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Biochar and Compost in the Soil: A Bibliometric Analysis of Scientific Research

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Biochar is a carbonized material obtained from the pyrolysis of biomass produced in a limiting environment of zero or very low oxygen. Its interest lies in its versatility for different applications in the water treatment, soil pollution, mitigation of greenhouse gases, etc. The synergy of this product with other amendments such as compost has been studied for different applications in the soil, including environmental remediation, crop yield, etc. The aim of the research is to identify the relevant aspects in the scientific literature of biochar, compost and soil through a bibliometric analysis for which 753 articles were selected from the Scopus database, having as keywords "biochar", "compost" and "soil". This research used R software, specifically the package Bibliometrix, to analyze descriptive analysis, author sources, document metrics, citation, co-citation analysis, co-occurrence network, co-word analysis, and collaboration analysis. Results showed that Zhang Z is the author with the greatest number of documents, and with a higher H index. Science of The Total Environment, Bioresource Technology, and Agronomy are the 3 topmost relevant sources. The keywords according to bond strength and most frequent use were biochar (538 occurrences), composting (349 occurrences), compost (436 occurrences), charcoal (295 occurrences), soil (255 occurrences). China is the country with the most collaboration. It is hoped that the bibliometric review will help to identify current research trends and provide information on the application of biochar and compost in the soil.

Keywords: biochar, compost, soil, bibliometric analysis, Bibliometrix.

Introduction

A large amount of solid waste is generated with the increase in the world population and due to the consumption behavior of inhabitants; so, the efficient management of solid waste is crucial for the successful disposal of waste (Hoornweg et al., 2013). Biochar fits perfectly as a method to contribute to adequate waste management, valuing it through pyrolysis and generating an amendment for the soil, so the numerous strategies to use the final product biochar facilitate zero waste and development of a circular economy (Hu et al., 2021).

Biochar is the product obtained from biomass pyrolysis under limiting conditions or in the absence of oxygen (Lehmann et al., 2011). The interest in biochar lies in the fact that it can be produced from different biomass, such as crops, agricultural remnants, industrial and municipal solid waste (Yaashikaa et al., 2020). Its application has shown efficiency in different areas such as water treatment; thus, many studies have been dedicated to research the application of biochar for the removal of contaminants from aqueous solutions (Tan et al., 2015) and the treatment of polluted soils with heavy metals. Kong et al. (2021) have mentioned that the most important factor that determines the effect of remediation in soils is the diversity of physical and chemical properties of biochar, such as the surface area, porosity and functional groups that vary with the type of biomass consumed in pyrolysis and the control of parameters.

Furthermore, its application includes the reduction of greenhouse gas emissions by capturing and carbon storage (CCS) and increased soil fertility in an environment friendly manner (Lee et al., 2019). IPCC (2019) provides updated guidance on specific issues to consider in national greenhouse gas inventories, and the guide now includes reports of non-CO2 emissions from biochar production and CO2 and CH4 emissions from flooded land.

From the past to the present, most people have used charcoal as the main source of energy for cooking because charcoal has several advantages, such as easy storage, high calorific value, and low cost. It is easy to store charcoal for longer periods and it is more durable than wood. The difference between biochar and charcoal lies in its application: while the first is for soil amendment, the second is to be used as fuel (Sangsuk et al., 2020).

There are other amendments that can be applied to the soil, such as charcoal, activated carbon, manure, ashes, lime, compost (Palansooriya et al., 2020). Due to its wide versatility and applications, biochar has been tested with different amendments such as compost, and the interest between both has been increasing over the years. Compost is a product obtained from municipal, agricultural or forestry organic waste (Hu et al., 2022), and it is produced under aerobic conditions (Lim et al., 2016). The application of biochar and compost in the soil can occur in two ways: the first is from a mixture of compost and biochar, that is, biochar-compost, where the biochar is produced from a residue and the compost from others, and when they are ready in terms of quality, they are mixed for soil application. The second interaction is when biochar is added to the composting process, which is known as co-composting.

The biochar-compost amendment interaction could increase the physical and chemical properties of the soil, by providing certain nutrients. It can also be used to recover degraded soils, which makes more agricultural land available, while increasing crop yields so that the need for expansion of agricultural land area decreases (Khan et al., 2016), as well as for co-composting; the integration of biochar in the compost at the production stage should result in a mature and suitable amendment for general soil improvement, with the added value of maximum potential as a biosorbent for metals in solution (Wang et al., 2019).

Bibliometrics can be defined as the exploitation of statistical techniques to understand and analyze global research in a particular field from publications retrieved from a database of academic literature (Wang et al., 2015). Bibliometrics helps to identify current research trends, provides information on specific and general aspects over time, and contributes to the development of important areas. Recently, bibliometric studies have been carried out on the topic of biochar research (Abdeljaoued et al., 2020; Qin et al., 2022), including trends in research on the effects of biochar in the soil (Yan et al., 2020). On the other hand, according to the literature, biochar and compost have positive effects in different research topics, for example, in mobility and toxicity of metals (Beesley et al., 2014), in the physical, chemical, and microbiological properties during the co-composting of spent mushroom compost and biochar (Zhang and Sun, 2014), soil quality, crop yield, and greenhouse gases in agricultural soils (Agegnehu et al., 2016). That is why the need arises in the literature for a bibliometric review focused on the analysis of both amendments and their application in the soil. In this sense, the aim of this research is to carry out a bibliometric analysis in order to explain recent trends, collaboration, and citations, among other relevant aspects.

Methods

Data source and search criteria

The bibliometric analysis that was carried out in research followed the procedure described by Zupic and Čater (2014) shown in *Fig. 1*, which includes five phases.

For the study design, the keywords used were "biochar", "compost" and "soil". The type of search applied was "advanced search" applying the following logic operation: TITLE-ABS-KEY(BIOCHAR) AND TITLE-ABS-KEY(COMPOST) AND TITLE-ABS-KEY(-SOIL) AND (EXCLUDE (PUBYEAR,2022)) AND (EXCLUDE (DOCTYPE,"re") OR EXCLUDE (DOCTYPE,"cp") OR EXCLUDE (DOCTYPE,"ch") OR EXCLUDE (DOCTYPE,"er") OR EXCLUDE (DOCTYPE,"no") OR EXCLUDE (DOCTYPE,"bk") OR EXCLUDE (DOCTYPE, "ed")), excluding the year 2022, and only research articles from the Scopus database were considered.

Data collection consisted in the use of the open source software R, using the Bibliometrix package developed by Aria and Cuccurullo (2017). The data from the documents obtained were exported and analyzed on bibliometric software.

Data analysis was conducted to obtain descriptive bibliometric analysis about all the articles. Data visualizations were conducted to analyze productivity of authors, how their evolution was over time, as well as the group of researchers who remain active and who represent a large part of the general effort of scientific production; therefore, it was important to classify the most productive researchers, and this was possible with Lotka's law (Kilicoglu and Mehmetcik, 2021). The productivity of the authors is controlled by this law (Lotka, 1926), since it explains the relationship between the number of authors and articles. It is also represented mathematically with the following equation:

$$yx^n = C$$

Where: x is the number of publications;

y is the expected percentage of authors (Kilicoglu and Mehmetcik, 2021);

n and C are constants (Kilicoglu and Mehmetcik, 2021; Urbizagástegui-Alvarado, 1999).

In addition, the analysis of the authors was carried out based on their H index, author-institution-country collaboration, corresponding author's country, most cited countries, and most relevant affiliations. Furthermore, Bradford's law was analyzed to obtain the main magazines in a period, which were classified according to their productivity. This law groups three zones, and each zone contains the same number of articles (Kilicoglu and Mehmetcik, 2021). Bradford's law is represented mathematically by the following equation:

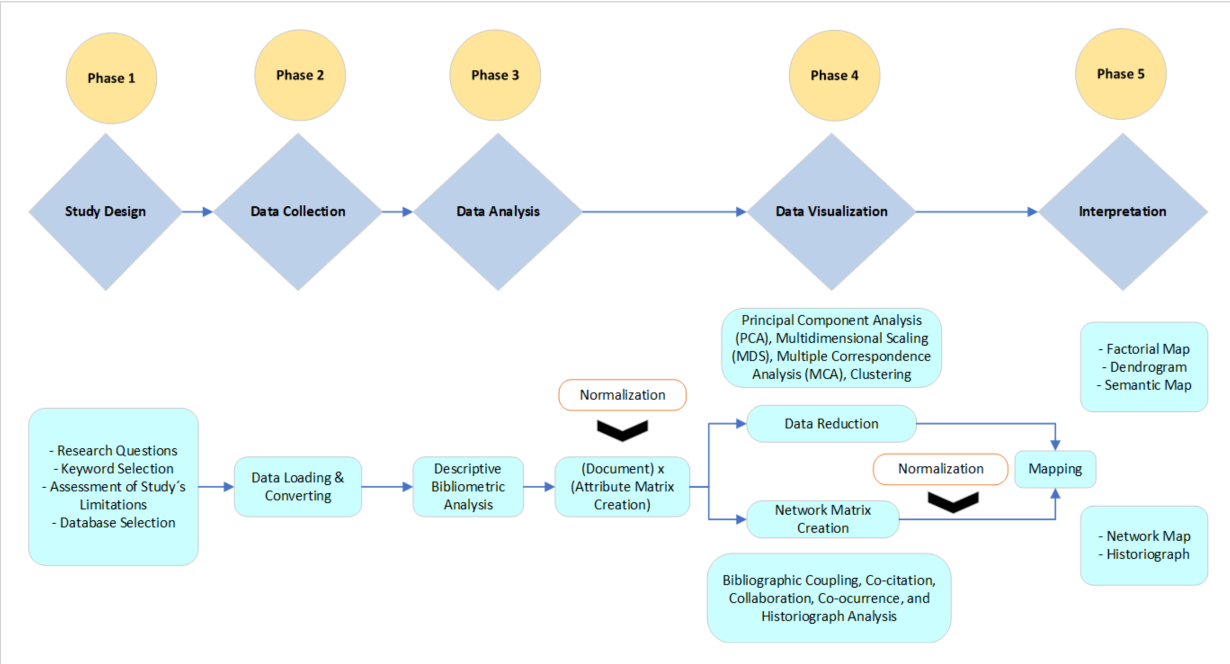
$$k = (e^y . Y_m)^{1/P}$$

Where: γ is 0.57,772 and Y_m is equal to the maximum productivity of the first magazine;

P is the number of groups (Andrés, 2009).

Source dynamics were conducted to evaluate the trend of the sources over the years. Regarding the analysis of documents, the top 10 were shown. In addition, the trend of the articles regarding biochar, compost and soil in its beginnings and the direction of research in recent years are discussed. Citation and co-citation analysis was conducted to obtain a

Fig. 1. *Phases of the research bibliometric analysis method*



bibliometric historiography. This mapping allows creating a historical network of direct citations from the most cited work and then visualizes a network in the chronological order (Garfield, 2016). Furthermore, co-occurrence network and co-word analysis were conducted to create a density map showing the co-occurrence of keywords. In the item density visualization, items are represented by their label in a similar way as in the network visualization (Su et al., 2022). Collaboration analysis was carried out to visualize which institutions have the greatest impact in collaboration. Finally, interpretation was conducted to analyze information with other studies.

