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A bibliometric analysis on the agricultural use of biochar in Brazil from 2003 to 2021: research status and promising raw materials

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Abstract

Biochar is considered a promising option for the development of sustainable agroecosystems, due to its diverse agronomic and environmental benefits. In this context, the aim of this study was to carry out a bibliometric analysis on biochar research in Brazil within an agricultural context, including investigating the raw materials most employed for its production in the country. The analysis was conducted based on a search for scientific articles (peer-reviewed papers) at the Web of Science database (WoS Core Collection) from 2003 to 2020 specifically in Brazil. A performance analysis was carried out by applying a descriptive and metric approach concerning research constituents (authors, institutions, countries and keywords) and science mapping to clarify scientific collaborations and cognitive and intellectual structure patterns regarding the biochar domain in Brazilian research, using the VOSviewer software. The obtained studies were also analyzed individually to classify the different raw materials employed in biochar production. A total of 261 scientific articles met the screening criteria, indicating that the beginning of biochar publications in Brazil took place in 2003, increasing until 2015 and peaking in 2021. Institutions and authors with the highest publication contributions were the Brazilian Agricultural Research Corporation (EMBRAPA) (Novotny E.), São Paulo University (USP) (Cerri C.) and Federal Lavras University (UFLA) (Melo L.). The United States, Spain, Australia, Germany and the Netherlands present the most collaborations on biochar research with Brazil. The biochar domain was highly associated with the following keywords: biochar, pyrogenic carbon, pyrolysis, charcoal, immobilization, black carbon, soil fertility and soil and characterization. Raw materials of plant origin were the most employed in biochar research in Brazil, with wood residues being the most studied and residues originated from the sugar-energy industry (straw, bagasse and filter cake) identified as exhibiting high potential for future studies. Poultry litter is the most promising animal waste for biochar production, while the use of biosolids can be innovative, contributing to the consolidation of biochar as an option for serious urban waste sanitary management problems.

Introduction

One of the great world agriculture challenges is to produce food, fiber and energy while maintaining high productivity without causing soil degradation, water pollution, biodiversity losses and the emission of greenhouse gases (Almeida Prado *et al.*, 2016). In this regard, the development of soil management and conservation practices is a strategy employed to mitigate the negative effects caused by conventional agricultural practices (Clare *et al.*, 2015; Ding *et al.*, 2016).

A restricted occurrence of soils called 'Terra Preta de Índio' (TPI, Amazonian Dark Earth), technically classified as Anthrosols (anthropogenic soils) is noted in the Central Amazon region (Amazonas-Solimões valley) (IUSS Working Group WRB, 2014) given this name due to their origin associated to strong changes caused by the long-term activities of pre-Columbian Amerindian populations 500–2500 years ago. The high pyrogenic carbon (C) contents of these Anthrosols are considered evidence of the use of charcoal as an additive, notably able to preserve high soil yield potential and fertility (Lehmann *et al.*, 2003; Glaser, 2007; Glaser and Birk, 2012).

Increasing interest in research on coals and partially carbonized residues has been noted in recent years, aiming at obtaining materials similar to the organic matter of TPIs, especially those containing pyrogenic C, for agricultural and environmental uses (Glaser, 2007; Novotny *et al.*, 2009). Biochar (a combination of the words 'biomass' and 'charcoal') defines pyrogenic C obtained through the thermal decomposition of plant or animal biomasses through pyrolysis under limited oxygen supply conditions and at different temperatures, ranging from 200 to 700°C (Lehmann, 2009).

Although worldwide biochar research interest has significantly increased and encompasses different fields, including environmental sciences, energy, soil science, biotechnology and microbiology, chemical engineering, environmental engineering and agronomy, biochar is still considered a relatively recent research domain, and the first scientific article publication considering the English term biochar took place only in the year 2000 (Trazzi *et al.*, 2018).

Even so, several literature reviews on different biochar relevance topics are available, indicating biochar as a promising alternative to improve agroecosystem sustainability, due to its specific properties, production and characterization displaying potential for agricultural use and soil management (Atkinson *et al.*, 2010; Sohi *et al.*, 2010; Novotny *et al.*, 2015; Laghari *et al.*, 2016; Kalus *et al.*, 2019; Panwar *et al.*, 2019), the improvement of soil fertility and nutrient availability (Schulz and Glaser, 2012; Kloss *et al.*, 2014; Ding *et al.*, 2016; El-Naggar *et al.*, 2019), applications in global warming mitigation strategies, soil carbon sequestration potential and other environmental issues (Laird, 2008; Singh *et al.*, 2010; Jeffery *et al.*, 2011; Ippolito *et al.*, 2012; Gurwick *et al.*, 2013; Mekuria and Noble, 2013; Saletnik *et al.*, 2019), soil contamination and remediation (Zama *et al.*, 2018) and public policies for biochar application recommendations (Pourhashem *et al.*, 2019). The aforementioned publications are typical examples of systematic reviews (reviews, comprehensive reviews, critical reviews, state-of-the-art reviews), which focus on the processes of searching, arranging, describing, analyzing and synthesizing a wide set of high-quality and relevant evidence to clarify specific research questions (Donthu *et al.*, 2021).

Despite growing concerns and publications about biochar, research addressing the analysis of the development of search fronts in the biochar domain is still scarce (Wu *et al.*, 2019). Thus, it is important to recognize the potential of bibliometric analyses as systematic review alternatives or complements (Donthu *et al.*, 2021).

The bibliometric analysis strategy allows for the investigation of research trends, deficiencies, gaps and directions (Donthu *et al.*, 2021), as well as the deciphering of cumulative scientific knowledge, making sense of large volumes of information, easily acquired in scientific databases, introducing quantitative rigor in subjective literature evaluations (Zupic and Čater, 2015; Donthu *et al.*, 2021) employing bibliometric software packages, such as SciMAT, CiteSpace and VOSviewer.

