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Highlights

- Scientific status in the application of biochar asa soil amendment is explored.
- 2982 bibliographic records from the Web of Science are analyzed critically.
- The results assist to identify the current trends and the existing knowledge gaps.
- Recommendations for the future studies are provided.
- The results can be used by various parties such as governments and academics.

Scientometric Analysis and Scientific Trends on Biochar Application as Soil Amendment

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Abstract

This manuscript presents a scientometric analysis on the studies performed on the application of biochar for soil amendment in order to investigate the research and developments in this field and to identify the existing gaps to provide recommendations for future studies. A total of 2982 bibliographic records were retrieved from the Web of Science (WoS) database using appropriate sets of keywords, and these were analyzed based on the criteria of authors, publishing journals, citations received, contributing countries, institution, and categories in research and development. Based on these data, progress of research was mapped to identify the scientific status, such as current scientific and technological trends as well as the knowledge gaps. The majority of scientific developments started in the early 2000's and accelerated considerably after 2014. China and USA are the 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 and understanding on 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 results 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 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 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 the mining activities [9]. These positive effects can result in the enhancement of microbial activity, leading to improved soil fertility [17].

Much evidence is available to prove that 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 world 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 performed here aims at determining the current trends in this scientific field, which will facilitate to identify the deficiencies and areas in which further improvements are needed 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 based on scientific history, the progress made, previous and current trends in this field, identifying the gaps and potentials for further developments. The present study 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 scientific developments 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 (5.6.R3) 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 (2000-2020). 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 88% of all the publications over the studied period. Figure 1 presents the respective results obtained.

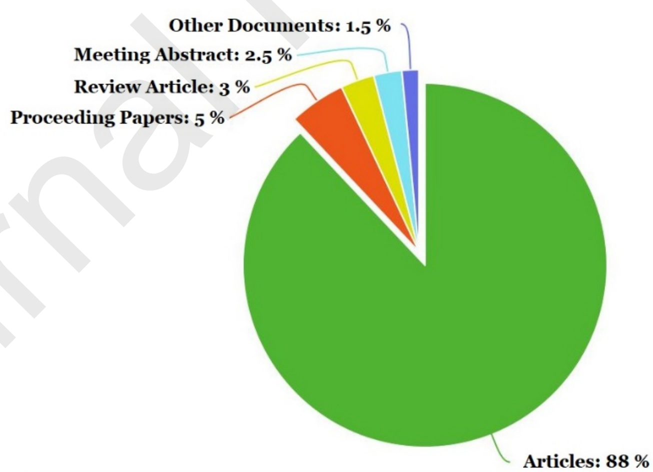

Figure 1. Types of documents published on biochar application in soil amendment.

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.

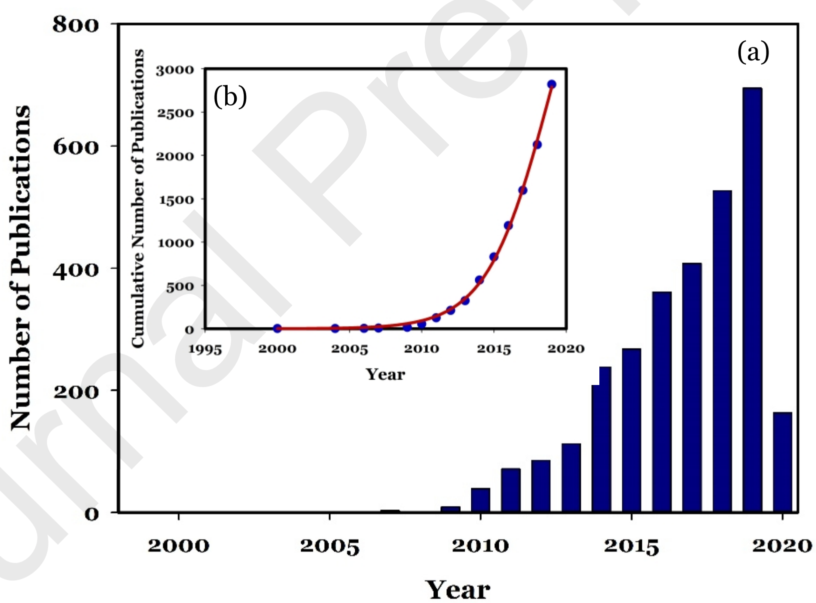

Figure 2. The number of published documents on the application of biochar for soil amendment (a) and cumulative number of publications indicating sigmoidal pattern of growth with and without curve fitting (b). It is worthy to mention that the documents published in 2020 have not been considered in the cumulative number of publications

over the years (b) due to this fact that the data includes the publication until the 1th of April 2020.

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 1195 documents) is the highest contributing country. Then USA and Australia with significant differences to China occupied the next places among the leading countries with 522 and 270 documents, respectively. However, there is no significant difference among the three upcoming countries including Germany (189 documents), Pakistan (185 documents), and Spain (162 documents) in terms of their publications on biochar application to improve the soil physicochemical properties.

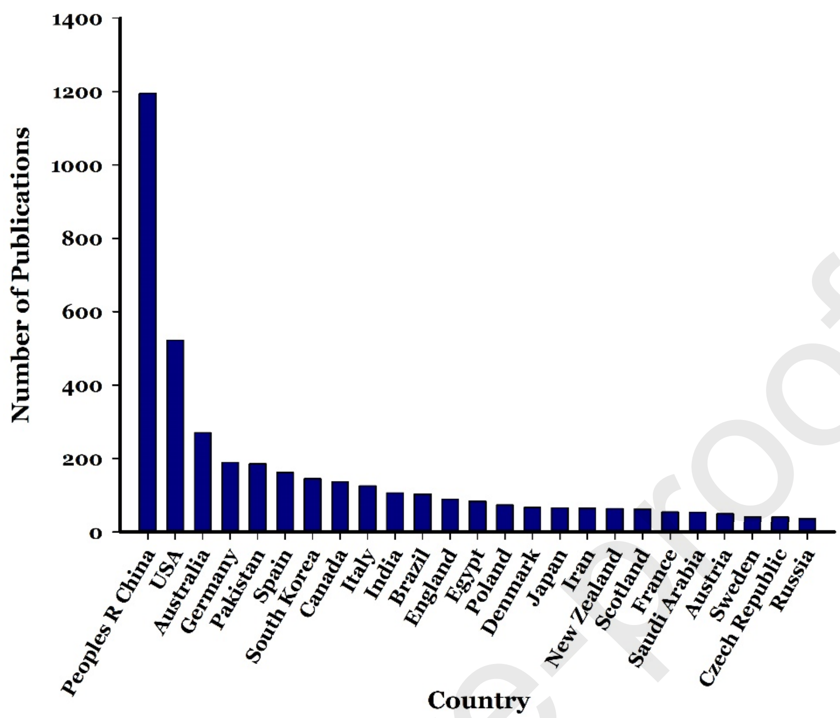

Figure 3. Contributions of various countries worldwide in the production of scientific documents on the application of biochar for the amendment of soils.