Results and Discussion

Descriptive analysis

Table 1 shows the main information of the bibliometric analysis that was carried out in the research. A total of 753 articles were published within the period 2008–2021, which were extracted from the Scopus database. It is highlighted that a total of 2643 authors published in that period, using a total of 1938 keywords, generating an average of 27.95 citations in each document. *Fig. 2* shows the number of articles in the period from 2008 to 2021. It is interesting to note that there is a growing trend of publications regarding biochar, compost and soil, highlighting a growing increase in articles published in 2020 and 2021. On the other hand, in 2008 there was only one article, and the topic was started with the following keywords “biochar Brazil” and “carbon” (Steiner et al., 2008).

Authors

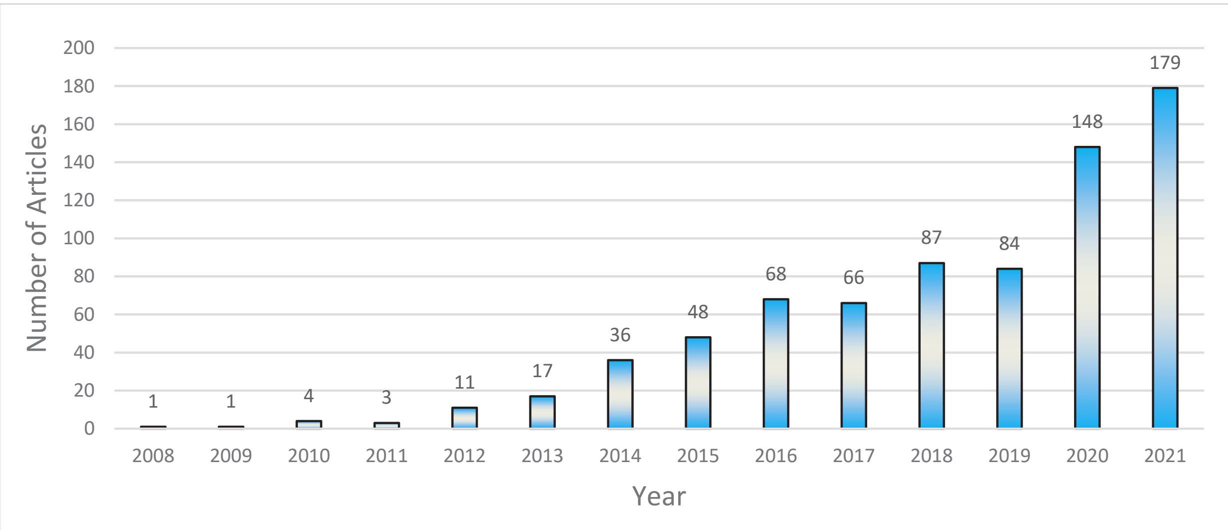
The top 20 authors about biochar, compost and its soil application research with the most published papers are shown in *Fig. 3.* In the first place, there is Zhang Z, with a total of 19 scientific articles. In the second place, there is Chen H, with a percentage distribution of 2.1%, with 16 documents. It is necessary to highlight that this graph shows all types of authorship (corresponding author, co-authors, etc.). With a smaller amount and in the same distribution are Ali S, Lebrun M, and Nandillon R with a total of 10 documents, and a percentage contribution of 1.3%.

Table 1. *Main information*

Main Information	Explanation	Number
Documents	Total number of documents	753
Sources	The frequency distribution of sources as journals	243
Author's keywords	Total number of keywords	1938
Period	Years of publication	2008–2021
Authors	Total number of authors	2643
Author appearances	The authors' frequency distribution	4217
Authors of single-authored documents	The number of single authors per articles	6
Authors of multi-authored documents	The number of authors of multi-authored articles	2637
Authors per document	Average number of authors in each document	3.51
Co-authors per documents	Average number of authors in each document	5.6
Average citations per documents	Average number of citations in each document	27.95

Adapted from Secinaro et al. (2020)

Fig. 2. *Annual scientific production*



The top authors over time are shown in *Fig. 4.* This analysis is important because it allows showing the evolution of each author over the years. *Fig. 4* shows that while the circle is bluer, it means that there is a greater total citation (TC) per year, while for a larger circle, it means that there is a greater number of articles (N. Articles). From 2008 to 2021, the most productive author was Zhang Z, with a total of 19 articles, while only for the year 2017, the most productive author was Chen H, with a total of 8 articles. Glaser B has been one of the pioneering researchers on topics related to biochar, compost and its application in the soil with an article published in 2008 (Steiner et al., 2008), keeping his participation in publications updated. While in 2016, the two articles of Ok YS collected a greater number of citations per year (67.29)

Fig. 3. *Authors with the highest scientific production*

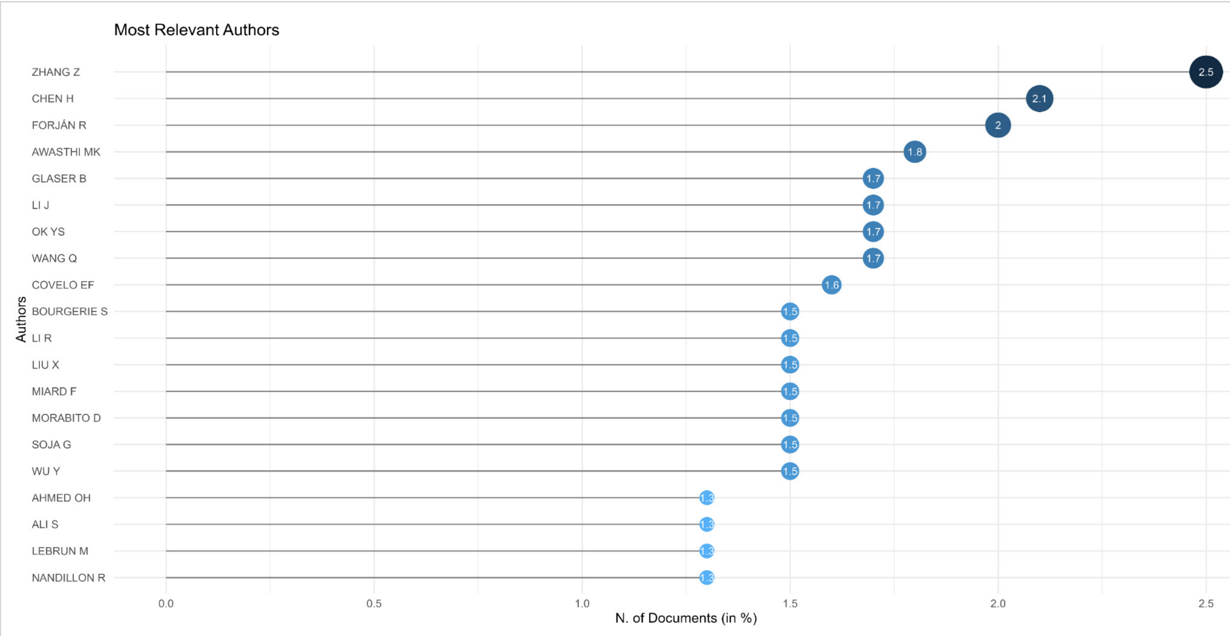
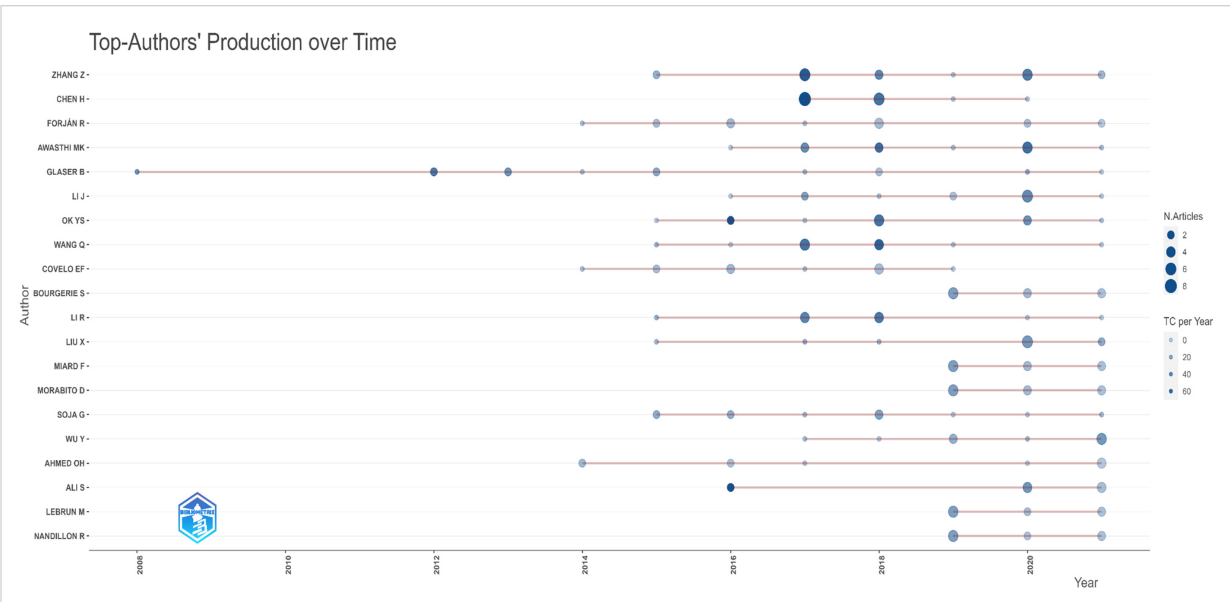


Fig. 4. *Top author's production over time*



compared with the other authors. When considering production over time, most authors started publishing on biochar, compost, and soil research within the year range 2014–2018 except for Glaser B, who already started publishing from 2008, with a relatively continuous production. It is interesting to note that the most productive authors Zhang Z and Chen H collaborated with three articles in 2017, focusing on the co-composting process, where they assessed the effect of biochar on bacterial and fungal diversities using sludge and organic waste (Awasthi et al., 2017). They also assessed the application of biochar and zeolite and their mixture on nitrogen conservation and organic matter transformation during pig manure composting (Kumar Awasthi et al., 2017), and the application of biochar in the composting of dewatered fresh sewage sludge (DFSS)-wheat straw (Wang et al., 2017).

From 2015 onwards, most authors show an active production trend until 2021, except for Covelo EF, who has not published articles in 2020 and 2021, and for Bourgerie S, who began publishing in 2019 with many articles.

The application of Lotka's law to the data, as illustrated in *Fig. 5* indicates the number of articles to which each author contributed. For the research, 73% of authors contributed with at least 1 study, while 15% with at least two articles and less than 1% of authors with at least 6 articles.