Bibliometric analyses on some biochar topics in the scientific literature include survey and research evolution (Wu *et al.*, 2019; Galindo-Segura *et al.*, 2020), agricultural crop productivity (Jeffery *et al.*, 2011) and biochar use as a soil corrective and conditioner (Kamali *et al.*, 2020).

Biochar research has evolved rapidly in terms of article publications, but many aspects of its use have only been superficially investigated, still indicating important knowledge gaps (Tammeorg *et al.*, 2017). This makes it difficult to establish parameters on biochar application as a soil improver in agricultural terms. In this sense, soil attribute modification depends on certain biochar characteristics, such as the employed raw material and pyrolysis temperature used during production (Joseph *et al.*, 2010; Bruun *et al.*, 2012).

Few bibliometric studies on the raw materials used for biochar production in Brazil as well as those addressing Brazil's relevance in biochar research are available. The main hypothesis of this study is that Brazil, being a large agricultural producer, also produces waste with the potential to produce and study biochar, making it one of the countries with great relevance in this field. In that context, the VOSviewer software was used to analyze scientific production in this regard in Brazil, and identify the main raw materials used for biochar production from 2003 to 2021, from the indexing of the first article that met the applied selection criteria available at the Web of Science Collection database. The main objective was to conduct a bibliometric analysis of scientific articles (peer-reviewed articles) to identify the contributions of the research components (numbers of publications over the years, authors, institutions, countries and international collaborations) and the raw materials used for biochar production research in Brazil in an agricultural context. A more specific analysis of the raw materials used for biochar production in Brazil was also carried out, with the purpose of understanding which are the most relevant biomass options to assist in the design of future research proposals.

Material and methods

Article selection and screening

Article selection and screening concerning biochar followed the bibliometric methodology recommended and applied by several authors (Gurwick *et al.*, 2013; Zupic and Čater, 2015; Wu *et al.*, 2019; Donthu *et al.*, 2021). The selected articles were obtained from the main collection of the Web of Science (WoS Core Collection) database, recognized as the most complete scientific literature database which indexes articles published in high-visibility international journals. Only scientific articles in English were considered. Data were collected on January 2022 with the aim of obtaining all articles associated with Brazilian researchers who assessed the biochar uses in an agricultural context, since the indexing of the first article on the topic in 2003 (Lehmann *et al.*, 2003) up to 2021. The option 'All Fields' was selected employing the terms (biochar* or 'black carbon') and (soil* or agr*). The search terms were chosen seeking to find articles that studied biochar in the agricultural context, after previous selections that were discarded for including other uses of biochar, such as its use for heating or wastewater treatment. Filters were then applied regarding type of document, selecting only scientific articles (primary research papers or peer-reviewed papers). Finally, Brazil was selected, with the aim of including only articles whose main authors were affiliated to Brazilian institutions (Fig. 1).

Subsequently, a critical and more specific selection was carried out to ensure adequacy concerning our objectives. This selection was made after reading the selected articles and determining if they met the search requirements. A quantitative literature characterization concerning type of biomass or raw material for biochar production was prioritized, excluding articles in which (1) the biochar was not studied for agricultural purposes; (2) Terras Pretas de Índio (TPIs) (Amazonian Dark Earth) were studied; (3) reviews and compilations on biochar but presenting no new scientific information.

Bibliometric analysis

The initial bibliometric analysis of the articles selected from the WoS database was conducted using the platform's own tools, resulting in the distribution of publications over time, involved

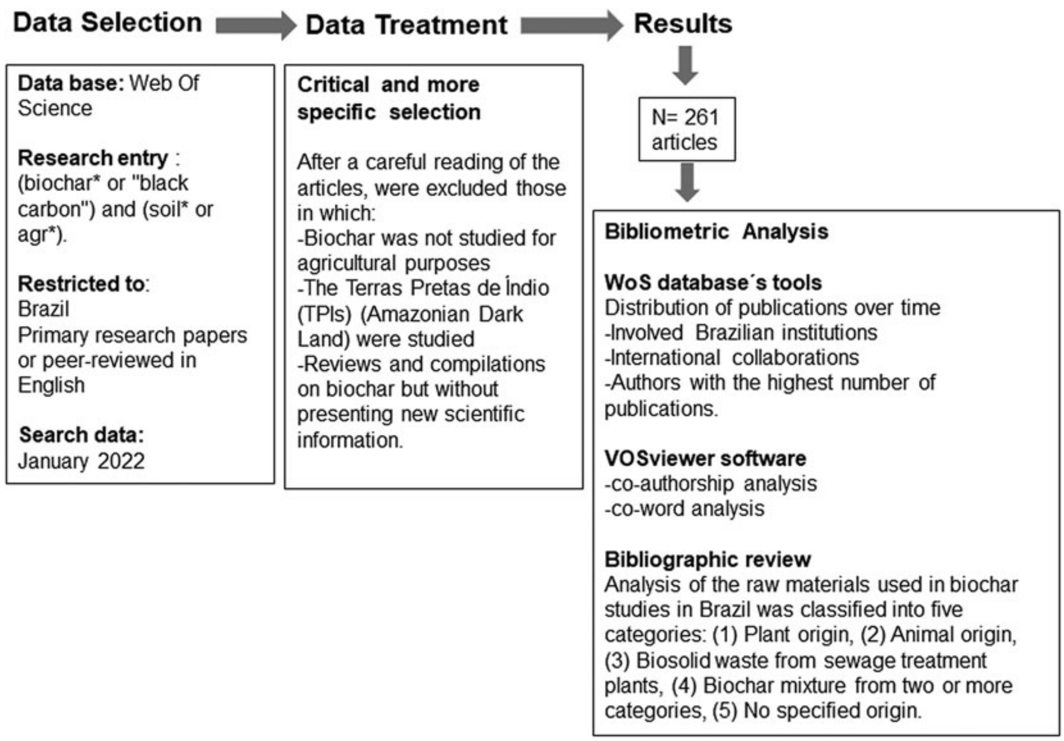

Fig. 1. Flowchart: article selection and analysis.

