CiteSpace software.

Table 5. List of the most cited authors on the application of biochar for the treatment of soils and respective parameters of scientometric analysis. The parameter "year" in this table indicates the specific year in which the citation burst was initiated.

Rating	Author	Year	Sigma	Centrality	Burst	Frequency
1	Lehmann J	2007			4.22	1830
2	Glaser B	2004			39.91	697
3	Spokas KA	2010			5.79	608
4	Chan KY	2007			20.18	598
5	van Zwieten L	2010			13.32	571

6	Jeffery S	2012	-	568
7	Major J	2010	12.58	551
8	Steiner C	2009	22.82	547
9	Novak JM	2010	10.78	526
10	Beesley L	2011	-	503
11	Laird DA	2010	12.9	472
12	Liang B	2010	26	471
13	Jones DL	2011	4.21	462
14	Zimmerman AR	2011	15.56	455
15	Atkinson CJ	2011	2.15	450
16	Sohi SP	2011	-	441
17	Ahmad M	2013	-	401
18	Cheng CH	2010	29.18	392
19	Uchimiya M	2011	-	378
20	Mukherjee A	2012	-	369

3.7 Cited journals analysis

In this section, variables regarding the number of citations related to each journal publishing the documents of this study were analyzed using CiteSpace software and the results are shown in Fig. 9 and Table 6. Regarding the CC analysis, “Plant and Soil” (cluser#0), “Soil Biology and Biochemistry” (cluster#0), and “Chemosphere” (cluster#1) have shown frequencies of 1461, 1372, and 1239, respectively. The CB analysis indicated that “Geochimica et Cosmochimica Acta” (cluster#0), “Frontiers in Ecology and the

Environment” (cluster#4), and “Global Biogeochemical Cycles” (cluster#3) had the burst strengths of 53.05, 50.56, and 41.26, respectively. Top journals containing the highest centralities were also identified as “Soil Biology and Biochemistry” (cluster#0, centrality= 0.13), “Biology and Fertility of Soils” (cluster#2, centrality= 0.12), and “Chemosphere” (cluster#1, centrality= 0.09). With regard to sigma analysis, “Frontiers in Ecology and the Environment” (cluster#4), “Global Biogeochemical Cycles” (cluster#3), and “Energy and Fuels” (cluster#3) showed sigma values equal to 8.38, 4.65, and 3.23, respectively.

The cited journal clustering analysis is shown in Fig. 10 and the two largest clusters are as follows. Similarly, this analysis was performed on the obtained results of the most cited journal with centrality. The first cluster, represented as cluster#0 and entitled as “biochar effect”, contains 22 members and the mean year of this cluster is 2009. The most active citer in this cluster is “Atkinson, CJ” (2010, for the document entitled “Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review” published in the journal of “Plant and Soil”)[53]. The second cluster labeled as cluster#1, entitled also as “biochar effect”, owns 16 members and the mean year of this cluster is 2010. The most active citer in this cluster is “Ding, Y” (2010, for the document entitled “Evolution of biochar effects on nitrogen retention and leaching in multi-layered soil columns” published in the journal of “Water, Air, and Soil Pollution”) [54].

Overall, the main focus of relevant journals has been on the biochar effects [52]. Two more smaller-size clusters (as cluster#3 entitled as “molar ratio” and cluster#4 as “biochar amendment”) can also be observed in Fig.10. However, the effect of biochar application and similar to the clustering of cited authors, the potential mechanisms of biochar as a soil amendment have received the highest attention in the literature. In addition, the location of cluster#2, (potential mechanism) at the center of Fig.10 represents its high degree of importance as one of the main items that the journals in this field have paid attention. Finally, the results of clustering of the most cited journals is in compliance with those obtained from the most cited authors, which are active in the field of biochar application as a soil amendment.