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", "amendment", and "black carbon" have appeared most frequently (in number of 1520, 569, and 566, respectively) among all the applied keywords to represent the documents published on the application of biochar for soil treatment. "charcoal", "carbon", and "soil" are the up-coming keywords from the frequent perspective, in number of 523, 470, and 368, respectively, which demonstrates the focus of studies in this field. In this regard, "biochar" has the highest frequency 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.

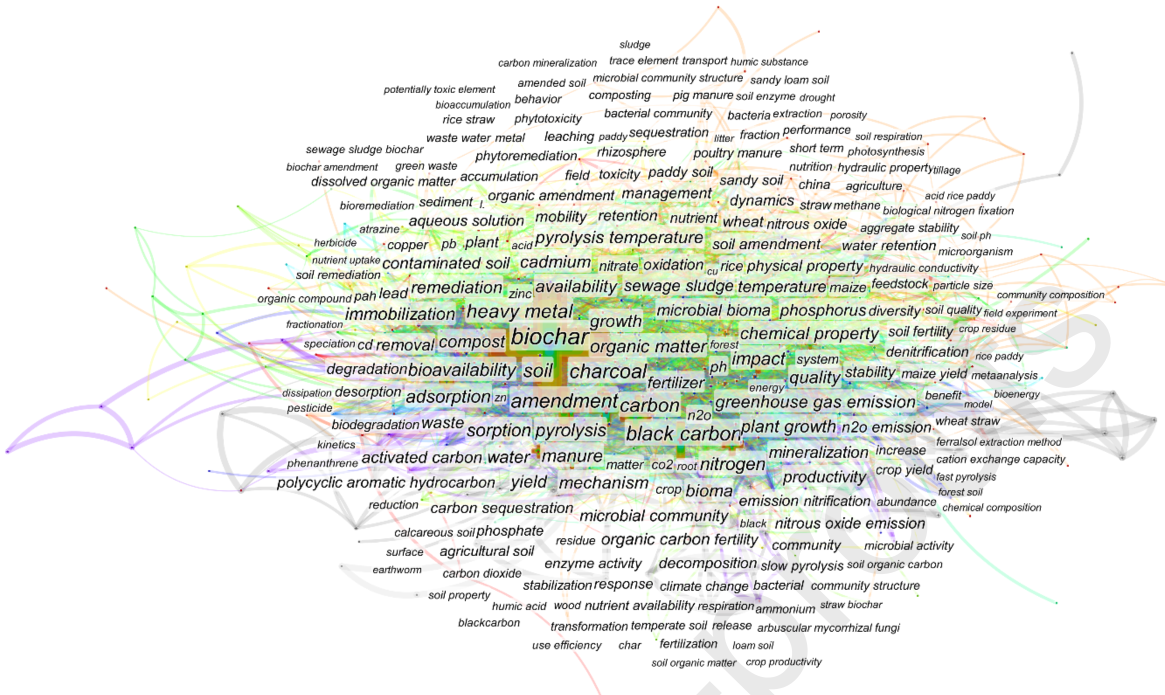

Figure 4. A schematic representation of co-occurring analysis of keywords appeared in scientific documents published on the application of biochar for soil treatment. In this figure, centrality was neglected to represent clear illustration. The figure containing the exact centrality is provided in the 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	Burst	Frequency
1	Biochar	-	1520
2	Amendment	-	569

3	Black Carbon	52.14	566
4	Charcoal	63.02	523
5	Carbon	-	470
6	Soil	2.83	368
7	Heavy Metal	-	362
8	Organic Matter	1.35	335
9	Impact	-	323
10	Pyrolysis	0.96	319
11	Nitrogen	-	316
12	Bioavailability	1.26	314
13	Sorption	2.63	306
14	Adsorption	1.01	276
15	Manure	3.24	246
16	Growth	-	236
17	Water	-	231
18	Bioma	2.18	222
19	Yield	1.21	217
20	Availability	-	197

21	Compost	-	190
22	Chemical Property	1.23	190
23	Greenhouse Gas Emission	-	188
24	Immobilization	-	183
25	Cadmium	-	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.