Brazilian institutions, international collaborations and authors with the highest number of publications. The selected articles were then exported to the VOSviewer software, a free access program developed in Java. The software uses the VOS (Visualization of Similarities) method to define the nodes and links of its analysis network, for later construction of network visualization maps, in which objects displaying high similarity are located more closely to each other (van Eck and Waltman, 2010). The VOSviewer analysis was performed considering co-authorship and keywords (Fig. 1).

The bibliometric analysis techniques applied herein were based on a performance analysis and science mapping (Zupic and Čater, 2015; Donthu *et al.*, 2021). A descriptive and analytical performance analysis was applied to understand research behavior in the specific biochar field or domain and the contributions of research constituents (authors, institutions and countries), especially concerning the publication standards of both individuals and institutions.

The relationships between research constituents were examined by scientific mapping, in order to clarify scientific collaboration patterns, cognitive and intellectual structures and the delimitation and evolution of the scientific field and the particular line of biochar research in Brazil. The following techniques were adopted to elaborate the spatial representation of the interrelationships between authors and keywords: (a) a co-authorship analysis, used to identify collaborations, interactions and the formality of intellectual collaboration between researchers who collaborate in a particular field of research. The identification of collaborations between researchers indicates that there may be improvements in research, due to greater clarity on the subject, richer perceptions and opportunities for insights for the construction of new research groups; (b) a co-word analysis, used to identify author keywords and relevant words that may occur more frequently in titles and abstracts. The co-word analysis also assumes that words that often appear together exhibit thematic identity. Collaboration mapping allows for the rectification of the intellectual trajectory of the most experienced researchers and provides direction for future researchers to reach interactions with groups displaying greater expression in the field of research.

The specific analysis of the raw materials used in biochar studies in Brazil was classified into five categories: (1) plant origin, (2) animal origin, (3) biosolid waste from sewage treatment plants, (4) biochar mixture from two or more categories, (5) no specified origin (Fig. 1).

Studies addressing the use of raw materials of plant and animal origin were then analyzed and categorized. Among plant-based biochars, four categories were considered: (1) wood origin, (2) non-wood origin, (3) residues from the sugarcane industry (sugarcane bagasse, sugarcane straw and filter cake) and (4) mixture of different categories of plant origin. Regarding animal origin, three categories were considered: (1) poultry litter, (2) animal waste (including bovine and swine manure biochars) and (3) pig bones.

Results

Performance analysis

Peer-reviewed papers

A total of 521 scientific articles were selected through the employed search terms, indicating that the scope of the study was large enough to justify the use of a bibliometric analysis (Donthu *et al.*, 2021). Following an individual review, 260 papers were excluded for not meeting the required conditions. Thus, 261 articles in total were analyzed, in which 304 types of biochar were identified and classified according to their raw material. Some studies addressed the use of more than one biochar, which explains the greater number of raw materials compared to the number of analyzed articles.

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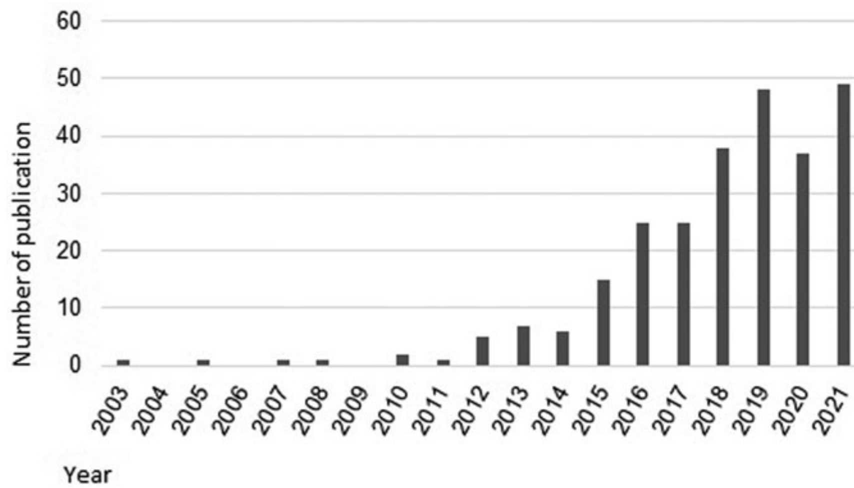

Fig. 2. Number of scientific articles on biochar published in Brazil between 2003 and 2021 indexed at the Web of Science database.

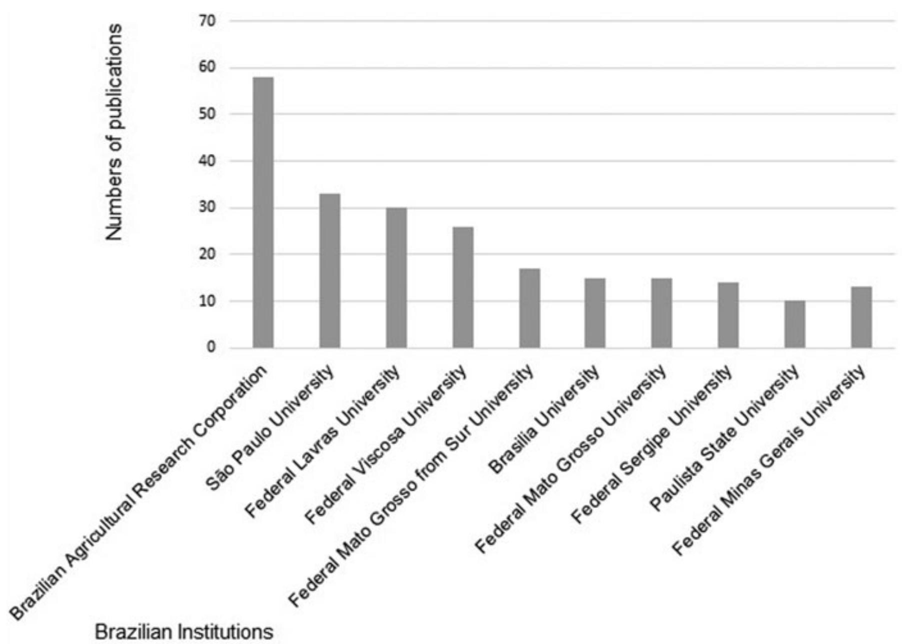

Fig. 3. Number of scientific articles on biochar published in Brazil, considering main researcher institutions between 2003 and 2021 indexed at the Web of Science database.