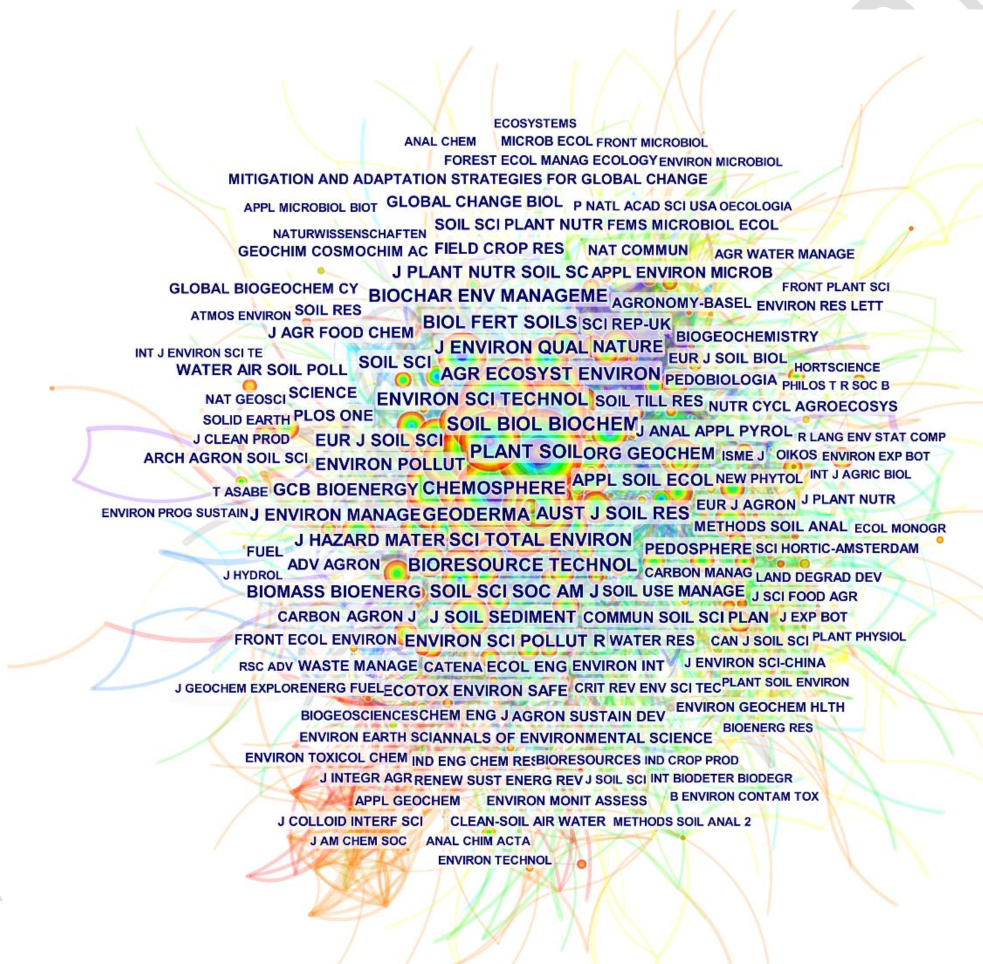

Figure 9. The cited journals analysis with minimum overlap obtained from CiteSpace. The analysis is based on the number of citations these journals received by publishing the documents gathered and analyzed in this study on the application of biochar for soil treatment. It is also worthy to mention that the centrality factor has been neglected while

creating this figure for a higher-quality illustration. The figure with actual centrality can be found in supplementary information.

Table 6. Detailed information about the journals, which has received the citations by publishing the documents collected for the present scientometric study on the application of biochar for soil amendment, and respective parameters of scientometric analysis.

