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REVIEW

Research Trend of Aging Biochar for Agro-environmental Applications: a Bibliometric Data Analysis and Visualization of the Last Decade (2011–2023)

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Abstract

The copious amounts of data generated through publications play a pivotal role in advancing Science, Technology, and Policy. Additionally, they provide valuable and detailed information on research topics, emerging thematic trends, and critical issues that demand increased focus and attention. Over the last few decades, biochar has produced an extensive body of high-quality papers and played a crucial part in achieving the long-term Sustainable Development Goals of the 2030 agenda of the United Nations about "Climate Change," "Sustainable Agriculture," "Environmental Sustainability," "Zero Hunger," "Human Wellbeing," and "Circular Bioeconomy". However, most of the research is on biochar that has been modified or functionalized using various chemical reagents or catalysts and reported widely in peer-reviewed, high-quality journals. No prior work analyzed the bibliometric data on aging biochar with (a)biotic processes. This study presents an innovative data-driven bibliometric analysis technique and paradigm for extracting the essence of the available peer-reviewed literature data to offer new perspectives on the research opportunities and potential of aged biochar for agro-environmental applications. The bibliometric data analysis indicates that aging biochar research for agro-environmental applications received attention, advanced, and resulted in 165 high-quality publications in reputed journals between 2011 and 2023. However, it is evident that there is still a considerable need for further attention in this area. The identification of the research trends/frontiers shows that biochar production effectively employs various biomass resources, aging with different (a)biotic factors, characterization, effects on global climate change, long-term carbon sequestration in soil, soil nutrient dynamics, restoration of multi-polluted soils and sediments, and plant growth all require continuous attention both now and in the future.

Keywords Aging biochar · (A)biotic processes · Agro-environmental sustainability · Data-extraction · Bibliometric analysis

1 Introduction

Nowadays, a shift in agricultural management and public policies towards a more Sustainable Development Model is necessary, according to claims that intensive conventional agricultural practices, climate change, rapid industrialization, and urbanization have caused environmental damage and compromised world food security (Ur Rahim et al., 2021). Countries are enticing researchers to take action and investigate new, effective, green, and sustainable approaches to achieve Sustainable Development Goals (SDGs) concerning, no poverty (SDG-1), zero hunger (SDG-2), good health and well-being (SDG-3), climate action (SDG-13), and life on land (SDG-15) (Rosati et al., 2021; Ur Rahim et al., 2021). Based on these urgent needs, the adoption of by-products of thermo-pyrolysis, specifically biochar, in agro-ecosystems stands out as a promising environmentally friendly material used as a soil amendment for supporting crop development and yield (Brassard et al., 2019).

Biochar is a solid, carbon-rich substance created through the pyrolysis of various feedstocks with a limited amount of oxygen and has a well-developed porous structure and

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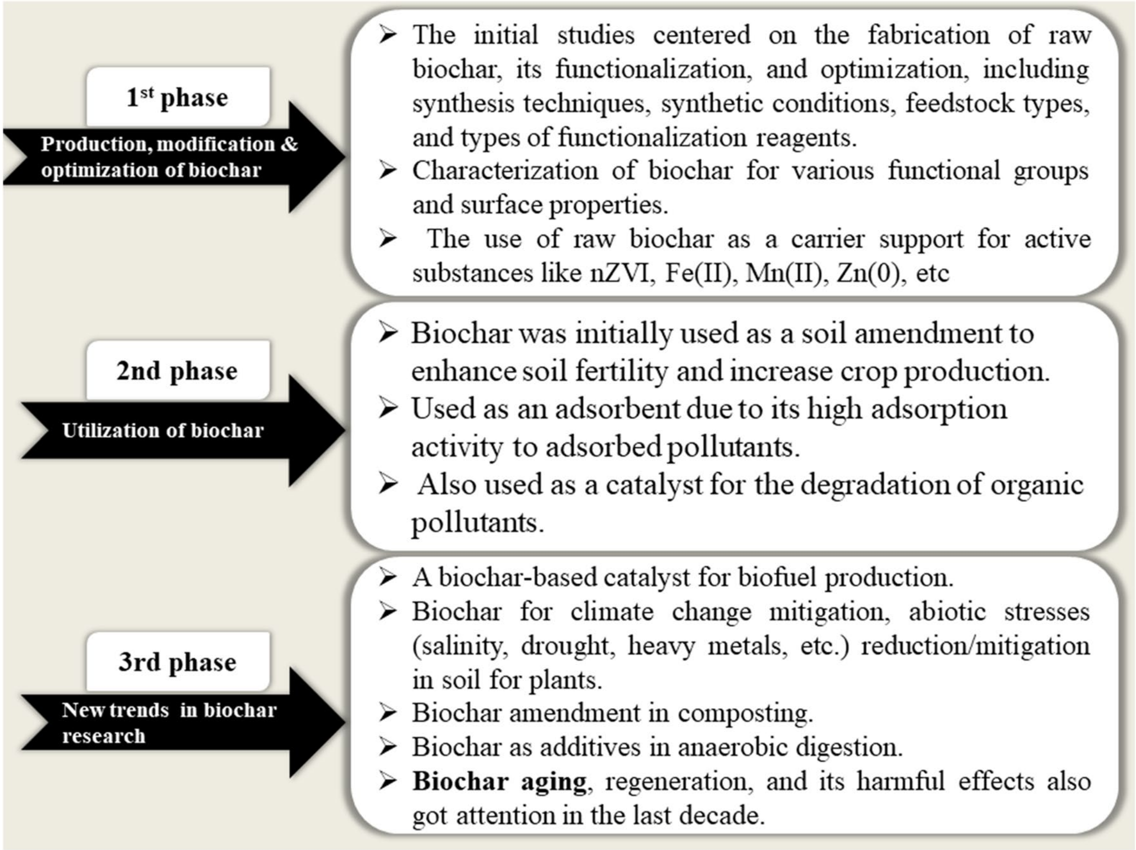
flexible functionality (Majumder et al., 2023). Several studies showed as biochar supports the shift to Sustainable Development Model easier by promoting climate change mitigation (Lehmann et al., 2021), increasing the amount of carbon in the soil (Novotný et al., 2023; Akbar et al., 2023a), lowering soil pollution (Rahim et al., 2022; Saleem et al., 2023), regulating nutrient and water cycles (Akbar et al., 2023b; Pan et al., 2021), and changing the physicochemical characteristics of soil (Mansoor et al., 2021), improving microbial activity (Palansooriya et al., 2019), enhancing plant performance and agricultural output (Yu et al., 2019). The previously listed benefits are mainly due to biochar's surface properties and the functional groups that facilitate their apparent performance, but it is impossible to ignore the biochar's in situ temporal performance in the complex soil system. This could be due to the several biotic and abiotic factors, e.g., temperature variations, precipitation events, and microbial activities, that modify biochar physicochemical and surface properties in the soil through fragmentation, dissolution, and oxidation (Wang et al., 2020).