Considering publications on biochar over the years (Fig. 2), the first biochar record available in WoS in research linked to a Brazilian researcher was published in 2003 (Lehmann *et al*., 2003). During the following 8 years, there was no increase in publications, with no publications in 2004, 2006 and 2009 considering the selected inclusion criteria. However, since 2012, a sustained increase in publications was observed, peaking in 2021, at 49 publications.

Main research institutions

The top ten institutions in terms of number of published articles were selected (Fig. 3). The Brazilian Agricultural Research Corporation (EMBRAPA) stands out among the most prominent Brazilian institutions concerning biochar research, with 58 scientific articles published between 2003 and 2021. The EMBRAPA units with the highest number of articles related to the search were EMBRAPA Solos, in the states of Rio de Janeiro and Pernambuco, EMBRAPA Meio Ambiente, in the state of São Paulo, and EMBRAPA Arroz e Feijão, in the estate of Goiás. The University of São Paulo (USP) was next, collaborating in 33 articles, followed by the Federal University of Lavras (UFLA), with participation in 30 articles.

International cooperations

Collaborations with 36 countries from five continents were identified (Fig. 4), considering that 71.26% of the analyzed articles comprised collaboration with researchers from countries other than Brazil. Spain and the United States comprised the highest number of total collaborations of the total number of evaluated articles, 16 and 13% respectively. Australia and Germany both ranked second, represented by 9% and, in third, the Netherlands, contributing with 6%. These five countries represent 53% of the total international collaborations of articles related to biochar studies.

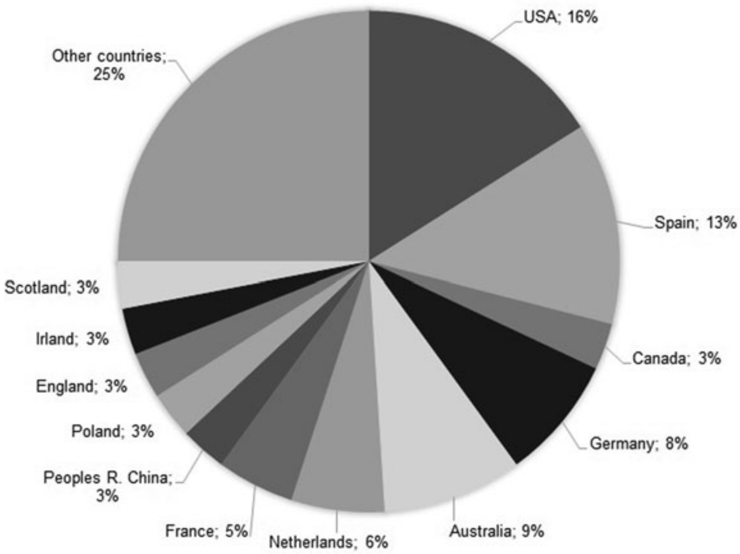

Fig. 4. Top ten countries associated with Brazilian institutions concerning scientific articles on biochar published in Brazil between 2003 and 2021 indexed at the Web of Science database.

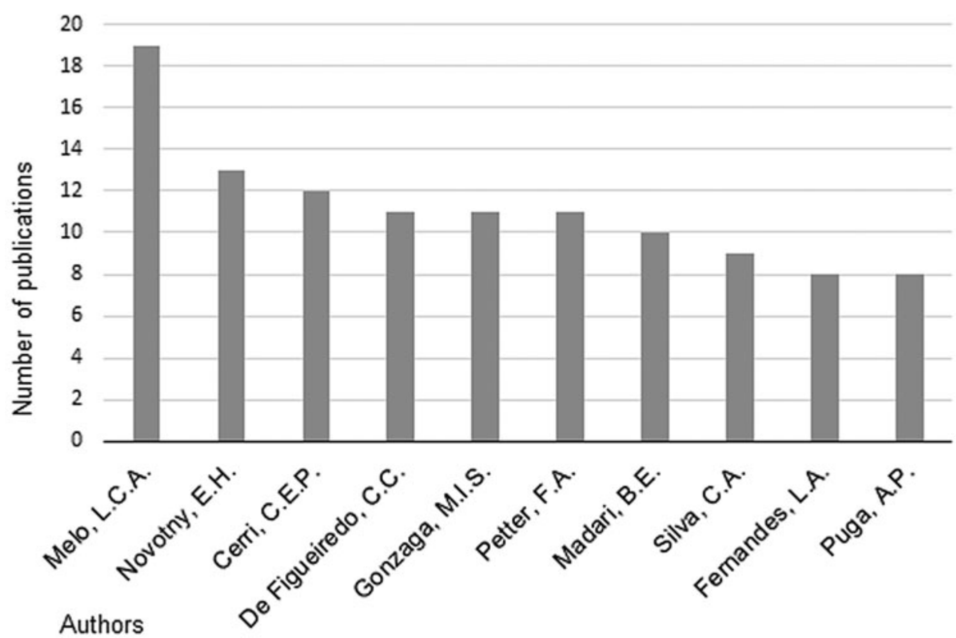

Fig. 5. Number of scientific articles on biochar published in Brazil considering main researchers between 2003 and 2021 indexed at the Web of Science database.