Rating	Journal	Centrality	Frequency
1	Plant and Soil	2007	1995
2	Soil Biology and Biochemistry	2004	1886
3	Chemosphere	2009	1789
4	Environmental Science and Technology	2007	1608
5	Geoderma	2009	1558
6	Science of the Total Environment	2009	1511
7	Agriculture, Ecosystems & Environment	2007	1429
8	Bioresource Technology	2000	1398
9	Agriculture, Ecosystems & Environment	2007	1377
10	Bioresource Technology	2009	1372
11	Soil Science Society of America Journal	2004	1369
12	Environmental Quality	2007	1194
13	Biology and Fertility of Soils	2009	1160
14	Australian Journal of Soil Research	2009	1057
15	Biochar Environmental Management	2010	994

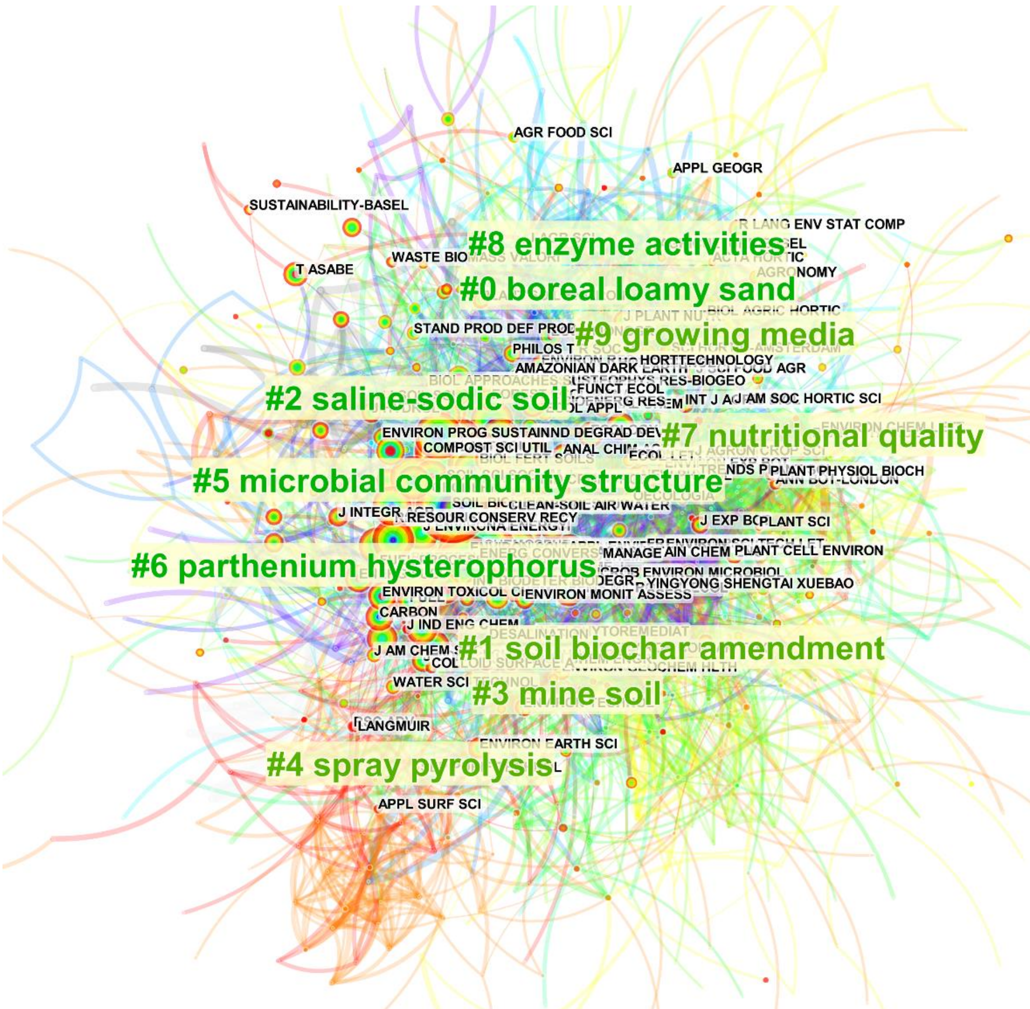

Figure 10. A schematic of the most cited journals clustering process, obtained from CiteSpace. The citations have been counted only for the documents gathered for the present scientometric study.