A common way to evaluate the impact of the authors is through their indices, such as the H index, which measures the productivity and the impact of the citations of the publications and is based on the set of the most cited articles (quantity) and the number of citations (quality) that it has received in other research; this is why this index is really important for bibliometric analyses. In *Fig. 6*, different groups are observed. In the first group (H index >10), the leader of the list is Zhang Z, with an H index of 15, with a total of 865 citations, while in the second group (7 < H index < 10), Wang Q, Covelo EF, Forján R, Liu X, Ren X, and Soja G have an H index of 9, and Awasthi SK, Rodriguez-Vila A, Sánchez-Monedero MA, Wang M, and Zhang J have an H index of 8. In the third group (H index < 7), Ali S, Li J, Li R and Liu T, have 600, 300, 581, and 152 citations, respectively.

Research is usually published in collaboration with other countries or institutions, so bibliometrics analyzes these collaboration networks. This way of collaboration can be studied at different levels: micro (individual), meso (institutions), and macro (countries) (Kilicoglu and Mehmetcik, 2021)

Fig. 7 illustrates the levels according to the research field of biochar, compost and its application in the soil. This analysis is only carried out for the affiliations and nationalities of the first authors. Zhang is affiliated with only one institution, Northwest AandF University, and he has had a large percentage of collaboration with 5 other countries; however, there are authors who also usually publish with different institutions, such as the case of OK YS, who publishes for Bahauddin Zakariya University, University of Agriculture, and Government College University.

The distribution of countries according to the number of publications carried out individually or in

Fig. 5. *Authors' productivity through Lotka's law*

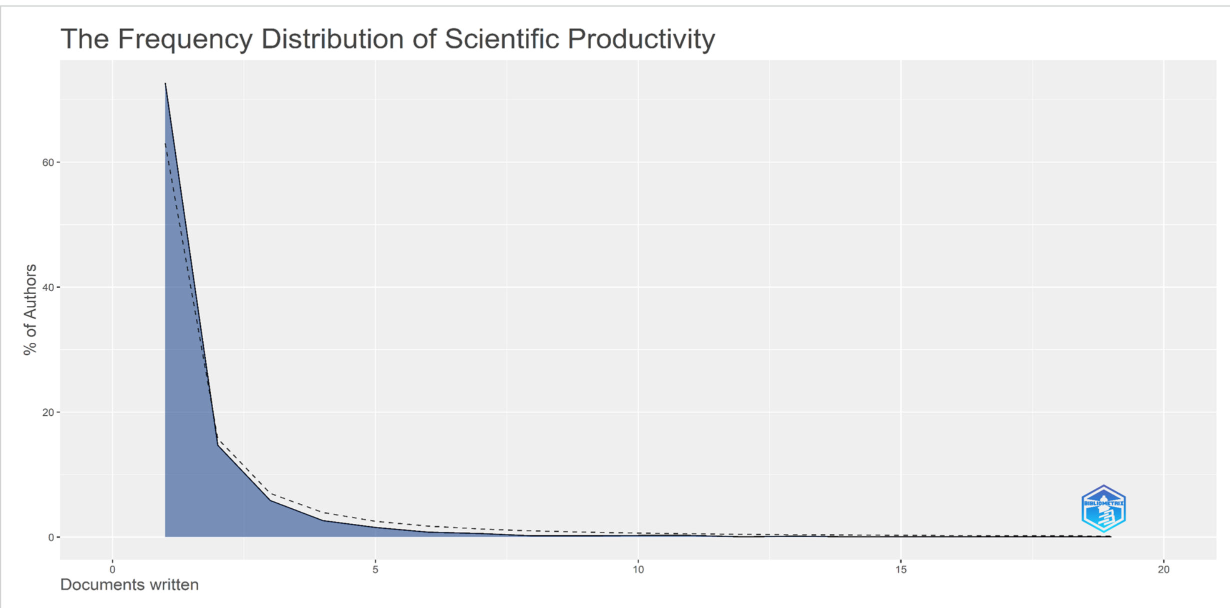


Fig. 6. *Author impact (H Index)*

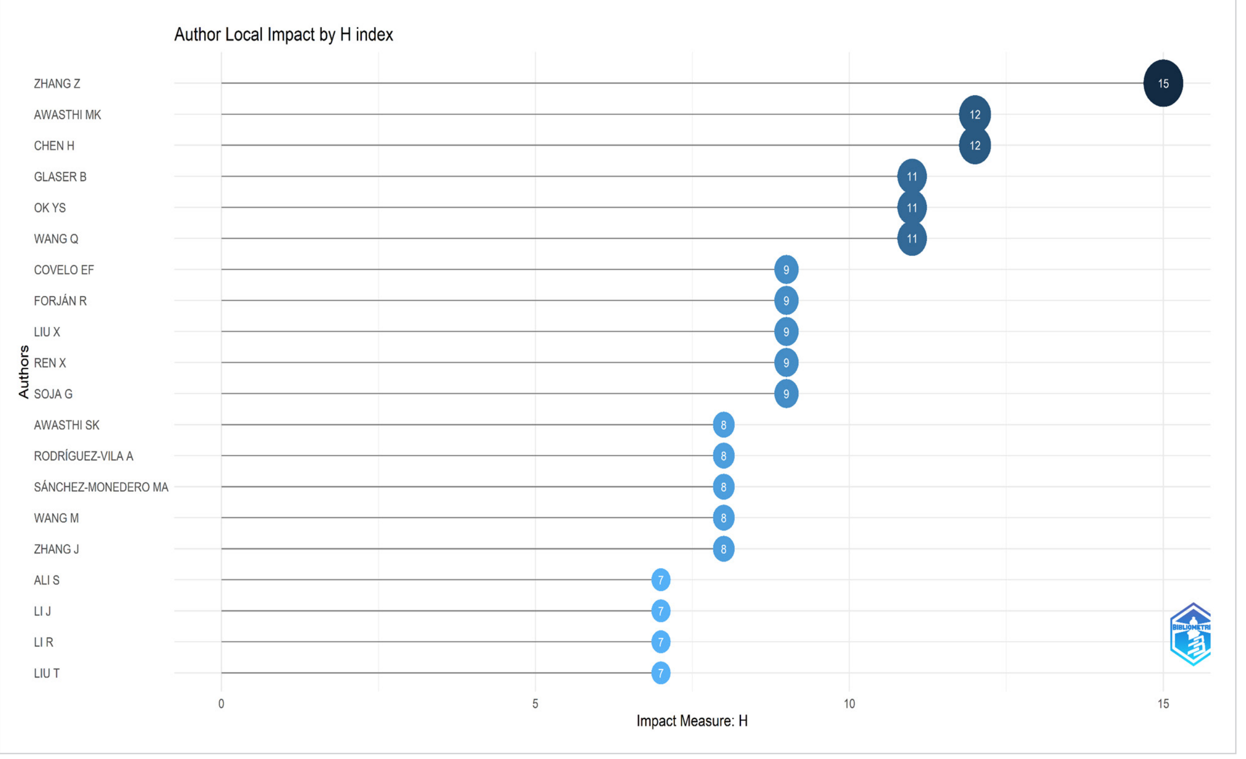
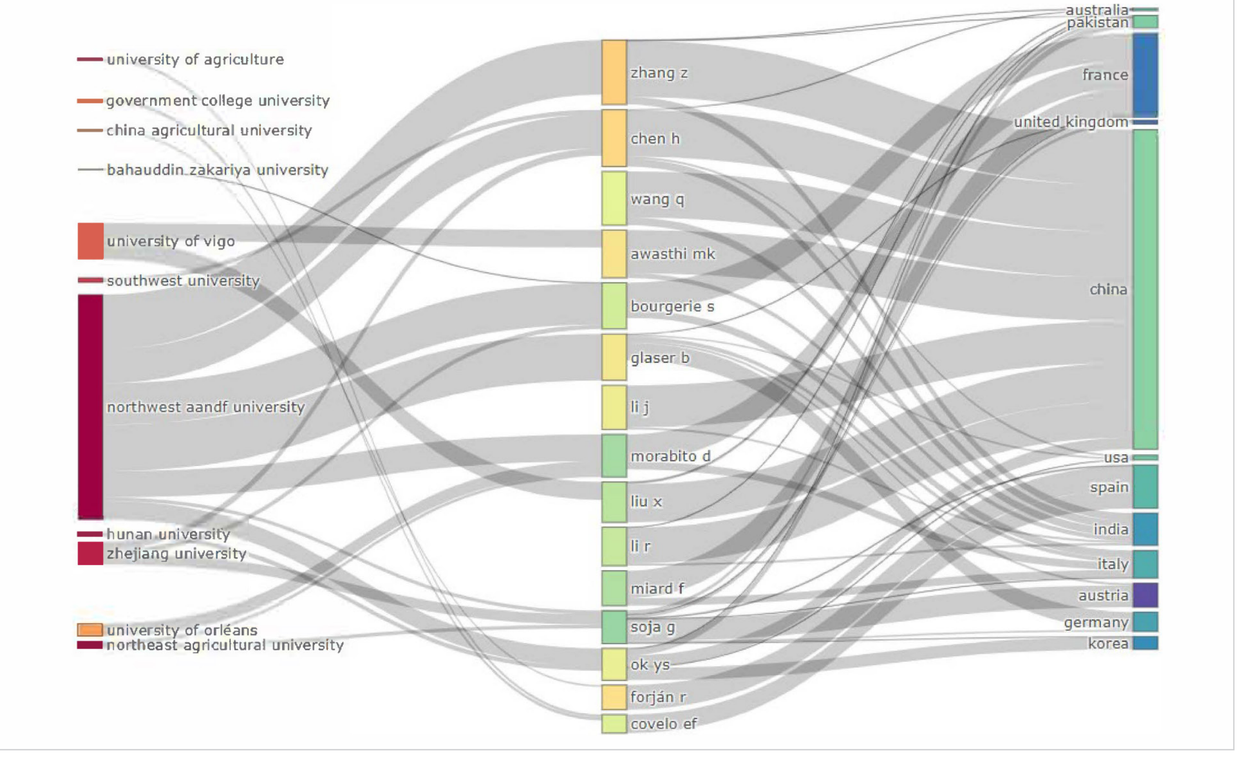


Fig. 7. *Author-institution-country collaboration*



collaboration with other countries is shown in *Fig. 8.* China leads the largest number of documents with a total of 175, which includes 124 individual country publications and 51 publications of collaborations between countries; the USA is in the second place with a total of 44 articles that include 35 individual country publications and 9 publications of collaborations between countries.