Leading researchers associated to biochar research

The authors with the highest number of published articles generally belonged to the institutions that published the highest number of articles. Among the main authors associated to biochar research in Brazil (Fig. 5), Melo L. was the most active and influential, with the highest number of published articles (19), mainly inserted in the environmental sciences field within WoS-established categories. The author belongs to the Federal University of Lavras (UFLA), which participated in 11.49% of the analyzed articles. Next, Novotny E., an Embrapa Solos researcher, participated in 13 articles, mainly in the WoS category of multidisciplinary agriculture. Cerri C., from the University of Sao Paulo (USP) participated in 12 articles. Figuereido C.C., from Brasilia University; Gonzaga M.I., from Federal University of Sergipe; and Petter F.A., from the Federal University of Mato Grosso (UFMT) participated in 11 articles.

Scientific mapping

Co-authorship bibliometric analysis

The co-authorship map included 75 authors, considering a minimum number of three publications. The authors were categoried into 11 groups (Fig. 6). All groups of authors maintained cooperative relationships with at least one other group.

Concerning the average year of publications for each author and group (Fig. 6), Novotny E., Glaser B., Teixeira W., Petter F. and Madari B.E. stand out as the first authors in terms of publications, while Santos J., Pellegrini-Cerri C., De Figuereido C., Lustosa J. and Dias Y. present a more recent publication average.

Co-word bibliometric analysis

Analyzing keywords reflects research topics and approach trends in a given field (Abdeljaoued *et al.*, 2020). The map prepared

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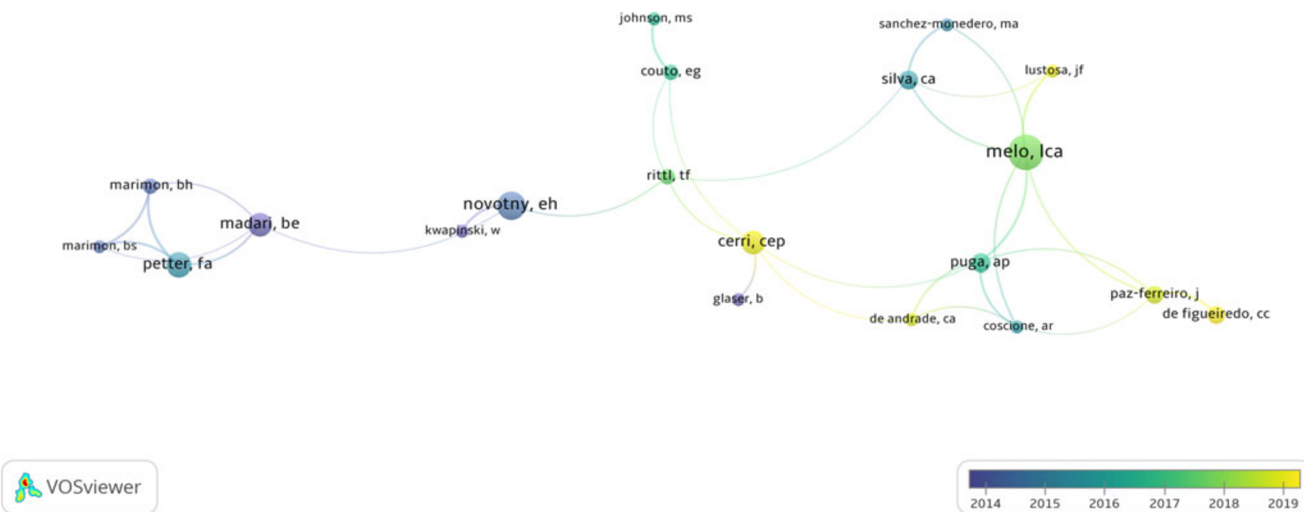

Fig. 6. Co-authorship map and the relationships between author groups over time concerning scientific articles on biochar published in Brazil, between 2003 and 2021 indexed at the Web of Science database.

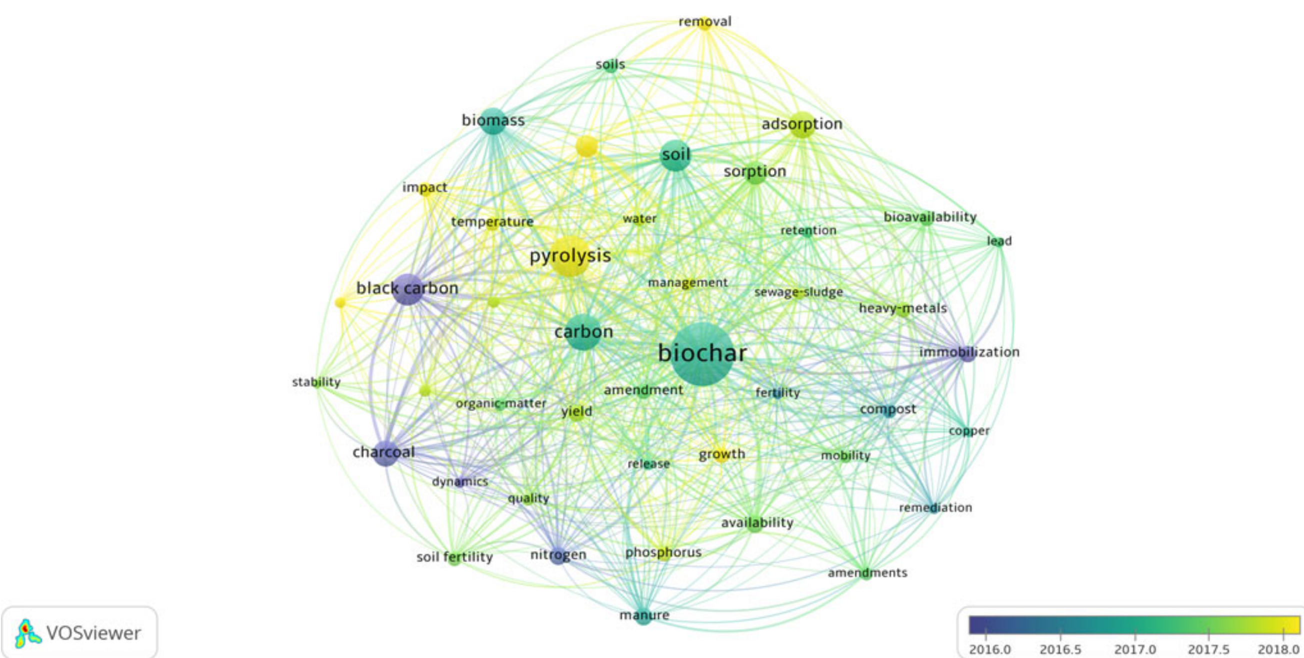

Fig. 7. Map of keywords and their inter-relationships over time in articles published on biochar in Brazil, between 2003 and 2021 indexed at the Web of Science database.