3.8 Categories

Categories analysis classifies the scientific documents published on the topic of biochar for the soil treatment in specific categories regarding their specific attributes such as representative scientific area analyzed using WoS database. Table 7 shows the detailed results achieved in this regard, and the most important categories identified in this field are "Environmental Science" (891 documents), "Soil Science" (598 documents), and "Agronomy" (278 documents).

Table 7. Information regarding the categories of published documents obtained from WoS.

Rank	Categories	Count (No.)	Contribution (%)
1	Environmental Science	891	25.54
2	Soil Science	598	17.14
3	Agronomy	278	7.97
4	Plant Science	163	4.67
5	Engineering Environmental	150	4.30
6	Agricultural Multidisciplinary	145	4.15
7	Energy Fuels	130	3.72
8	Ecology	109	3.12
9	Biotechnology Applied Microbiology	105	3.01
10	Water Resources	90	2.58
11	Multidisciplinary Science	75	2.15
12	Agricultural Engineering	68	1.94
13	Chemistry Multidiciplinary	64	1.83
14	Green Sustainable Science Technology	62	1.77
15	Geosciences Multidisciplinary	57	1.63
16	Chemistry Analytical	48	1.37
17	Food Science Technology	42	1.20

18	Horticulture	41	1.17
19	Engineering Chemical	40	1.14
20	Toxicology	36	1.03

3.9 Cited documents

The results obtained from WoS analysis on the most cited documents published in the literature on the chosen topic are shown in Table 8. As can be observed, “Biochar effects on soil biota - A review” [55] (2011, CC= 1335), “Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)” [56] (2010, CC= 953), and “Biochar as a sorbent for contaminant management in soil and water: A review” [36] (2014, CC=949) are the leading documents in this field.

Table 8. List of the most cited documents in this field obtained from WoS.

Rating	Title	Year	journal	Citation (No.)
1	Biochar effects on soil biota - A review	2011	Soil Biology and Biochemistry	1335
2	Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	2010	Environmental Science and Technology	953
3	Biochar as a sorbent for contaminant management in soil and water: A review	2014	Chemosphere	949

4	Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review	2010	Plant and Soil	752
5	A review of biochar and its use and function in soil	2010	Advances in Agronomy	747
6	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis	2011	Agricultural Ecosystems & Environment	689
7	Agronomic values of green-waste biochar as a soil amendment	2007	Australian Journal of Soil Research	666
8	Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	2010	Plant and Soil	590
9	Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	2011	Soil Biology and Biochemistry	554

10	Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil	2009	Soil Science	501

4. Discussion

4.1 General considerations

Biochar is a carbon-neutral or carbon-negative compound, which is generally produced by the thermal decomposition of an organic feedstock (plant whether crop or residues), animal based, sludges (municipal or industries), and solid waste (agricultural or municipal)) in the absence or limited presence of O_2 [1,57]. The type of feedstock fed into the pyrolyzer (kiln) and also the applied pyrolysis conditions (e.g., the highest temperature, heating rate, and residence time) can directly determine the properties of biochar produced [57] such as total carbon content, ash content [58], liming ability (pH) [18], leaching and bioavailability of nutrients and toxic metals [59], surface area, porosity [60], etc.

Various reasons have been reported for the positive effects of biochar on soil properties, especially for agricultural applications. Its role in soil decontamination was reported by the adsorption of potential toxic metals such as Cd and Cu, which may result in the decrease of bioavailability of such potential toxic metals for the plants [61–63]. It also provides the required nutrients for plant growth because biochar is usually enriched with various metals such as C, Fe, Mn, Zn, etc. [43,64–66]. It also contributes to the improvement of critical properties of the soil such as water holding capacity (WHC) as well as bulk density and porosity, which may result in better fertility of the soil for crop production [67]. Moreover, there are some pieces of evidence in the literature for the positive effects of biochar with alkaline nature on the pH of the soil, which is among the main limitations for some soils such as those, which are under mining activities [9]. At any rate, it must be emphasized that the number of reports on the application of biochar for large-scale and field applications [68,69] is still somewhat limited.