Fig. 9 illustrates the number of citations that each country received in total according to the topic of biochar, compost and soil research. The countries that exceed 2000 citations are China, the United Kingdom and Australia. China is in the first place, with a total of 5779 citations. According to *Fig. 10* (most relevant affiliations), the institution that leads the list is the Northwest AandF University with a total of 197

Fig. 8. *Corresponding author's country*

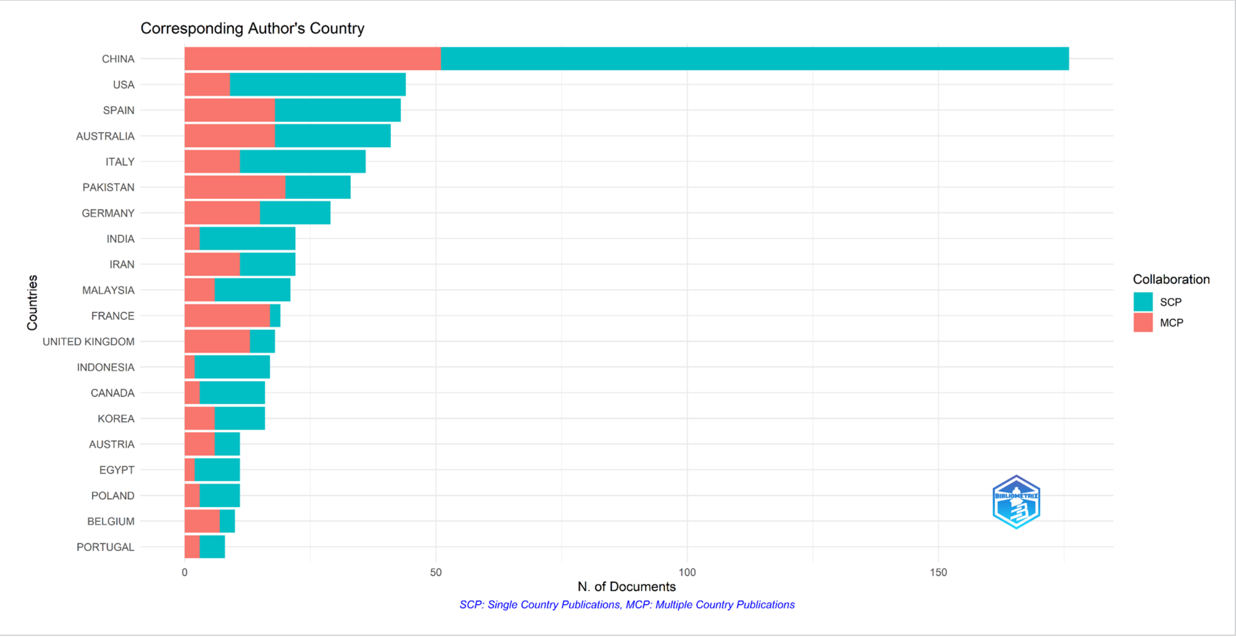


Fig. 9. *Most cited countries*

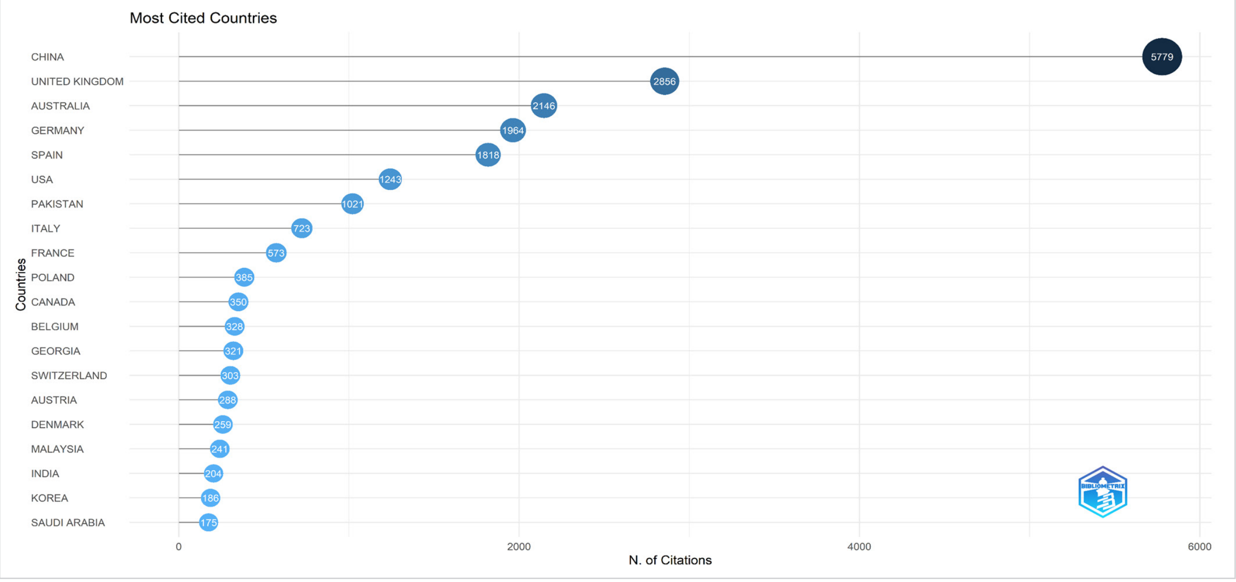
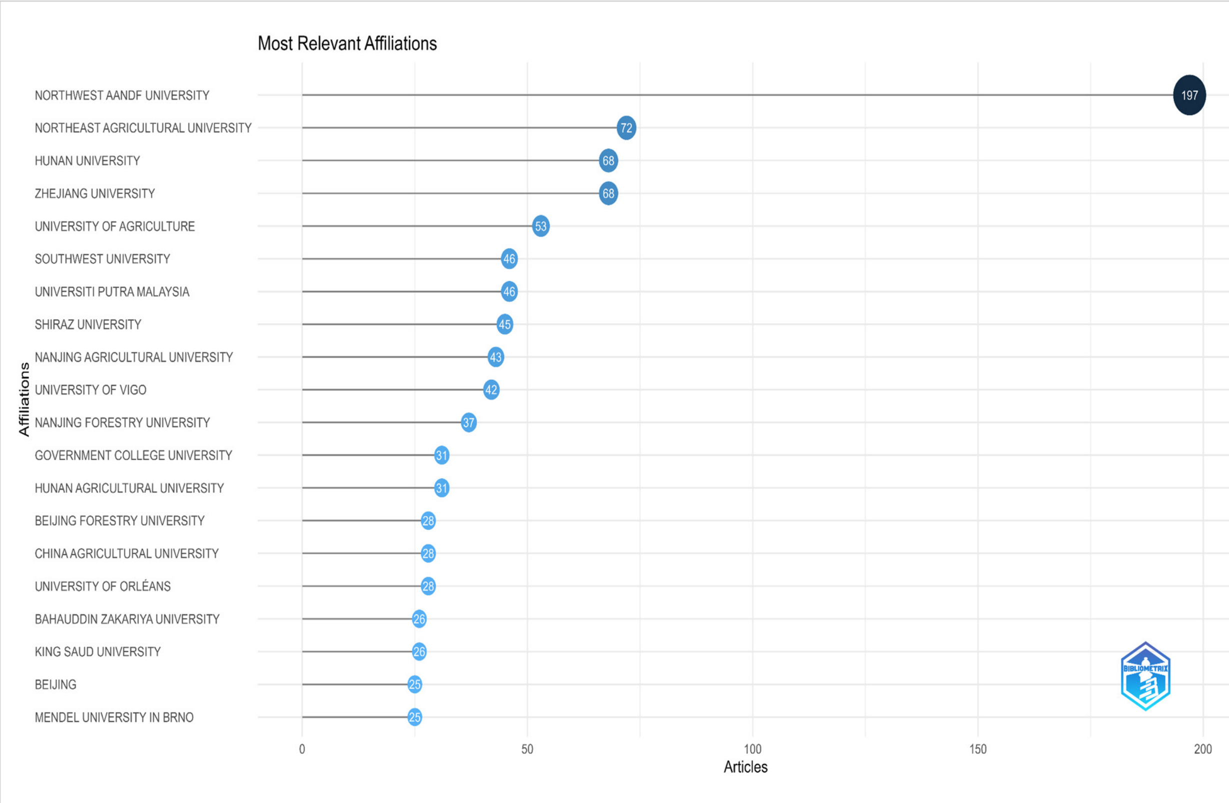


Fig. 10. *Most relevant affiliations*



documents, while 4 institutions are in the range of 50–100 documents and they are Northeast Agricultural University, Hunan University, Zhejiang University, and University of Agriculture.

Sources

Fig. 11 shows the most relevant sources. The top 3 are Science of The Total Environment, Bioresource Technology and Agronomy with 52, 38 and 34 documents, respectively; however, when considering the number of citations, the top 3 are made up of Bioresource Technology, Science of The Total Environment, and Environmental Pollution with 2461, 2374, and 1363 citations, respectively. On the other hand, *Fig. 12* shows the source local impact by H index. Science of The Total Environment is in the first place with an H index of 28, while the second place is still occupied by Bioresource Technology with an H index of 24, and the third place is occupied by Chemosphere, with an H index 21.

There are sources that already have topics positioned so that the authors can decide to publish their research to have visibility. Bradford's law is one of the methods to determine the leading sources in each topic during a period of time. *Fig. 13* lists the leading sources in biochar research, compost and soil, since Bradford's law classifies sources according to their productivity. The first central zone will contain a limited number of entries, while each subsequent zone will contain an increasing number of sources. It is illustrated that Science of The Total Environment, Bioresource Technology, and Agronomy are the sources with the highest productivity within the field of study of this research.

Fig. 14 illustrates the cumulative source dynamics. This graph allows us to observe the cumulative number of documents in the sources over the years. It is interesting to note that until 2012 approximately all the sources had a similar number of documents; from 2014, a change began to be noticed, where Bioresource Technologies was leading in terms of the