herein concerning the selected articles indicates each group with their respective keywords and their inter-relationships (Fig. 7). The keyword cluster analysis indicated a total of 47 keywords distributed in four clusters: (1) biochar, (2) black carbon, (3) pyrolysis, (4) charcoal.

Figure 7b indicates word groupings according to the period of their appearance. This application is able to reveal the characteristics and development trends of a certain research field (Zhi and Ji, 2012). The first articles corresponded to words related to black carbon use to modify soil nutrient properties in an agricultural context, such as dinamycs, immobilization and remediation. Over time, published articles began to be associated to terms such as biochar (instead of charcoal or black carbon), terms related to intrinsic properties of biochar (pyrolosis, biomass, feedstock) to soil quality (soil fertility, phosphorus, nitrogen, availability, adsorption and sorption). Feedstock, waste, removal and wroth are the most recent words associated with biochar articles.

Analysis of the main raw materials employed in biochar production

Most biochars studied in the selected articles were of plant origin (76%) (Fig. 8), while animal origin corresponded to 9% and biosolid residues, 7% of the analyzed materials. A total of 3% of the biochars presented in the selected articles did not specify biochar origin.

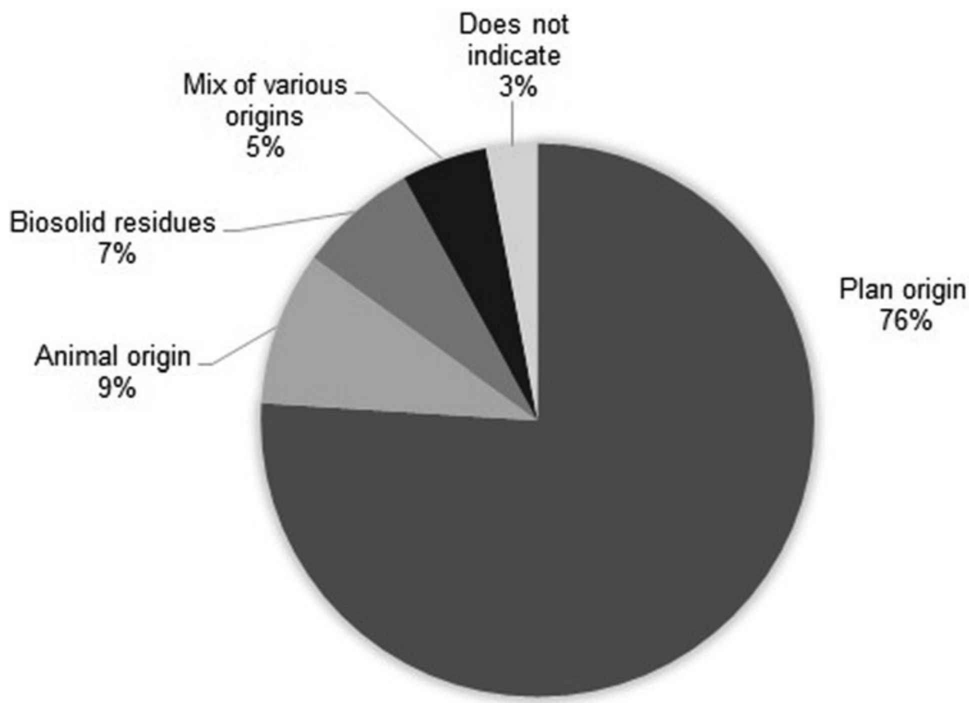

Fig. 8. Classification of raw materials used in research on biochar in Brazil in articles indexed at the Web of Science database between 2003 and 2021.

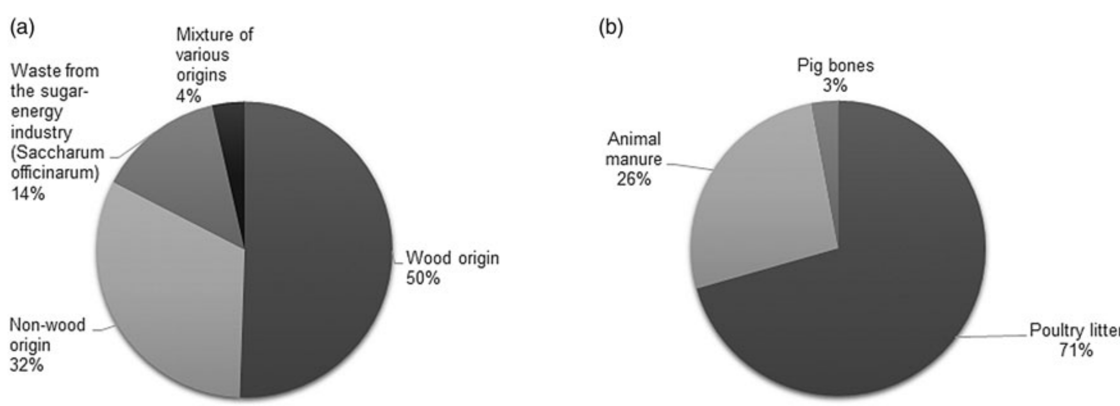

Fig. 9. Classification of raw materials of plant origin (a) and animal origin (b) used in research on biochar in Brazil in articles indexed at the Web of Science database between 2003 and 2021.