Literature suggests potential improvements in the application of biochar for soil improvement. For instance, although studies performed recently revealed that biochar can significantly improve the microbial activity of the soil, yet problems exist for further investigations such as specific impacts of biochar on the functioning of microorganisms in carbon and nitrogen cycle [67]. Additionally, effect of biochar addition on soil respiration component, including autotrophic and heterotrophic has not yet been fully understood [70]. The need for additional fertilizers besides biochar is another field of interest for which there is limited information in the literature. The cost effectiveness of biochar application compared to other existing methods to improve soil properties may be considered a fertile area with the need for further efforts to distinguish the real cost-effectiveness of this method compared to conventional approaches for soil amendment.

Although the majority of studies have reported the positive effects of biochar on the properties of soils, the real fate of potential toxic metals, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs) and other matters released from biochar are not well understood [71]. Moreover, the so called “exact biochar service life” is still poorly understood. In other words, the decomposition of biochar in the soil has not been well-studied to determine the required period of amendment with biochar [72]. Thus, in order to determine the growth of science in the application of biochar as a soil amendment and also to distinguish the trends and milestones in this field, a scientometric study was conducted. The obtained results are discussed in separate sections as follows.

4.2 Scientific documents

According to the existing literature, it can be stated that application of biochar for soil redemption is still in the pre-commercialized stage [73]. This can be due to two main reasons including the expense of pyrolysis process and the existing uncertainties regarding toxic consequences, which may be caused by the addition of various types of produced biochars [18]. Moreover, majority of research efforts in this area have been implemented in the laboratorial scales with very few exceptions of field experiments [74]. On the other hand, most of the existing regulations about contamination of soil and the corresponding limits of compounds as heavy metals such as Zn, Cr, etc., are oriented based on the corresponding amounts of contaminants in the fields [75]. Thus, the effectiveness and competitiveness of biochar application for real applications still remains a challenge without any valid solution.

The results of this study demonstrate that most of the scientific efforts that have resulted in the indexed publications have been mainly after the 2000s. Between 2000 and 2010, only a limited number of publications have been reported regarding the application of biochar to soil, indicating that scientific knowledge in this area was just beginning. After 2010 however, there has been a substantial increase in the number of published documents with multiple behavior such as an adsorbent, a soil amendment material or a material to be used for carbon storage, and for climate change mitigation [76]. Although the number of publications shows a growing trend, the cumulative number of documents published in the literature (Fig. 2) indicate sigmoidal pattern. Thus, it can be concluded that research and science in this field have almost reached a high degree of maturity.

Analysis of the most cited documents published emphasize on some specific features of biochar such as liming effect, high carbon content, high specific surface area, porosity, potential to enhance water holding capacity, cation exchange capacity, electrical conductivity, inertia and stability, potential to immobilization of contaminants, enhancing the bioavailability of nutrients such as N and P, and consequently the positive effects of biochar on soil fertility and crop production. However, in some cases, the opposite results are observed from experiments on the applicability of biochar for soil treatment. This may be explained by the various set-ups and experimental conditions (such as type of soil utilized, properties of biochar applied, biochar to soil ratio, duration of experiments, etc.) [36,53,55,56,58,74].

4.3 Trends in biochar application for soil treatment

The evolution occurred in scientific literature can be discussed based on the results of keywords appearance as demonstrated in Figures 4 and 5. In the period in which this study covered (since 2000), keywords such as "biochar", "amendment", "microbial communities", "heavy metals", "sorption", etc. appeared in certain milestones, which can be used to identify the trends. From the keyword timeline as displayed in Fig.4, it is observed that before 2009 and prior to the introduction of keywords such as "biochar" (as the main trend illustrated with the biggest cross) and "charcoal", the only repeated keyword was "manure". This is in compliance with the historical background of biochar application, which can go back to as much as 500 to 2500 years ago, which is assumed to be practiced by the Ancient Amazonians, Japanese, African, Roman, and Egyptians, who used to convert the animal manure and fish bones to biochar to be applied for soil amendment [18].