Fig. 11. *Most relevant sources*

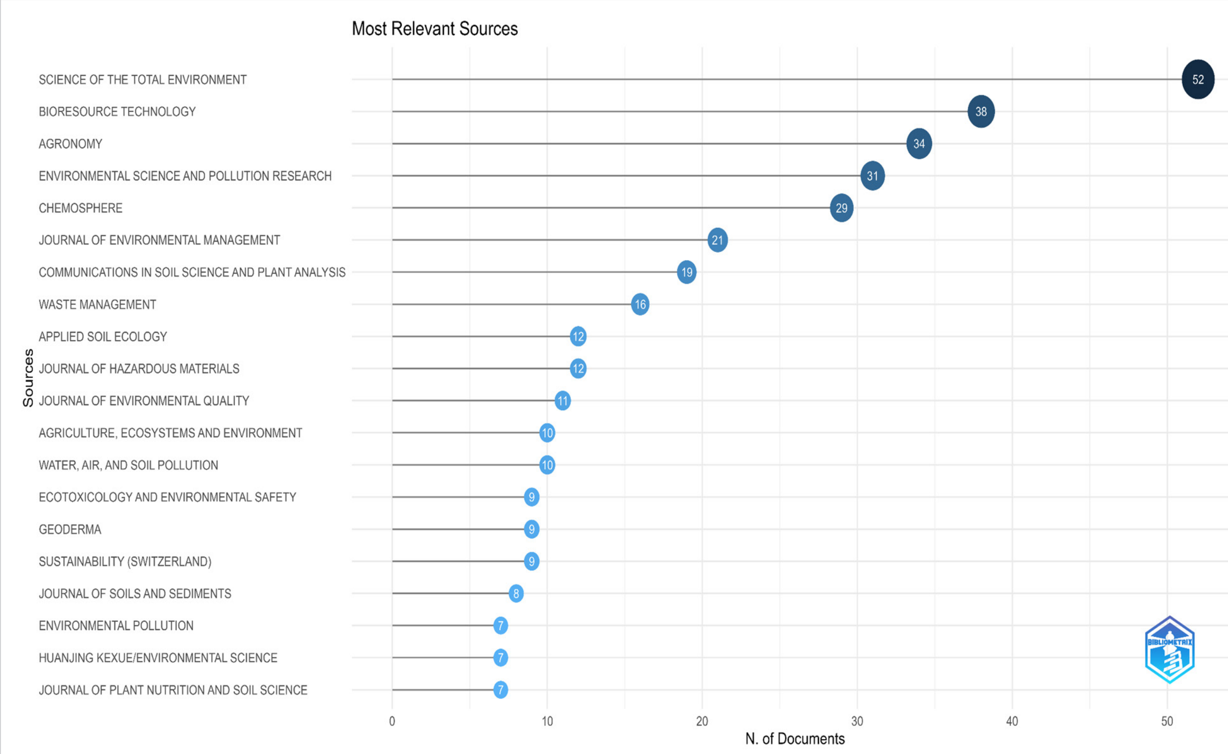


Fig. 12. *Source local impact by H index*

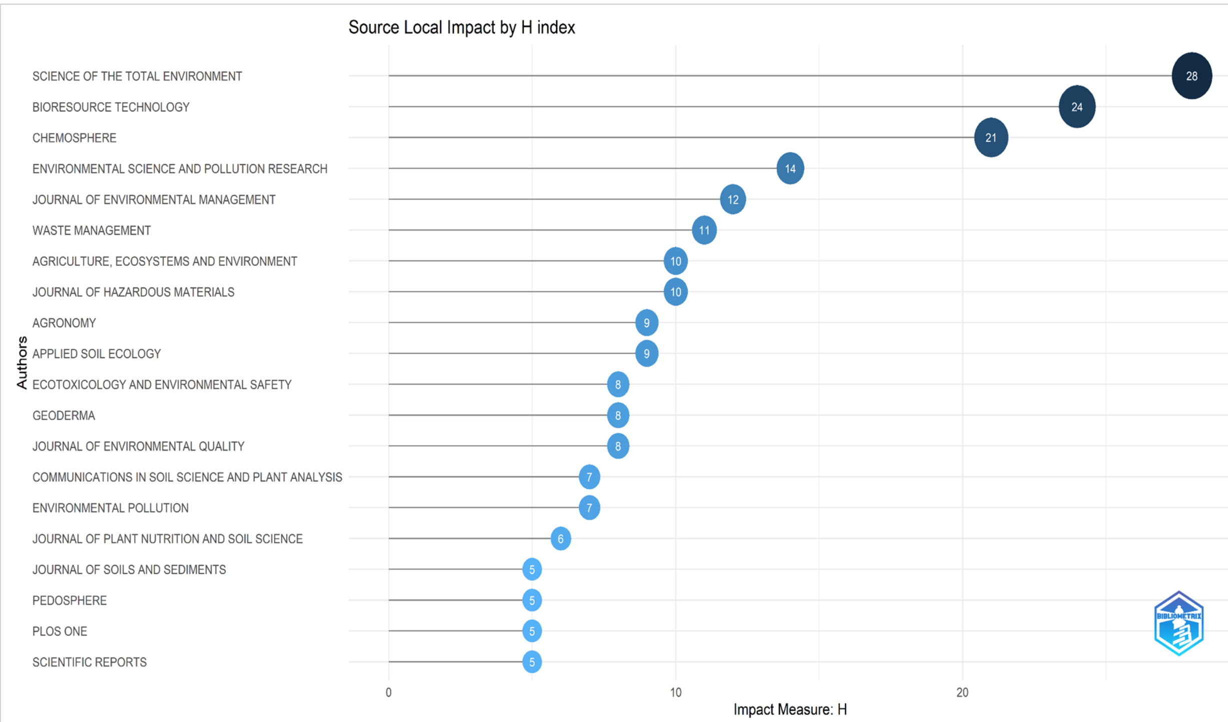


Fig. 13. *Bradford's law and the basic sources*

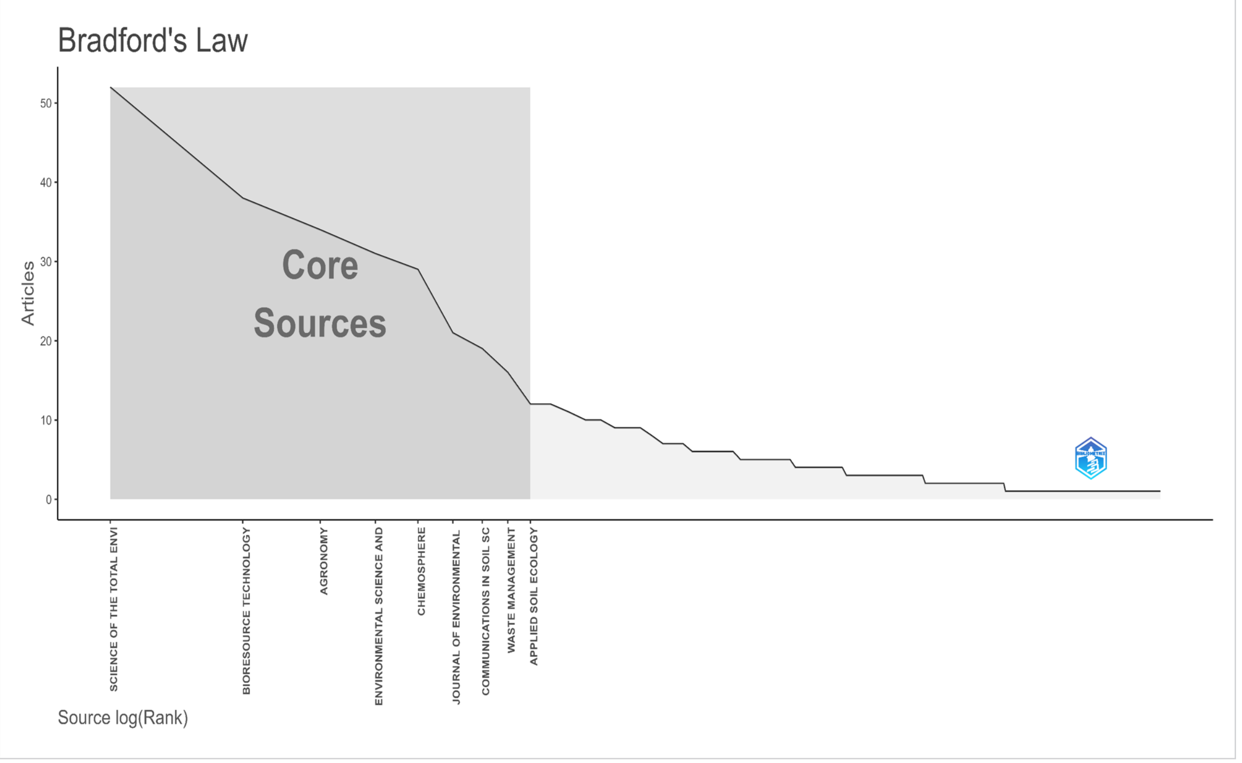
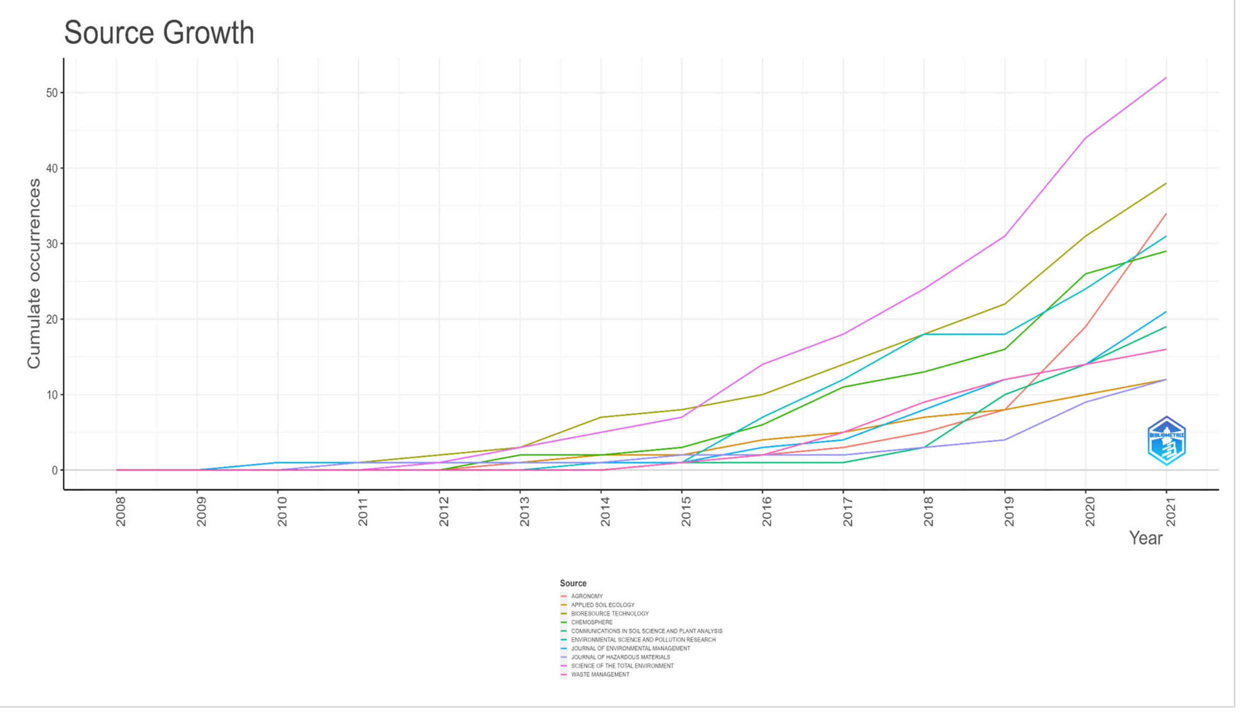


Fig. 14. *Source dynamics*



number of documents; however, in 2016, Science of The Total Environment began to have a greater number of documents and its position still prevails in the year 2021 compared with the other sources.