Concerning plant-based biochars, most articles employed wood (50%), from *in natura* wood or residues obtained from the wood industry (Fig. 9a). The non-wood origin biochar category, which did not refer to by-products of the sugar-energy industry, includes plant residues such as bagasse, lees, bark, bunches, fibers, flour, nuts, leaves, pruning residues, seeds, sawdust and silages, represented 32% of all plant-based biochars. Sugarcane straw and bagasse and filter cake were grouped into a specific category (waste from the sugar-energy industry), representing 14% of the analyzed materials.

Concerning biochar produced from animal production residues (Fig. 9b), poultry litter corresponded to 71% of the total analyzed biochars. Animal manure, including bovine and swine manure, represented 26%, while 3% of the studied raw materials corresponded to pig bones biochar (Fig. 9b).

Discussion

A higher number of publications on biochar in Brazil is noted from 2010, in line with world research trends, as the number of biochar publications has increased in various fields worldwide, especially since 2008 (Ahmed *et al.*, 2018), after the term biochar was unified at the first International Biochar Conference in 2007 (Yan *et al.*, 2020). Due to the fact that scientific consensus on the term biochar was reached in 2008, articles with equivalent terms but which were not used as biochar or bio-char may have been previously published, but were not considered in this study.

The discovery of fertile anthropogenic soils, mainly TPIs, boosted the volume of Brazilian scientific research on the conversion of organic residues into biochar, since the high organic matter soil contents (>150 g kg^{-1}), higher nutrient availability and

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high cation exchange capacity (CTC) of TPIs are attributed to black carbon content, about 70-fold higher than that of adjacent infertile soils (Ferralsols, Acrisols, Lixisols and Arenosols) (Grossman *et al.*, 2010; Glaser and Birk, 2012).

Regarding the most relevant Brazilian institutions concerning biochar research, EMBRAPA is noteworthy as one of the first institutions to carry out research on the subject in the country and as the first in number of published articles. This is explained, on the one hand, by the fact that EMBRAPA has offices in several Brazilian regions, which justifies its position among the first in number of articles published on agricultural issues. In addition, it has displayed particular interest in biochar studies, proven by the fact that it organized the III International Conference on Biochar in 2010.

The institutions that follow EMBRAPA regarding number of published articles are located in the Southeast and Midwest Brazilian regions. These regions, mainly the Southeast, display high demographic densities (IBGE, 2019) and, consequently, high waste production with the potential to be used for biochar production. The University of São Paulo (USP), identified herein as the second most prominent biochar article produces in the country, is located in the same state.

It appears that the authors with the highest number of published articles generally belonged to the institutions that published the highest number of articles. International collaborations were carried out with countries that are among the first places in terms of publications when employing the same words used to search for the data of this review, such as China, which ranks first, participating in 4849 publications, the United States with 3329 entries, Germany with 1085 entries, Australia with 829 publications and Spain with 629 publications worldwide. The importance of this data resides in the fact that it indicates the support of the main countries that research biochar in an agricultural context, which determines that biochar innovations and application forefronts are also investigated by Brazil, despite the country not emerging as the world's leader in number of publications.

The first articles corresponded to words related to black carbon use to modify soil nutrient properties in an agricultural context, such as dynamics immobilization, and remediation. Over time, published articles began to be associated to terms such as biochar (instead of charcoal or black carbon), terms related to intrinsic properties of biochar (pyrolosis, biomass, feedstock) to soil quality (soil fertility, phosphorus, nitrogen, availability, adsorption and sorption). Feedstock, waste, removal and wroth are the most recent words associated with biochar articles indicating the expansion of possible fields of study on biochar applications, such as pyrolysis studies and its effects on raw materials and soil, the employed biomass and its characteristics, and the reuse of residues for biochar production and the ability of biochar to remove certain metals from the soil.

Regarding raw materials, a clear preference for plant residues for biochar production in an agricultural context is noted. This may be related to their easy access, as Brazil is one of the main agricultural producers in the world, with an estimated agricultural production of 242.1 million tons in the 2018/19 harvest (MAPA, 2019). Consequently, this activity generates significant amounts of waste displaying potential for biochar production.

The preference for raw material of plant origin is also justified by different soil conditioning properties of plant-based biochars compared to biochars produced using animal residues. For example, regarding the possibility of modifying apparent soil density, Randolph *et al.* (2017) reported that the greater initial amount of lignin in the raw material, the greater the apparent density of the produced biochar. On the other hand, in terms of ash generation, biochar production from plant materials generates less ash compared to biochar produced from biosolids and animal waste (Li *et al.*, 2019). In this sense, Domingues *et al.* (2020) evaluated different raw materials and observed that ash contents ranged between 0.7 and 56%, according to the following order: chicken litter > coffee husk > sugarcane bagasse > Eucalyptus sp. The authors, thus, state that raw materials with high ash content are potential sources of biochar displaying higher CTC, which contributes to increased soil fertility. However, biochars with high ash content can generate high amounts of material that blocks internal biochar pores, thus limiting accessibility to these sorption sites (Enders *et al.*, 2012).

A key attribute for understanding soil health is total carbon content. Some authors have demonstrated that biochars produced from plant residues contain higher amounts of total carbon compared to those produced from animal residues (Jindo *et al.*, 2014; Sarfaraz *et al.*, 2020). This is due to the presence of labile organic compounds in animal waste, which are often lost at high temperatures (Domingues *et al.*, 2017). This characteristic reinforces the preference of researchers regarding the choice of plant raw material for biochar production.

In a global context, the use of lignocellulosic biomass has gained attention, due to its renewable properties, availability and costs (Yaashikaa *et al.*, 2019). Wood residues were the preferred raw material in the obtained papers, as they contain higher lignin content (between 25 and 33%) depending on the type of wood, consequently, leading to greater associations between the amount of employed raw material and the obtained biochar (Lee *et al.*, 2017).Cellulose and hemicellulose pyrolysis produce more volatile compounds, while lignin pyrolysis produces more solid biochar (Wang *et al.*, 2017). Because of this, in general, biomasses that contain more volatile compounds are preferred for bio-oil production, while biomasses presenting higher carbon content are used for biochar production (Yaashikaa *et al.*, 2019).