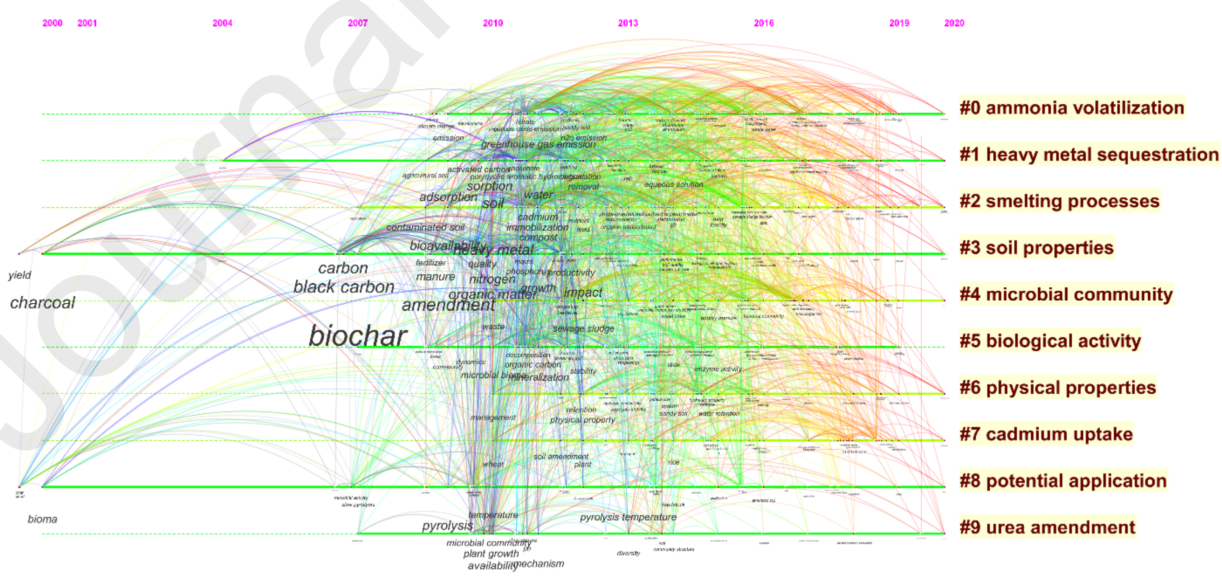

Figure 5. Appearance of time-line of keywords applied to represent the scientific documents published on the application of biochar for amendment of soil.

From Fig. 5, it is observed that most frequent keywords, “biochar”, “black carbon”, and “charcoal” have appeared simultaneously in 2007. 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 analysis” criterion represents 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, “OK YS” (Yong sik Ok), with 78 documents from South Korea, “Joseph S” with 50 documents from China, and “Genxing Pan” with 35 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.

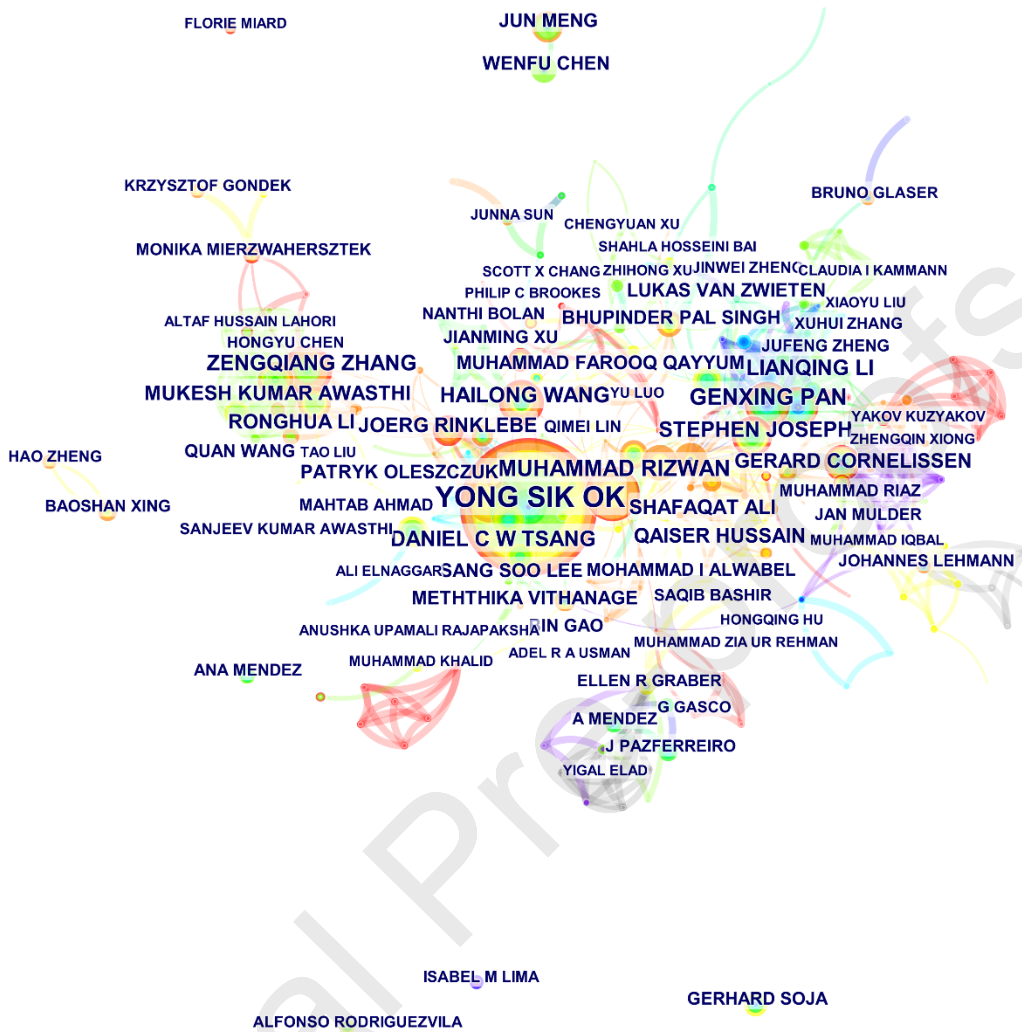

Figure 6. A scheme to illustrate the authors contributed in scientific publications on the application of biochar for soil amendment. This figure is produced with minimum overlaps. The figure containing the exact centrality is provided in the supplementary information. This analysis was performed considering 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	Country	Count (No.)	Contribution (%)
1	Ok YS	South Korea	82	2.74
2	Joseph S	China	50	1.67
3	Pan GX	China	35	1.17
4	Rizwan M	Pakistan	34	1.14
5	Wang HL	China	32	1.07
6	Van Zwieten L	Australia	31	1.03
7	Li LQ	China	29	0.97
8	Paz-Ferreiro J	Norway	26	0.87
9	Cornelissen G	Norway	26	0.87
10	Gasco G	Spain	24	0.80
11	Mendez A	Australia	24	0.80
12	Meng J	China	24	0.80
13	Chen WF	China	24	0.80
14	Singh BP	Australia	24	0.80
15	Zhang ZH	China	24	0.80
16	Oleszczuk P	Poland	23	0.77
17	Lee SS	South Korea	20	0.67
18	AL-Wabel MI	Saudi Arabia	20	0.67
19	Graber ER	Israel	20	0.67
20	Vithanage M	Sri Lanka	19	0.63