The relevant aspects such as the type of feedstock used and kilns were introduced in the literature only after 2009 (Fig.5). In addition some other keywords such as “nitrous oxide” and “stability”, appeared between 2010 to 2013, which is related to the discovery of biochar capability to eliminate nitrogen leaching in the soil and also to release the greenhouse gases into the atmosphere. Moreover, compared with the common fertilizers and liming agents employed in agriculture, biochar has demonstrated a more stable composition and remains semi-permanent, while the mentioned fertilizers vanished in a relatively short time, which contributed to the release of high amounts of greenhouse gases. Also, as the agricultural activities are responsible for the release of approximate 25% of total anthropogenic greenhouse gases (mainly CO_2, then CH_4 and N_2O), the application of biochar besides carbon storage in soils can be considered as a tool to mitigate the climate change [77].

4.4 Scientific contributions

As indicated in Table 3, among the contributing countries, China has the highest share in the number of publications, due to the active scientific programs followed by China, especially in recent years. To highlight these programs, it should be considered that China has established two main activities including “special economic zones of the People's Republic of China”[78] and “economic and technological development zones” [79] with the goal of accelerating high-tech scientific-based activities by attracting foreign investments to facilitate the progress in this area. As a result, China, in recent years, has become the main contributor to research and development (R&D) activities, making this country a large producer of scientific articles besides the United States [80].

Effective collaboration between active researchers in this field may overcome the present barriers for wider applications of biochar in soil amendment and facilitates the eliminations of uncertainties about the behavior of various types of biochar prepared from various feedstocks and under different pyrolysis conditions considering the specifications of studied soil. The results of the contributing authors analysis (Fig. 6), reinforce the idea that proper scientific communications have been stablished all over the word, which would facilitate to share the information among scientific communities. However, among the most impacting authors in this field, there are some groups with high scientific outputs, but low degree of co-operations with other scientific communities.

The keyword clustering methodology applied on the results obtained from the cited authors analysis demonstrate the main trends and frontiers. These results emphasize that the initial and main trend in biochar as an amending tool for soil has been due to the potential mechanisms of biochar interaction with soil, expressed as cluster#0, which is the largest cluster among others. Moreover, due to the fact that second largest cluster, expressed as cluster#1, is entitled as “nutrient status”, it can be concluded that the main variation in defining biochar characteristics were oriented on the utilized feedstock and its corresponding properties. However, pyrolysis condition as another main factor in the determination of biochar characteristics did not receive the same attention, and more studies in this field are required to further remove the existing barriers for a rapid commercialization of biochar for an effective soil amendment.

Cited journal analysis is also considered as another important parameter to demonstrate the contributing parties in the science and technology of biochar application for soil application. Based on the results obtained from the cited journal analysis, it may be concluded that the main active journals, which have received the highest number of citations, are mainly concerned about the application of biochar on crop yield and its impacts on microbial communities or activities in the soils. This might be due to biochar capabilities to replace the conventional organic and inorganic fertilizers with a positive effect on climate change.

Finally, analyzing the results achieved from the categories analysis reveal that "environment" and "agriculture" are the main categories that have attracted the attention of contributors in this field. This can clearly reflect the potential contribution of biochar towards sustainable waste management by satisfying the stringent environmental regulations regarding the elimination of solid waste landfilling and conversion of a problematic substance into chemically stable product along with its potential for decontamination of polluted soils, mitigation of climate change and the possible increase in crop yield of the agricultural products. From these attractive aspects, it can be concluded that application of biochar as a soil amendment can be in compliance with the sustainable development goals, assigned by the United Nations [12–14,81], although more studies are required to deal with the existing uncertainties of some aspects of biochar application such as long-term effects of biochar in the soil as well as the most suitable feedstock, biochar production conditions and the optimum conditions for soil applications of biochar.