By-products from the sugar-energy industry also play an important role in biochar research in Brazil, since the country is the world's largest sugarcane producer, which displays significant importance for the Brazilian agribusiness, with an estimated 2019/2020 harvest of 630,710.9 thousand tons (CONAB, 2015). The Southeast is the main producing region in the country, coinciding with one of the regions with the most biochar research publications.

The by-products generated by the sugar-energy industry have considerable potential for large-scale biochar production in the country, with several benefits, such as the high ratio between the employed raw material and produced biochar (Lee *et al.*, 2017), or a higher amount of carbon compared to biochars produced from animal waste (Sarfaraz *et al.*, 2020). Despite material availability, some limitations regarding these by-products are noted, as they are widely employed in other agricultural processes involved in the sugarcane chain, for fertilization and energy generation purposes (Bhat *et al.*, 2016; Purnomo *et al.*, 2018).

Considering animal origin residues, poultry litter was the most employed in the obtained studies. In the last 40 years, poultry meat production has increased 22-fold in Brazil, reaching approximately 4 billion birds per year, making Brazil the second largest producer of this type of animal protein worldwide (Santos Dalólio *et al.*, 2017; IBGE, 2019). This leads to a high generation of waste, around 8–10 million ton per year (Santos Dalólio *et al.*, 2017), making this an agricultural sector concern, which is, therefore, now searching for sustainable alternatives.

Biochar production from poultry litter, in addition to reducing waste volume, also reduces or eliminates the damage derived from incorrect poultry litter management, such as soil (Leinonen *et al.*, 2012; Gupta *et al.*, 2021) and water body contamination. Consequently, research on this material should be increased, in order to promote adequate waste disposal and reduce damage resulting from the incorrect poultry litter management. It is noteworthy that, despite being less efficient in biochar production, biochars produced from animal waste generally contain higher amounts of nitrogen when compared to biochars produced from plant residues (Tag *et al.*, 2016).

This study also allowed for the identification of the promising character of biochar for biosolid disposal from sewage treatment plants. In a context in which the amount of municipal biosolids produced annually worldwide has increased dramatically over the decades (Arulrajah *et al.*, 2011), options for the destination of this waste are crucial. In this sense, research on biochar using biosolids has been increasing over time (Fonts *et al.*, 2012). However, the physico-chemical characteristics of biosolids of this type differ significantly according to wastewater sources, wastewater treatment processes and sewage sludge treatment methods (Metcalf *et al.*, 2004). These variations create difficulties to establish generalizations about the properties and potentialities of soil application of biochars produced from these biosolids.

It is worth noting that, in addition to improving soil characteristics, the use of different raw materials also generates several benefits and opportunities for environmental management, allowing for reducing the volume of organic waste generated in Brazil, including in relation to the disposal of biosolids from sewage treatment stations and by-products generated by the Brazilian sugar-energy industry.

The analysis of the articles showed that although biochar is considered a 'soil improver', it is still not possible to make generalizations regarding its impact on soil attributes, which makes it difficult to establish doses in a general way. It would be necessary to carry out an analysis of the soil and determine which soil characteristics to improve and based on that evaluate the best type of biochar. However, it is possible to get some information that can guide the choice of Biochar. For example, if desired to increase the density of a soil, then it is recommended to use plant-based biochar, because this raw material produces a material with higher bulk density (Randolph *et al.*, 2017). In addition, if the desire is to increase the carbon content, over other nutrients, it is recommended to choose plant-based biochars. On the other hand, other nutrients such as nitrogen are found to a greater amount in biochars of animal origin (Jindo *et al.*, 2014; Sarfaraz *et al.*, 2020).

Conclusions

Publications on biochar in the Brazilian agricultural context began in 2003, with a tendency to rise from 2015 and an observed peak in 2021. The Brazilian Agricultural Research Corporation (EMBRAPA) exhibited highest publication contribution scientific studies, with Novotny E. and Madari B. as the most prominent authors, within that Brazilian research corporation. In second and third place, respectively, the largest contributions come from the University of São Paulo (USP) and the Federal University of Lavras (UFLA), with emphasis on researchers Cerri C. and Melo L. respectively. Important collaborations were identified in biochar research in Brazil alongside researchers from countries with outstanding efforts for the evolution of knowledge on biochar, mainly the United States, Spain, Australia, Germany and the Netherlands.

Plant-based materials are the most employed for biochar production in Brazil, mainly of wood origin. An evident and promising tendency to use plant residues from the sugar-energy industry is noted, especially straw, bagasse and sugarcane filter cake, as well as animal residues, especially poultry litter, both comprising abundant options for raw material originated from important agricultural chains in Brazil for biochar production. To a lesser extent, an interest in using biosolids for biochar production was also identified. Those materials, from the sugar industry and biosolids, despite their great availability in Brazil are not among the most researched for the agricultural context, suggesting the opportunity to explore and the need to carry out new research in this field. Brazil's predisposition to use this type of waste represents an important direction in contributions toward biochar technology, overcoming its restricted use for agricultural purposes and offering solutions to serious urban waste sanitary management problems.

In addition, each biochar presents variables that will determine the variations in the soil where it is applied. Among these variables are the raw material, the pyrolysis temperature, the pyrolysis time, and the final size of the biochar. This situation determines the difficulty to establish generalizations regarding the benefits of biochar in any soil. For this reason, it is necessary to carry out more studies to understanding how the biochar variables impact on the different types of soil.

Finally, gaps in the literature concerning studies on raw materials of organic origin are noted, which still require further assessments, highlighting the potential that biochar may present in solving problems related to urban waste management or the reuse of animal waste.

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