Documents

A citation represents the recognition of the author's contributions in the field of science, so determining which publications have been the most cited is important not only for the author because they will gain reputation, but also for evaluation of the impact of a journal. *Table 2* illustrates the top 10 authors with the most cited publications. In 2010, there is the research of Beesley et al. (2010) with the highest number of citations, with a total of 793 citations. In fact, it corresponds to one of the first researches about "biochar", the aim of which was to assess the effects on mobility, bioavailability and toxicity of inorganic (Cu, As) and organic contaminants using biochar, compost and their mixtures; therefore, the main conclusion was that biochar has a greater potential to beneficially reduce the bioavailability of organic and inorganic contaminants than green waste compost in this multi-element contaminated soil, being especially effective in reducing phytotoxic concentrations of Cd and water soluble Zn as well as heavier organic contaminants. The research of Steiner et al. (2008) with a total of 435 citations is in the second place. In this research, the topic of the study was to establish a field test in the central Amazon, in order to study the influence of charcoal (vegetable carbon) and the compost produced from forest biomass, fruit residues, manure and kitchen residues in the retention of nitrogen in the soil, for which it was concluded that the greater retention of this element significantly improved the nitrogen cycle in the plots that received charcoal. Karami et al. (2011) are in the third place, with a total of 388 citations. This research with the following keywords "biochar", "compost", "heavy metal", "porewater remedy", and "ryegrass" assessed the effect of compost from green waste by itself and in combination with biochar, using ryegrass, concluding that therefore the two amendments have opposing metal specific suitability for treating this contaminated soil regarding whether it is a maximum reduction in plant tissue metal concentration or a maximum reduction in the harvestable amount of metal that is required.

Table 2. *Top 10 authors with the most cited publications*

Ranking	Keywords	Journal	Citations	Reference
1	Biochar; Compost; PAHs; Pore water; Trace metals	Environmental Pollution	793	(Beesley et al., 2010)
2	Biochar Brazil; Carbon; Nitrogen cycling; Slash-and-burn; Soil organic matter; Terra Preta	Journal of Plant Nutrition and Soil Science	435	(Steiner et al., 2008)
3	Biochar; Compost; Heavy metals; Pore water; Remediation; Ryegrass	Journal of Hazardous Materials	388	(Karami et al., 2011)
4	Agricultural practices; Amendments; Antioxidant enzymes; Essential nutrients; Food security; Growth and yield; Reactive oxygen species	Environmental Science and Pollution Research	334	(Rizwan et al., 2016)
5	Biochar; Co-composted biochar-compost; Compost; Ferralsol; Greenhouse gas fluxes; Soil quality	Science of The Total Environment	331	(Agegnehu et al., 2016)
6	Coffee husk; Humic substances; Nitrogen losses; Sawdust	Bioresource Technology	316	(Dias et al., 2010)
7	Carbon sequestration; Crop response; Soil amelioration; Soil fertility; Terra preta	Journal of Plant Nutrition and Soil Science	302	(Schulz and Glaser, 2012)
8	Not found	Journal of Environmental Quality	297	(Steiner et al., 2010)
9	Organic amendments, Porewater Soil contamination; Speciation; Trace elements	Environmental Pollution	281	(Beesley et al., 2014)
10	Biochar; Compost; Green waste; Spent mushroom compost; Two-stage co-composting	Bioresource Technology	255	(Zhang and Sun, 2014)

On the other hand, regarding the keywords of these studies, the term biochar and compost are the ones that predominate. However, in 2014 (position 10 of *Table 2*), the keyword "co-composting" was included. This co-process was also studied by Agegnehu et al. (2016) in the journal Science of The Total Environment.

When research began on biochar, compost, and soil, the topics used to be about general applications of biochar, compost and its mixture in plant performance, such as in *Avena sativa L.* (Schulz and Glaser, 2012), assessment of the yield of *Lactuca sativa* and *Brassica chinensis* (Carter et al., 2013) pine, soil fertility and greenhouse gas emissions (Agegnehu et al., 2015). In addition, research carried out the assessment of biochar in the composting process. For example, Jindo et al. (2012) assessed the quality of a composting mixture prepared with poultry manure and different local organic waste by adding biochar. Another common topic was the status of heavy metals in the composting process, for example, by adding biochar and humic acid (Hou et al., 2014). Likewise, studies focused on the removal of heavy metals in the soil, such as Cu, Ni, Pb, Zn, assisted with *Brassica Juncea L.* (Rodríguez-Vila et al., 2015), in the reduction of the bioavailability of Cd, Cu, Zn, Pb in wetland soils (Zeng et al., 2015), and in assisted phytoremediation with biochar and compost, with *Helianthus annuus* (Chirakkara and Reddy, 2015). Recent articles focus on more specific aspects regarding the performance of species. Biochar, compost and mycorrhizae are mixed to avoid Bary disease in soybeans (Safaei Asadabadi et al., 2021). In addition, evaluation of the performance of low concentrations of lead in contaminated soils using biochar, compost and rhizobacteria is conducted (Zafar-ul-Hye et al., 2021). While in the composting process, the application of biochar in the maturation process during aerobic composting assisted by electric field is evaluated (Fu et al., 2021). Furthermore, the research of Duan et al. (2021) is focused on the pollution control aspect of gaseous mitigation and heavy metal passivation as well as their associated bacterial communities driven by apple tree branch biochar (BB) during sheep manure composting. Regarding the removal of heavy metals, Irfan et al. (2021) have evaluated the phytoremediation of *Zea mays L.* focusing on the influence on the microbial population, Li et al. (2021) mixed biochar, compost and humic acid on the bioavailability, transformation, and accumulation of heavy metals by pakchoi cabbage in soil contaminated with multiple elements.

Citation and co-citation analysis

Fig. 15 shows historiography of historical networks of direct citations and a representation of the relationship between authors by visualizing how the citations are distributed over time. The network starts with the article of Wu H, 2016.

Co-occurrence network

The analysis of the co-occurrence of keywords is shown in *Fig. 16.* This analysis is a tool to identify critical points and research frontiers (Ye et al., 2020). The more co-occurrence between two keywords, the closer their relationship (Chen et al., 2016). The words with the highest co-occurrence are biochar, composting, compost. The colors indicate different clusters (green, blue and red), and the generation of each cluster is based on the relationship of the elements, which gives a set of closely related elements. In the period from 2008 to 2021, 753 documents and 4320 keywords related to biochar, compost and soil were found. The keywords according to bond strength and most frequent use were biochar (538 occurrences), composting (349 occurrences), compost (436 occurrences), charcoal (295 occurrences), and soil (255 occurrences).

Co-word analysis

A Multiple Correspondence Analysis (MCA) was performed to understand the conceptual structure of this research. *Fig. 17* illustrates 3 clusters. The words for the green cluster included soil pollutant, soil pollutants, bioremediation, soil remediation, soil pollution, heavy metal, copper. This group was related to the bioremediation of contaminated soils. The words for the red cluster are the following: chemistry, nonhuman, unclassified drug, priority journal, microbial community, biochars, phosphorous, composting, biochar, compost, soils, soil amendment, biomass, organic carbon, charcoal, soil, article, controlled study. This group was oriented to see more the interactions of the amendments in the soil. And finally, the blue cluster, which has the following words: nutrients, carbon, nitrogen fertilizers, manure, manures, animal.