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#10), Glaser B (cluster#12), and Spokas KA (cluster#7) with the frequencies of 1830, 607, and 608, respectively are considered as the highlighted authors. With regard to CB analysis, Glaser B (2004, cluster #12), Cheng CH (2010, cluster#6), and Liang B (2010, cluster#6) have the highest burst strengths of 26.83, 26.74, and 25.61, respectively. For the centrality, Lehmann J (cluster#10), Zimmerman AR (cluster#5), and Kuzyakov Y (cluster#6) have the highest respective centralities of 65, 62, and 52 among all the authors published in this field. With regard to sigma analysis, Lehmann J (cluster#10), Zimmerman AR (cluster#5), and Kuzyakov Y (cluster#6) received the highest sigma, 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 "toxic element", with cluster strength of 0.858 was formed in 2016, and contains 160 members. The most active citer in this cluster is "Mandal, Sandip" (2020), for the document entitled "Progress and future prospects in biochar composites: application and reflection in the soil environment" published in the journal of "Critical Reviews in Environmental Science and Technology") [51]. The cluster#1, entitled as "microbial community composition", has the cluster strength of 0.68 and was arranged in 2014, containing 150 members. The cluster#2 entitles as "greenhouse gas emission", with the cluster strength of 0.78 has 148 members. It can further be stated that the potential mechanisms involved in the application of biochar for soil amendment mainly to deal with toxic elements have gained most attention by the authors and other aspects such as microbial community composition (cluster#1), greenhouse gas emission (clusters#2), and soil physical properties (cluster#4) have received the next importance by the most cited authors. Similarity in the title of the main 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 cluster#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.

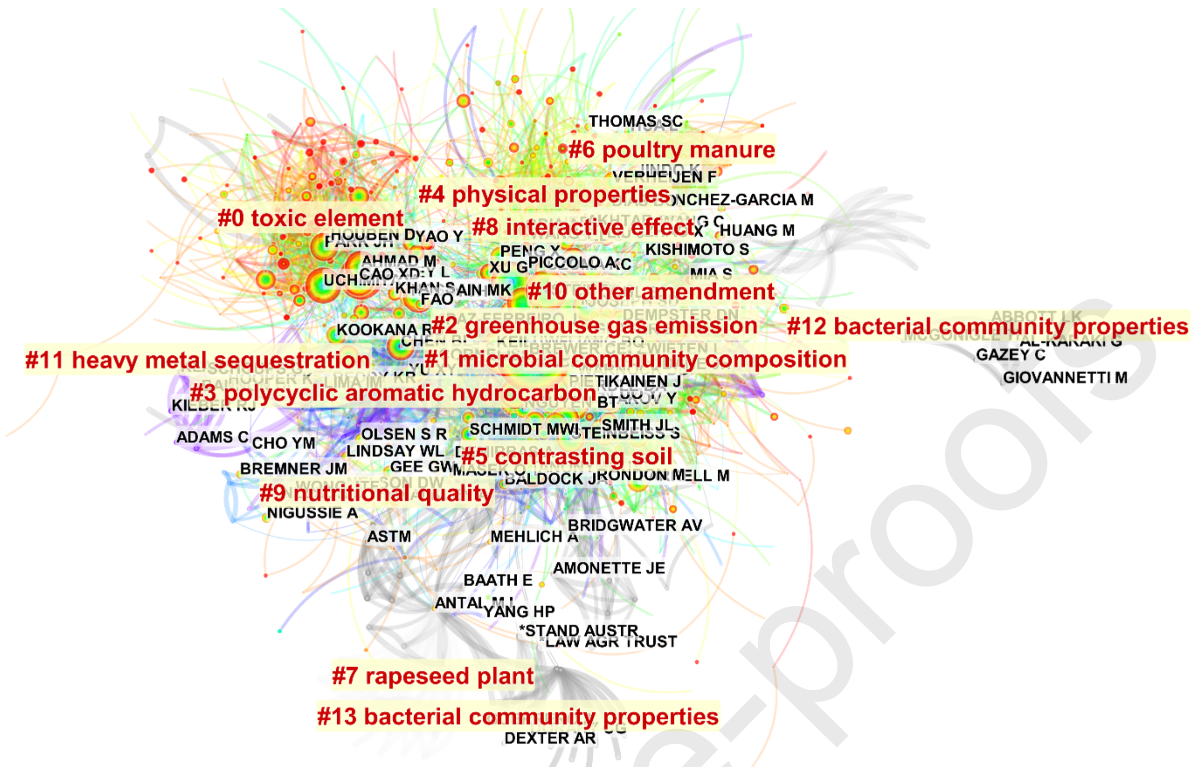

Figure 8. Clustering of cited authors on the application of biochar for the treatment of soils extracted using CiteSpace software.

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	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#10), “Soil Biology and Biochemistry” (cluster#0), and “Chemosphere” (cluster#1) have shown frequencies of 1995, 1886, and 1789, respectively. The CB analysis indicated that “Organic Geochemistry” (cluster#9), “Frontiers in Ecology and the Environment” (cluster#9), and “Mitigation and Adaptation Strategies for Global Change” (cluster#10) had the burst strengths of 43.71, 39.12, and 25.13, respectively. Top journals containing the highest centralities were also identified as “Agriculture, Ecosystems & Environment” (cluster#10, centrality= 83), “Biology and Fertility of Soils” (cluster#13, centrality= 74), and “Plant Soil” (cluster#10, centrality= 71). With regard to sigma analysis, “Agriculture, Ecosystems & Environment” (cluster#10), “Biology and Fertility of Soils” (cluster#13), and “Plant Soil” (cluster#10) had the greatest sigma values, 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 “boreal loamy sand”, contains 142 members and the mean year of this cluster is 2014. The most active citer in this cluster is “Khalid, Sana” (2020, A critical review of different factors governing the fate of pesticides in soil under biochar application” published in the journal of “Science of the Total Environment”)[54]. The second cluster labeled as cluster#1, entitled also as “soil biochar amendment”, owns 136 members and the mean year of this cluster is 2014. The most active citer in this cluster is “Naveed, Muhammad” (2020, for the document entitled “*Burkholderia phytofirmans PsJN* and tree twigs derived biochar together retrieved pb-induced growth, physiological and biochemical disturbances by minimizing its uptake and translocation in mung bean (*Vigna radiata L.*)” published in the journal of “Journal of Environmental Management”)[55].

Overall, the main focus of relevant journals has been on the biochar effects [52]. Two more smaller-size clusters (as cluster#2 entitled as “saline-sodic soil” and cluster#4 as “mine soil”) 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, (saline-sodic soil) 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.