5. Conclusions

Biochar, a main product from biomass pyrolysis, has been utilized as an environmentally friendly amendment and fertilizer applied to a variety of soils. Its use has been referred as modifying the physicochemical properties of soils. Also, it has been accounted to be able to immobilize contaminants in the soil, sequester carbon, mitigate greenhouse gas emission, and improve the quality of the soil. Due to the fact that the application of biochar as the soil remediation approach has been emerging in recent years, therefore scientometric analysis was performed in order to map the research efforts in this exciting field. To proceed with the analysis, ISI Web of Science core collection was adopted as the database and relevant bibliographic records were collected. A total of 2123 documents in English were collected within the period of 2000 to 2018. The results indicate that the subject has reached a relative maturity although there are still some barriers to overcome to promote the application of biochar for amendment of the soils for various purposes, mainly for crop production.

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Supplementary Information

Application of biochar for soil amendment – Scientometric graphs with actual centralities

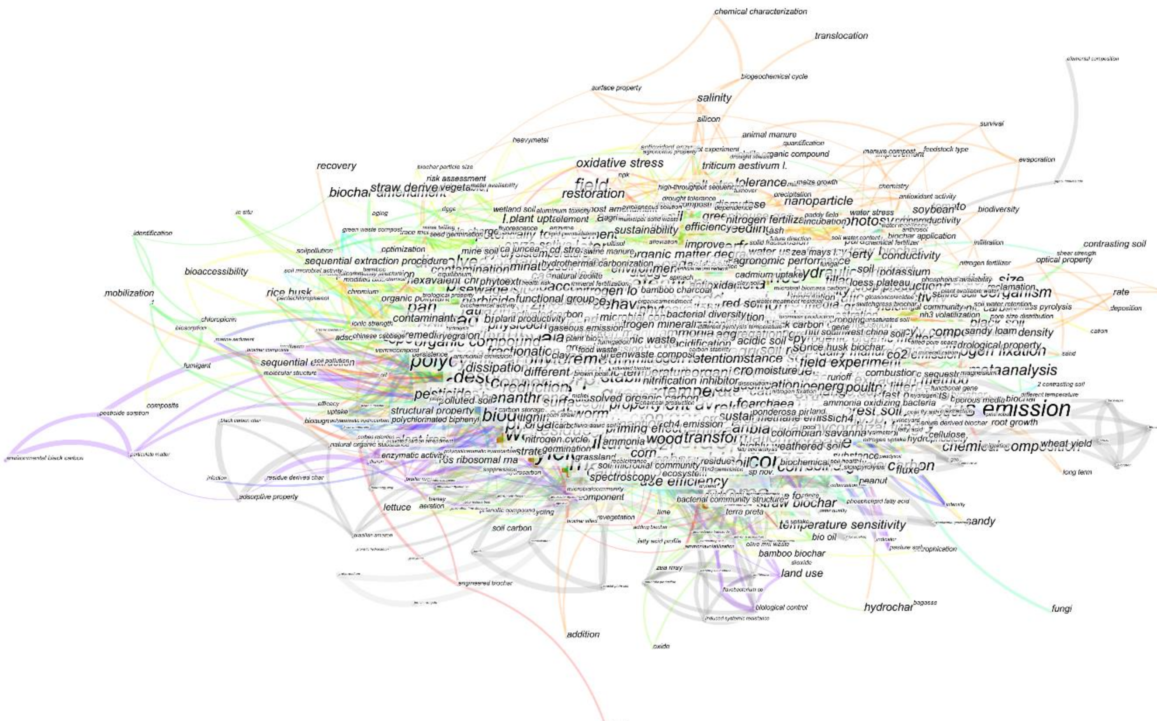

Fig. A.1.

A schematic representation of co-occurring analysis of the keywords appeared in the scientific documents published on the application of biochar for soil treatment with actual centrality.