Fig. 15. *Bibliometric historiography showing the citation network*

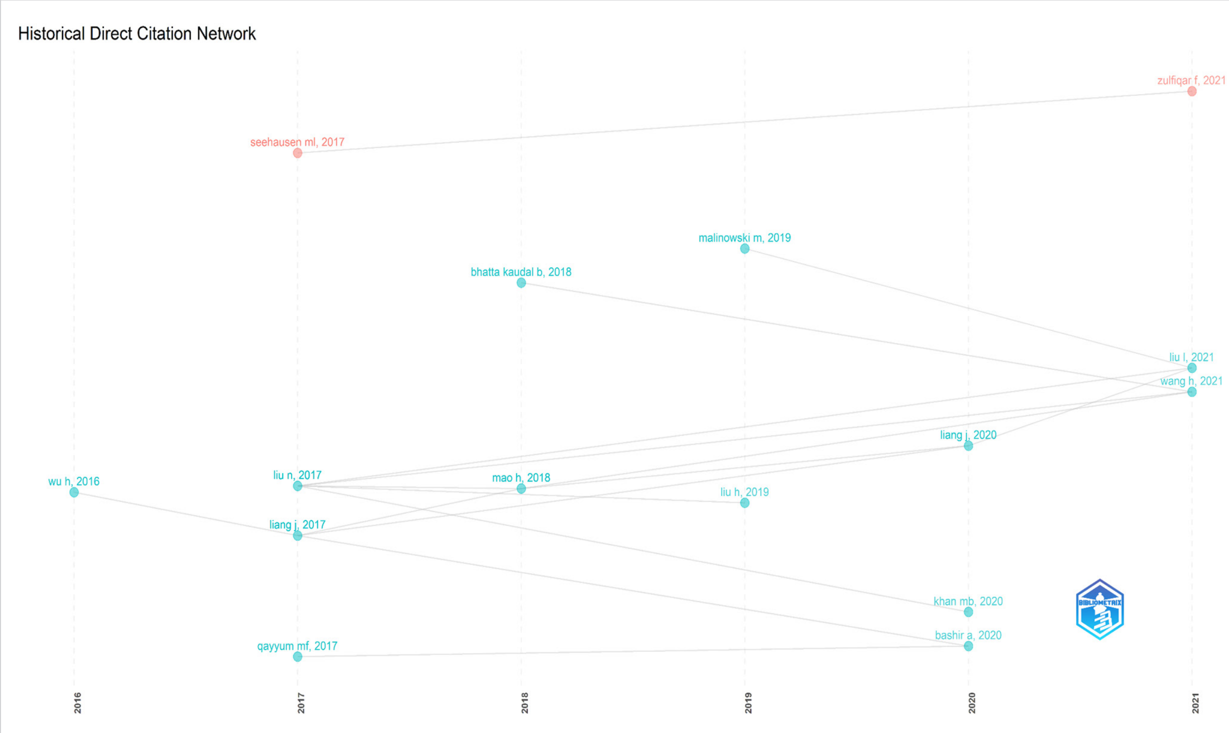


Fig. 16. *Co-occurrence keywords*

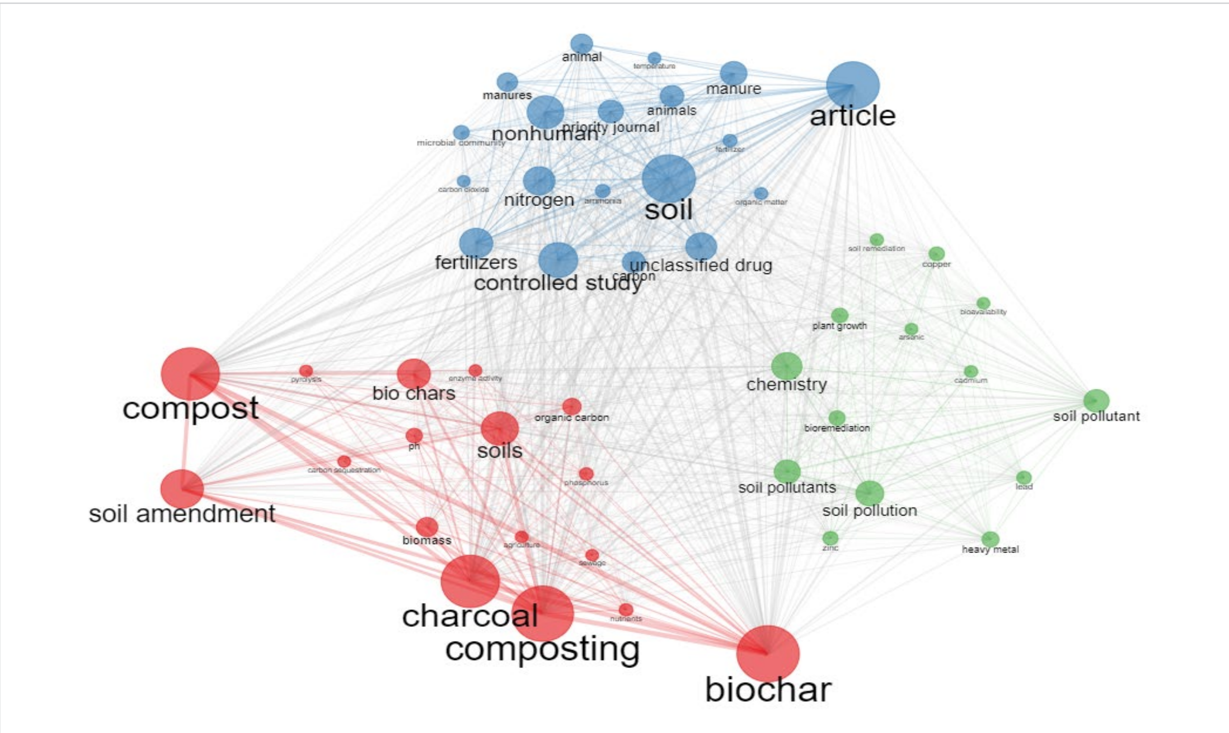
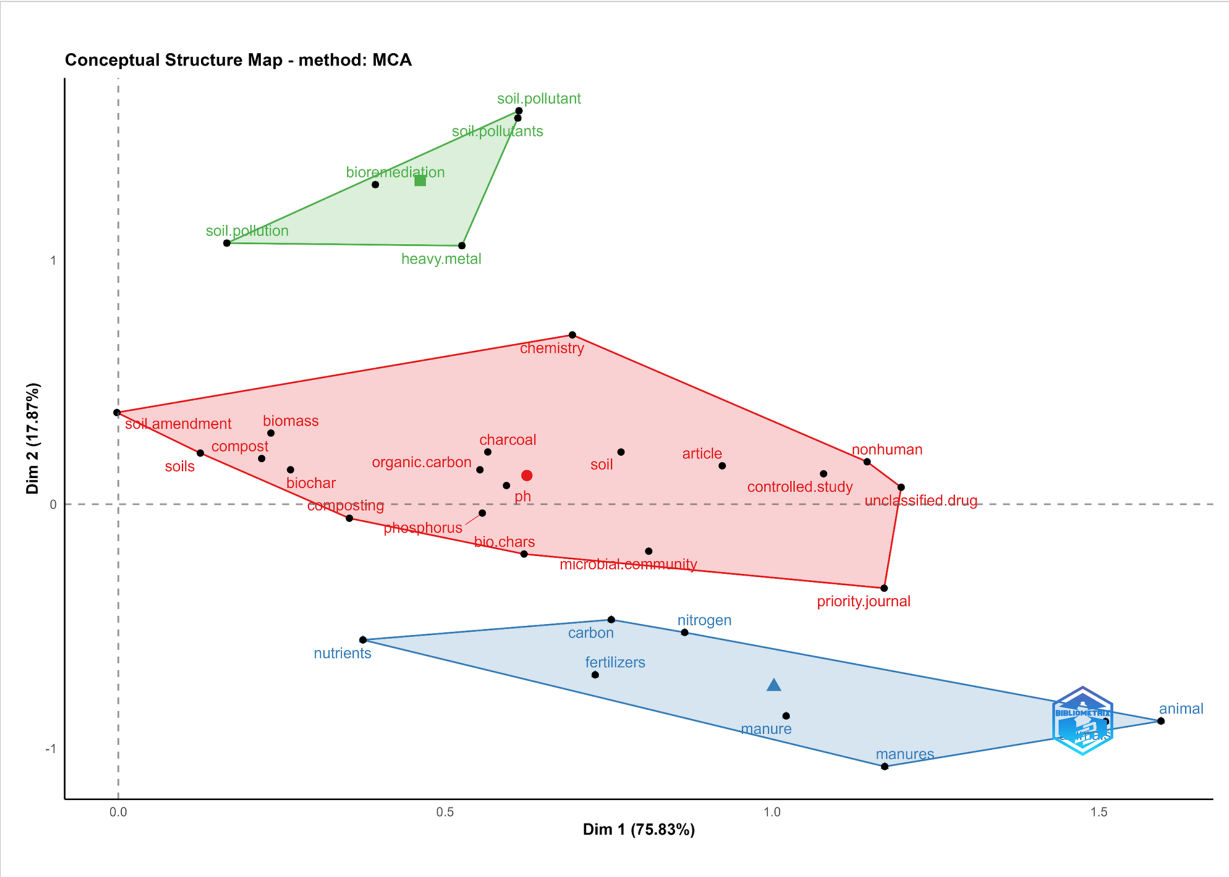


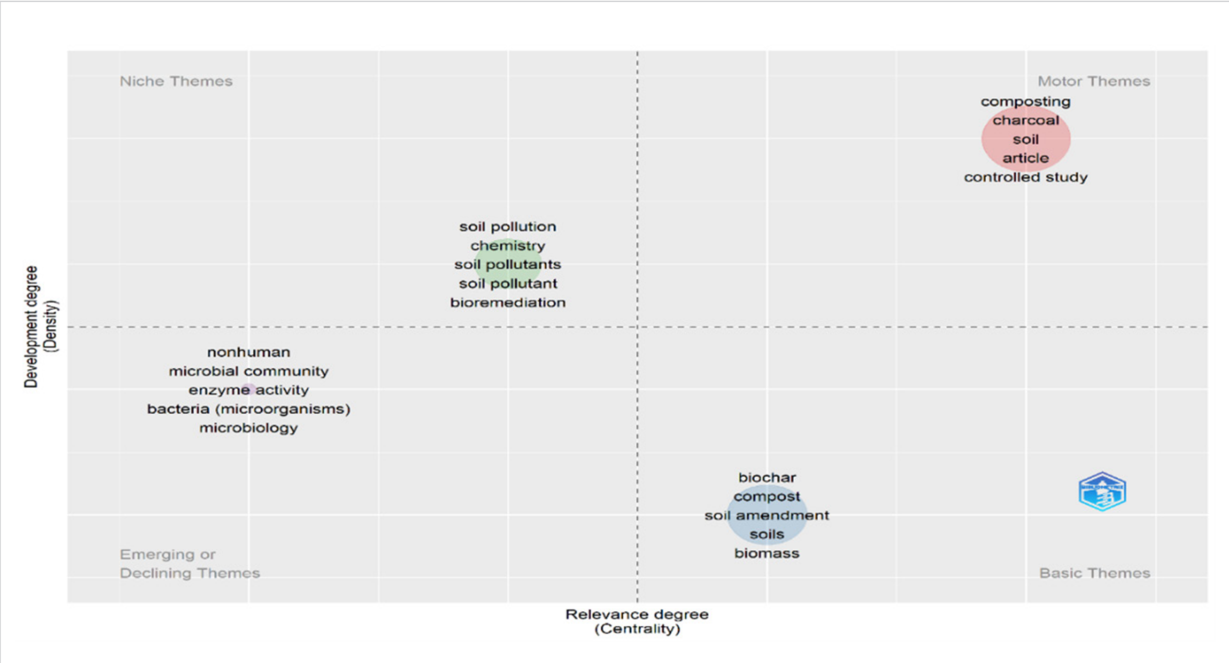
Fig. 17. *Conceptual structure map*



This cluster was oriented where the biochar or compost were obtained and to show some basic properties of the effect that amendments can perform.

In *Fig. 18*, the thematic map groups the keywords of the authors focusing on the relevance and the field of research. This map is divided into four sections: i) motor themes, ii) basic themes, iii) emerging or declining themes, and iv) very specialized/niche themes. In this research, the keywords “composting”, “charcoal”, soil”, “article”, and “controlled study” belong to the motor themes category. This quadrant is characterized by having a high centrality and density which means that they are well developed and important topics; on the other hand, “biochar”, “compost”, “soil amendment”, “soils”, and “biomass” are considered within the category of basic topics, that are important for research but not well developed, which is verified since the biochar-compost issues such as mixtures and application are still few in the scientific literature. This means that they present a low density and high centrality, and that more research and analysis are needed in the future. In the lower left quadrant are emerging or declining themes. In this research, the themes “microbiology”, “bacteria”, “enzyme activity”, “microbial community”, and “nonhuman” emerge. For example, Jiang et al. (2022) point out that the combined addition of biochar and garbage enzyme (GE) improves the humification and succession of the fungal community during the composting of sewage sludge; however, few studies pay attention to the effect of GE on the humification process, and the influence of the combined addition of GE and biochar on

Fig. 18. *Thematic map*



the composting process was also not well evaluated, so more research is needed in this field. Furthermore, some research about applying bacteria (microorganisms) assessed the effect of green waste biochar and wood biochar, together with compost and plant growth promoting rhizobacteria (*Bacillus subtilis*) on tomato yield *(Solanum lycopersicum L.*) (Rasool et al., 2021), assessed the integrated application of biochar, compost, fruit and vegetable waste, and *Bacillus subtilis* (SMBL 1) to soil in sole application and in a combined form (Anwar et al., 2021), and evaluated the response of the structure of the arbuscular mycorrhizal fungi community through the application of fertilizers, biochar and compost in a karst mountainous area for 24 months (Yan et al., 2021). In the case of co-composting, biochar and solid digestate from anaerobic digestion were also assessed (Casini et al., 2021).

Collaboration analysis

Fig. 19 illustrates the network of authors who have researched biochar, compost, and their application to the soil for the period from 2008 to 2021. Each color represents a cluster associated with authors. The larger the circle, the greater the number of citations it has received. According to this author, the lines between the researchers represent links, and the distance between the researchers is associated with the strength of their relationship. It is observed that there is distancing in the publications, and collaboration is restricted by certain groups of authors.

Another dimension studied in the bibliometric analysis is the collaboration between institutions. *Fig. 20* shows different clusters, and their size is related to the number of collaborations that have been carried out. It is observed that there is collaboration between certain groups of institutions and that the University of Agriculture leads in this aspect.