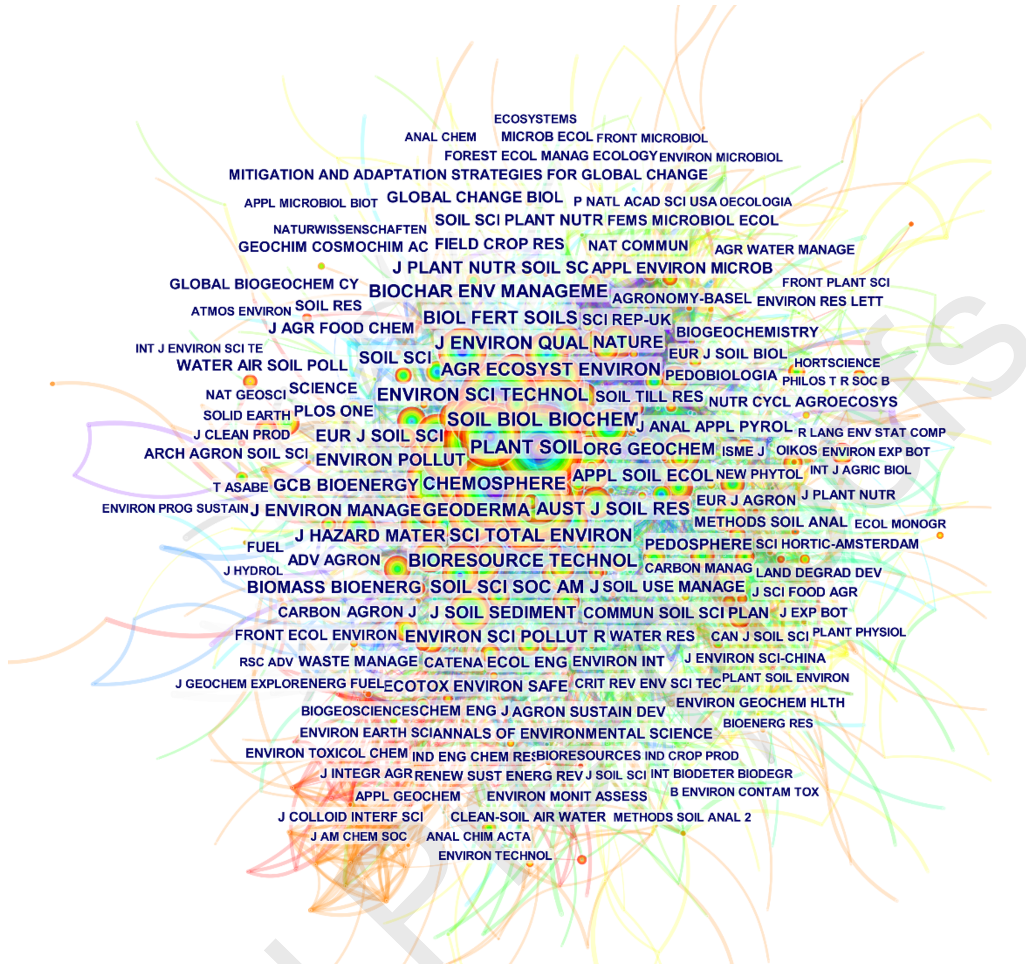

Figure 9. The cited journals analysis with minimum overlap obtained from CiteSpace. The analysis is based on the number of citations these journals received by publishing the documents gathered and analyzed in this study on the application of biochar for soil treatment. It is also worthy to mention that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

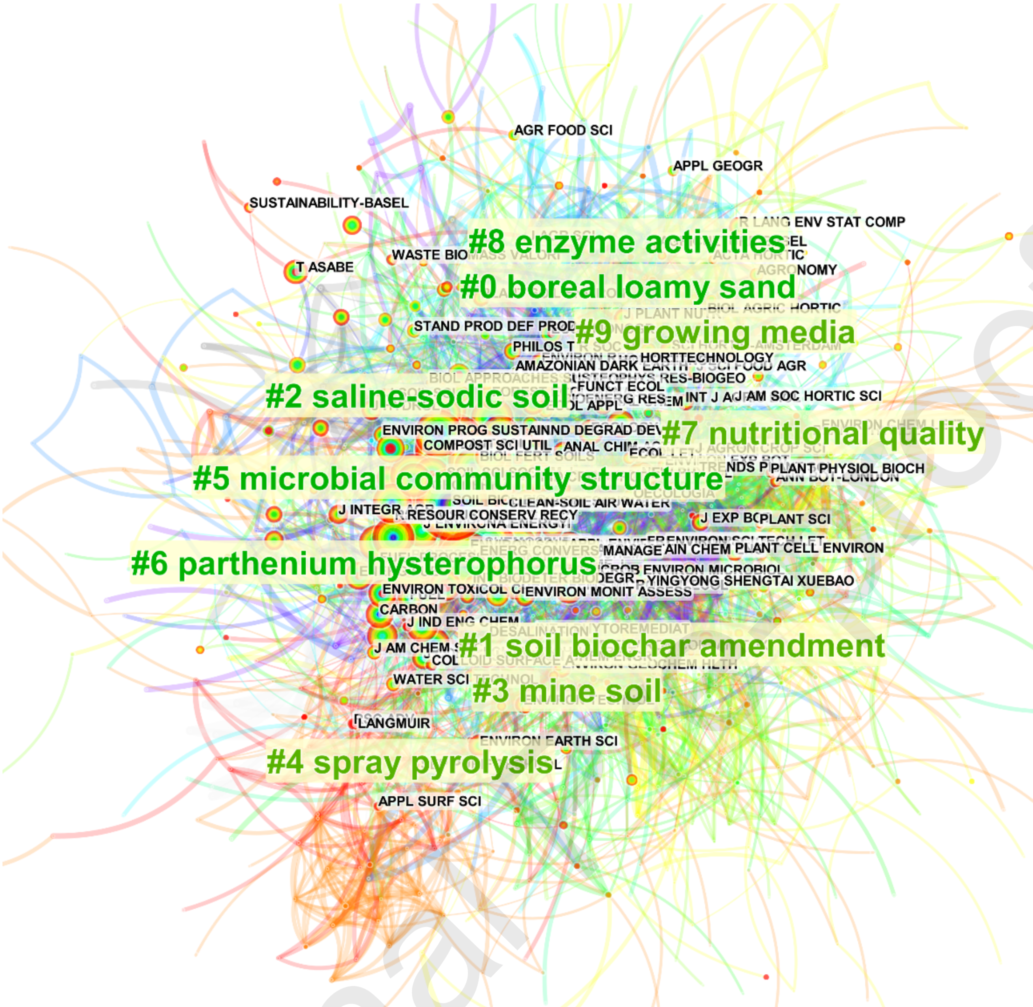

Figure 10. A schematic of the most cited journals clustering process, obtained from CiteSpace. The citations have been counted only for the documents gathered for the present scientometric study.