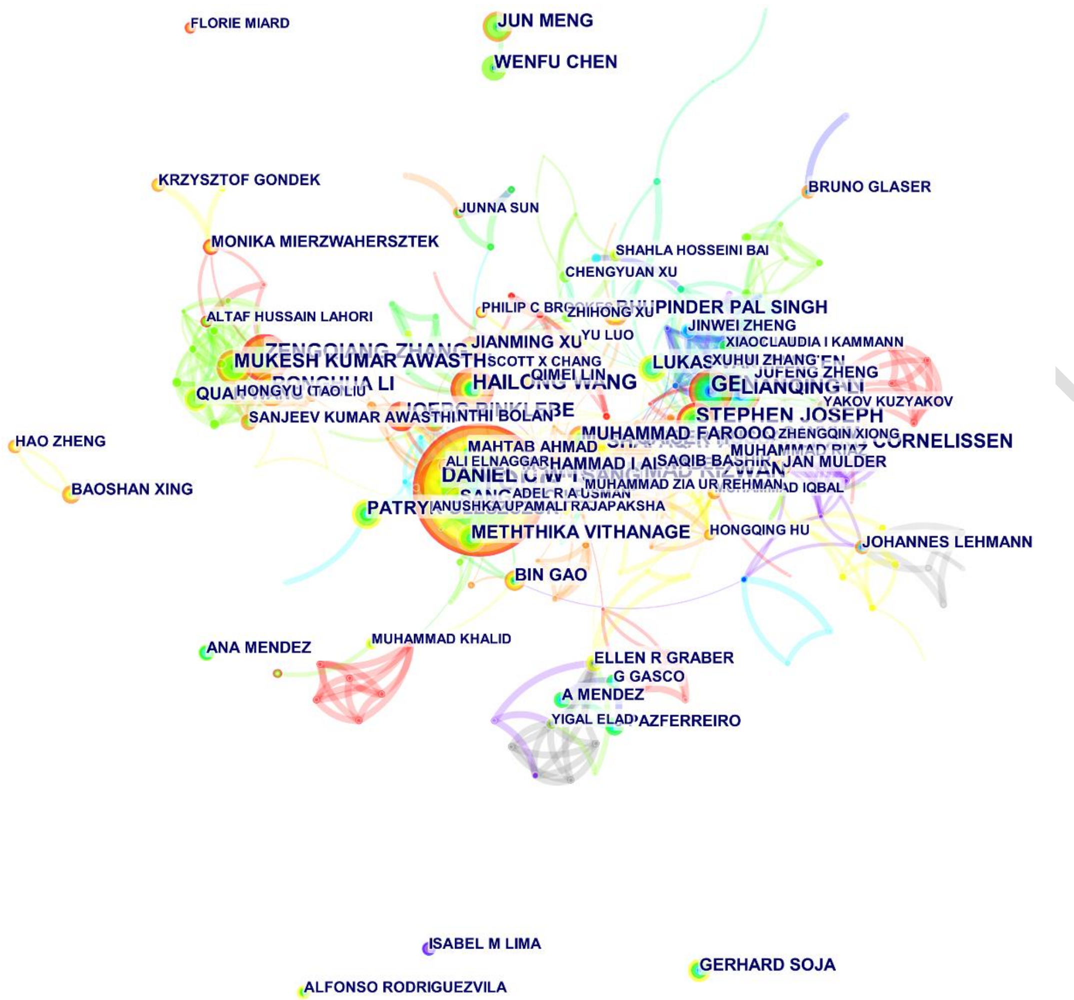

Fig. A.2.

A schematic to illustrate the authors contributed in scientific publications on the application of biochar for soil amendment with actual centrality.

Fig. A.3.

A schematic illustration demonstrating the most cited authors publishing scientific documents on the biochar application for the soil amendment with actual centrality.

Fig. A.4.

The cited journals analysis with minimum overlap obtained from CiteSpace with actual centrality.