Finally, the collaboration between countries is shown in *Fig. 21*. It is observed that China is a country that continuously collaborates with different countries. While countries like Hong Kong, Belgium, Japan, Indonesia Denmark, and Malaysia should strengthen ties.

Fig. 19. *Collaboration network (co-authorships)*

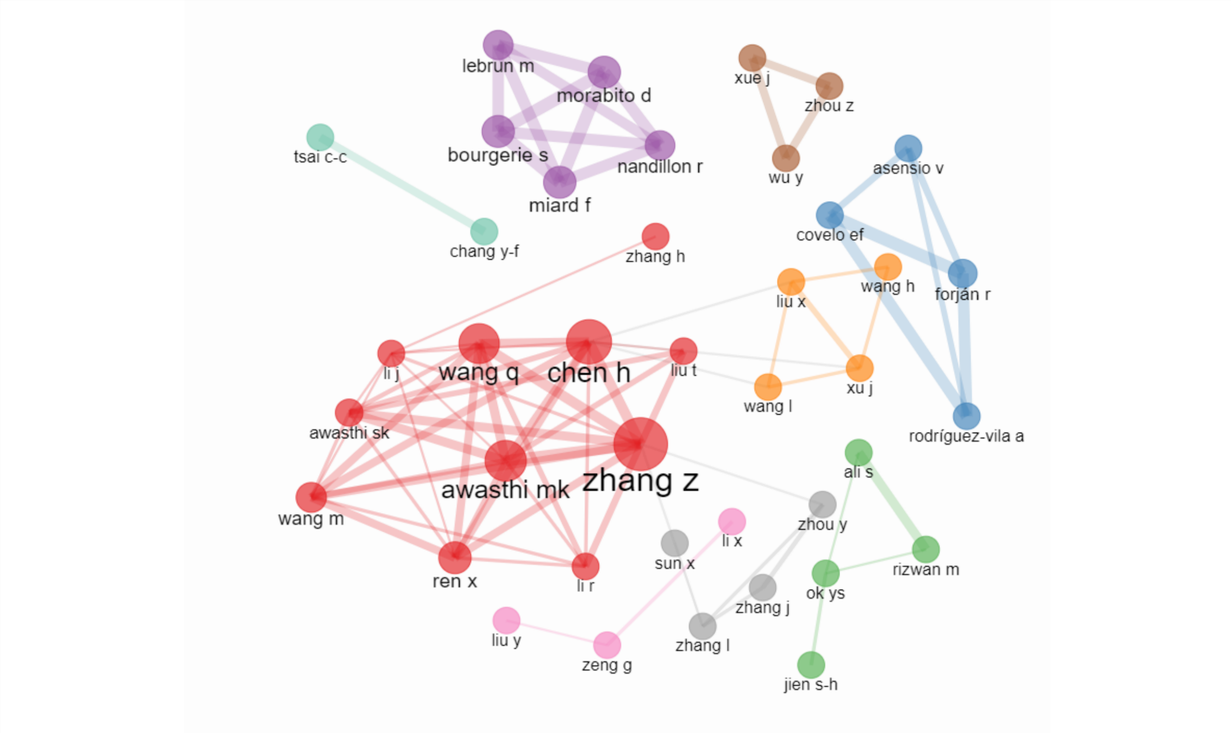


Fig. 20. *Collaboration network (institutions)*

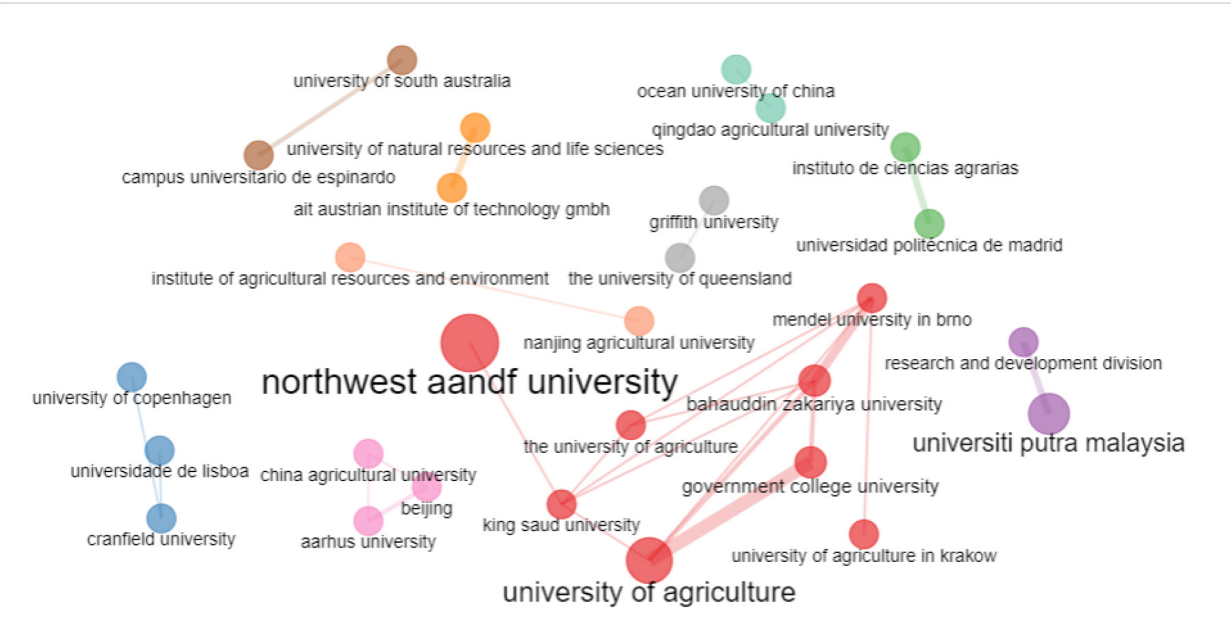
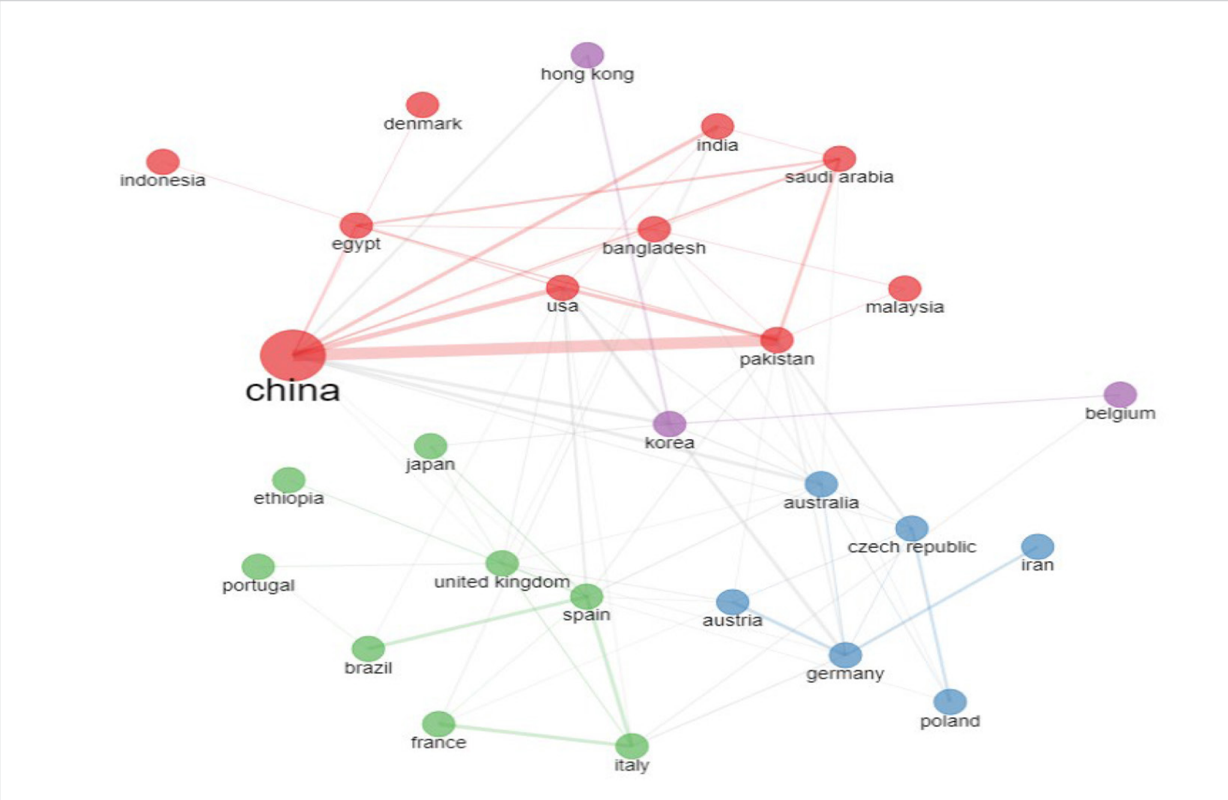


Fig. 21. *Collaboration network (countries)*



Conclusions

There is little literature on bibliometric studies, and the synergy that may exist between biochar and other amendments like compost for its application in the soil. This study carried out a bibliometric analysis using the keywords "biochar", "compost" and "soil" for a period of 2008–2021, identifying 753 articles.

According to the descriptive analysis, a strong trend of biochar, compost and soil publications is observed in the last two years. For the metrics of the authors, Zhang Z is the author with the largest number of documents, 21 in total and with a distribution of 2.5% for the present study. Zhang Z is also the one with the highest H index, as well as Glaser B, who has been one of the pioneer researchers on topics related to biochar, compost and its application in the soil. Zhang Z and Chen H are the authors who have collaborated most with other countries.

For the analysis of the sources, Science of The Total Environment is the one with the largest number of documents, H index, and as of 2016, it has positioned itself with the theme of biochar, compost and its application to the soil. For citation and co-citation analyses, a continuous branching is shown from the year 2016 and 2017. For co-occurrence network, the keywords according to bond strength and most frequent use were biochar (538 occurrences), composting (349 occurrences), compost (436 occurrences), charcoal (295 occurrences), and soil (255 occurrences). On the other hand, a strong trend is observed in clearly differentiated fields (multiple correspondence analysis), bioremediation, analysis of parameters in the soil, and analysis of the quality of manure, compost.

For collaboration analysis, China is the country with the highest collaboration worldwide, and there are collaboration gaps in some countries such as Hong Kong, Belgium, Japan, Indonesia, Denmark, and Malaysia.

An interesting finding was found that the articles from now on tend to focus a lot on microbiological analysis, enzymes, bacteria, and these are emerging issues; that is, they should be strengthened to better understand the synergy of biochar, compost and microbial activity in the coming years, and as pointed out (Jiang et al., 2022), the combined addition of biochar and garbage enzyme (GE) improves the humification and succession of the fungal community during sewage sludge composting. However, few studies pay much attention to the effect of GE on the humification process. The influences of the combined addition of GE and biochar on the composting process were also not well evaluated. Finally, more information and research are needed regarding the microbiological field and interactions of bacteria and enzymes in the application of biochar compost.

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