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” (1295 documents), “Soil Science” (789 documents), and “Agronomy” (278 documents).

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

Rank	**Categories**	**Count (No.)**	**Contribution (%)**
1	Environmental sciences	1295	43.47
2	Soil science	789	26.48
3	Agronomy	382	12.82
4	Plant sciences	244	8.19
5	Engineering environmental	222	7.45
6	Agriculture multidisciplinary	170	5.7
7	Energy fuels	169	5.67
8	Biotechnology applied microbiology	142	4.76
9	Ecology	123	4.12
10	Water resources	116	3.89
11	Green sustainable science technology	97	3.25

12	Agricultural engineering	95	3.18
13	Multidisciplinary sciences	92	3.08
14	Chemistry multidisciplinary	89	2.98
15	Geosciences multidisciplinary	86	2.88
16	Chemistry analytical	70	2.34
17	Toxicology	66	2.21
18	Engineering chemical	65	2.18
19	Horticulture	59	1.98
20	Food science technology	47	1.57

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” [56] (2011, CC= 1661), “Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)” [57] (2010, CC= 1153), and “Biochar as a sorbent for contaminant management in soil and water: A review” [36] (2014, CC=1316) 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	1661
2	Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	2010	Environmental Science and Technology	1153
3	Biochar as a sorbent for contaminant management in soil and water: A review	2014	Chemosphere	1316
4	Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review	2010	Plant and Soil	912
5	A review of biochar and its use and function in soil	2010	Advances in Agronomy	868
6	A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis	2011	Agricultural Ecosystems & Environment	837
7	Agronomic values of	2007	Australian Journal of	818

	greenwaste biochar as a soil amendment		Soil Research	
8	Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	2010	Plant and Soil	744
9	Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	2011	Soil Biology and Biochemistry	641
10	Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil	2009	Soil Science	575

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 [1,58]. 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 [58] such as total carbon content, ash content [59], liming ability (pH) [18], leaching and bioavailability of nutrients and toxic metals [60], surface area, porosity [61], 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 [62–64]. It also provides the required nutrients for plant growth because biochar is usually enriched with various metals such as C, Fe, Mn, Zn, etc. [43,65–67]. 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 [68]. 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 [69,70] 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 [68]. Additionally, effect of biochar addition on soil respiration component, including autotrophic and heterotrophic has not yet been fully understood [71]. 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 [72]. 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 [73]. 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.

According to the existing literature, It is worthy to mention that the application of biochar for soil redemption is still in the pre-commercialized stage [74]. 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 [75]. 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 [76]. Thus, the effectiveness and competitiveness of biochar application for real applications still remains a challenge without any valid solution.

4.2 Scientific documents

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 [77]. 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.) [36,53,56,57,59,75].

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. 5, it is observed that appearance of keywords such as “manure” 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 2007 (Fig.5). In addition some other keywords such as “nitrous oxide” and “organic matter”, 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 [78].

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"[79] and "economic and technological development zones" [80] 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 [81].

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 of biochar to deal with soil pollutants, 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 "microbial community composition", it can be concluded that the a number of studies in this field has been oriented on the impacts of the biochar addition on the soil microbial community which can potentially alter the soil properties and the crop production [82,83]. However, the biochar production conditions such as pyrolysis as another main factor in the determination of biochar impacts on soil microbial community has not yet received enough 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 "environmental science" and "soil science" (from Table 7) 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 [12–14,84], 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. Future research directions

Based on our data, the following research directions are recommended for future continuing research in this field.

a) The composition and assemblage of the microbial community in soil can potentially influence the soil properties and its appropriateness for crop production purposes [17,83]. However, the effects of biochar on soil microbial community have not yet been well studied and highlighted in the literature. There is also a need to explore the effects of biochar production conditions on those properties of the biochar, which can potentially affect the soil microbial structure.

b) Further studies are highly encouraged to optimize the biochar properties considering the variables such as the feedstock applied, the operating conditions, the required functionalization, etc. In this regard, adoption of cost-effective and efficient optimization methodologies such as Taguchi experimental design [85] can be highly recommended.

c) Long-term effects of biochar on soil properties have not been highlighted among the many studies done so far. In this regard, further research is needed on the fate of biochar in the environment after being used and the probable environmental and health consequences.

d) There are some studies available in the literature on sustainability assessment of the novel technologies for environmental applications [62,86,87]. However, there is a lack of such studies in order to evaluate sustainability of the methods so far developed and applied for soil treatment. Such studies can considerably push the commercialization of these novel technologies by introducing more efficient, environmentally friendly, economic and socially acceptable methods among the thus far developed methods for biochar production and application.

5. Conclusions

Biochar, which is the 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 2982 documents in English were collected within the period of 2000 to 2020. 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

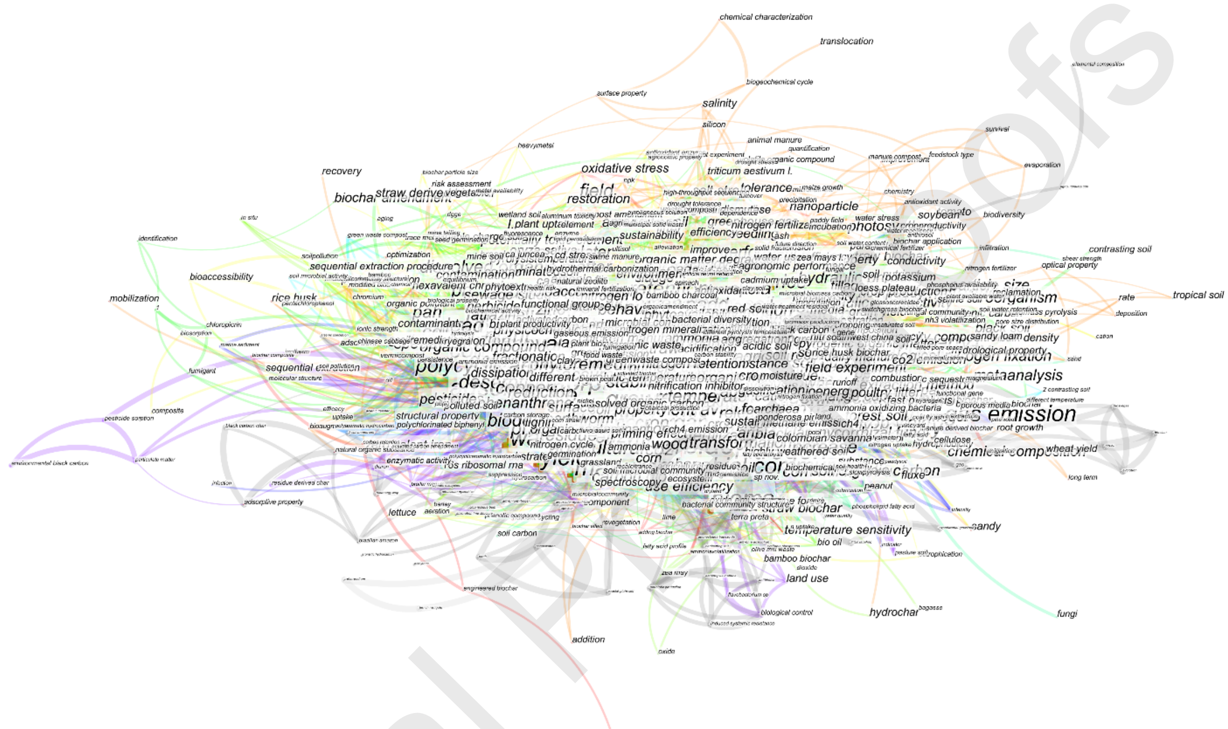

Fig. A.1.

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.

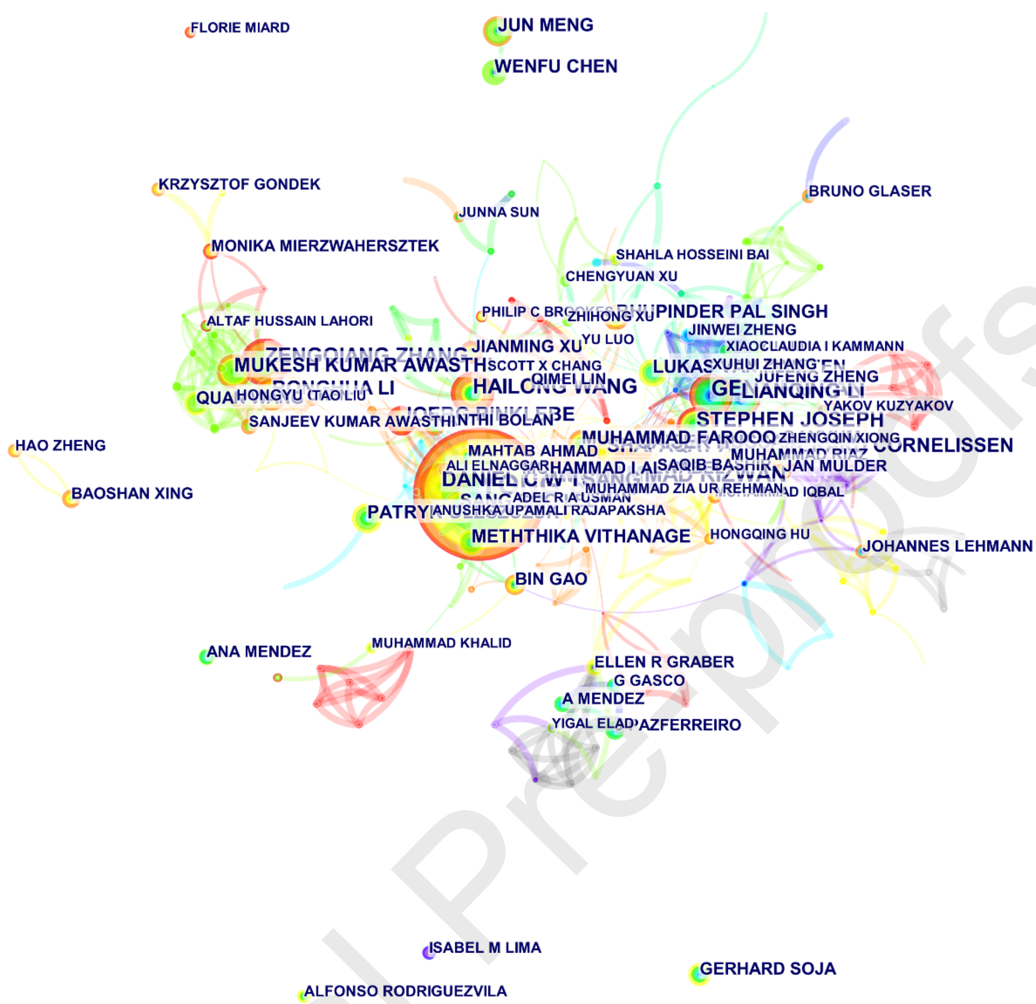

Fig. A.2.

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

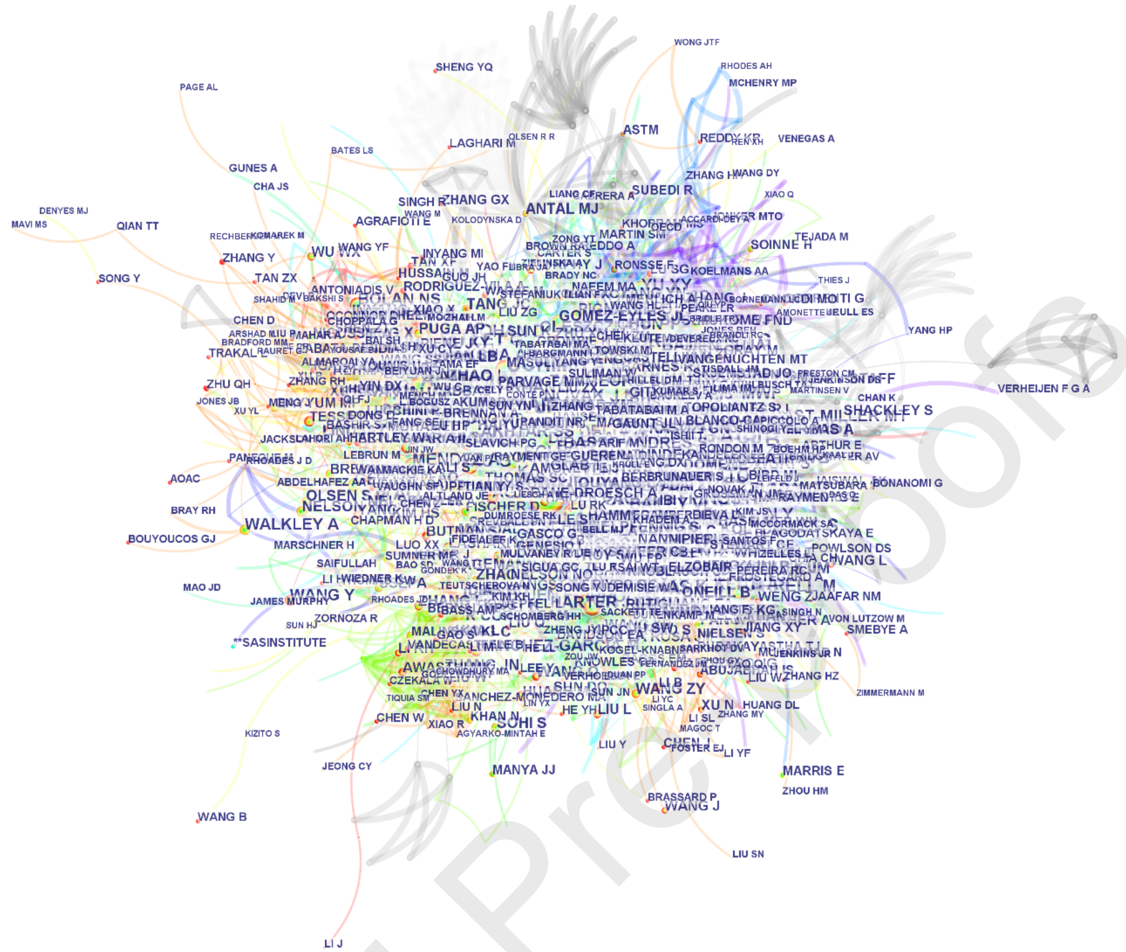

Fig. A.3.

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

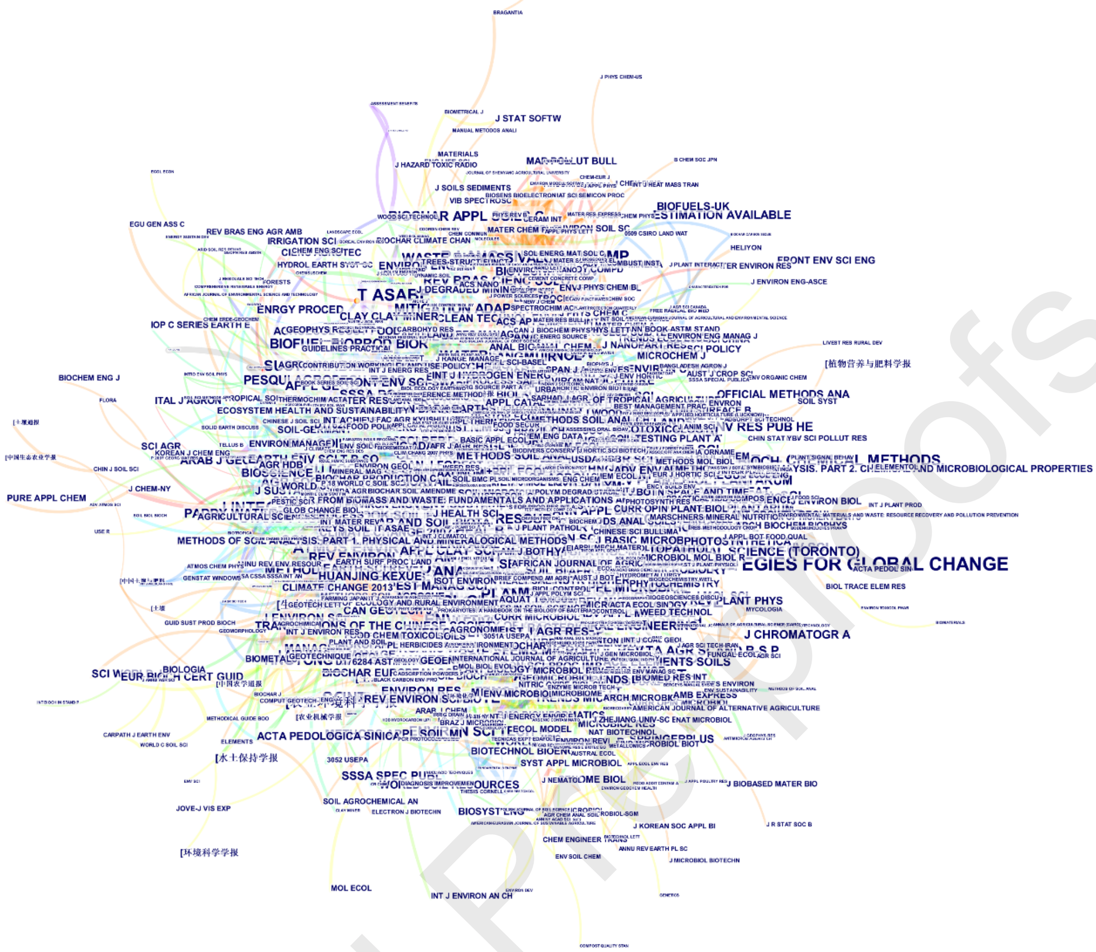

Fig. A.4.

The cited journals analysis obtained from CiteSpace with actual centrality.

Declaration of interest

The authors declare no conflict of interest.