Although biochar research has exploded in recent years, as shown in Fig. 1, up to date the long-term responses of biochar have received far less attention than other research areas, such as short-term performances. Once biochar is applied to the soil, it undergoes natural aging processes involving various factors influencing its surface morphology and functional groups. This aging process occurs due to several environmental and soil-related factors and processes, including (i) physical aging, primarily by freeze-thaw cycles, changes in temperature and moisture (these cycles may lead to the expansion and contraction of the biochar structure, potentially affecting its surface properties), aeration (accelerate oxidation processes affecting the surface chemistry of biochar), pH (influence chemical reactions occurring on the surface of biochar), and natural organic substances in soil, which influence the biochar surface morphology and functional groups (Cao et al., 2019; Cheng and Lehmann, 2009; Hale et al., 2011; Yang et al., 2018), (ii) chemical aging, through abiotic oxidation upon exposure to various oxidizing agents, such as, hydrogen peroxide (H_2O_2), nitric acid (HNO_3), sulfuric acid/nitric acid (H_2SO_4/HNO_3), potassium dichromate ($K_2Cr_2O_7$), hydrogen peroxide/potassium dichromate ($H_2O_2/K_2Cr_2O_7$), phosphoric acid (H_3PO_4), and many other (Xia et al., 2023, Han et al., 2018, Chu et al., 2018, Cross and Sohi, 2013; Gámiz et al., 2019a; Huff and Lee, 2016), and (iii) biological aging, biotic degradation



- The initial studies centered on the fabrication of raw biochar, its functionalization, and optimization, including synthesis techniques, synthetic conditions, feedstock types, and types of functionalization reagents.
- Characterization of biochar for various functional groups and surface properties.
- The use of raw biochar as a carrier support for active substances like nZVI, Fe(II), Mn(II), Zn(0), etc

- Biochar was initially used as a soil amendment to enhance soil fertility and increase crop production.
- Used as an adsorbent due to its high adsorption activity to adsorbed pollutants.
- Also used as a catalyst for the degradation of organic pollutants.

- A biochar-based catalyst for biofuel production.
- Biochar for climate change mitigation, abiotic stresses (salinity, drought, heavy metals, etc.) reduction/mitigation in soil for plants.
- Biochar amendment in composting.
- Biochar as additives in anaerobic digestion.
- **Biochar aging**, regeneration, and its harmful effects also got attention in the last decade.

Fig. 1 The review of the trends in peer reviewed papers in BC research and corresponding physical and chemical modifications of biochar by microbes (fungi and bacteria) and other soil organisms (Laird et al., 2010; Osorio et al., 2014; Santos et al., 2012). Similarly, before being used as an amendment in soil, biochar underwent several artificial aging processes, including chemical oxidation, mineral alteration, and wet-dry cycling (Li et al., 2019; Wang et al., 2020). These aging processes may alter the physicochemical and surface properties of biochar, which may improve or impair the material's effectiveness in field applications and long-term carbon storage over time (Wang et al., 2020). Nevertheless, not enough research has been done to determine how naturally aged biochar or artificially aged biochar could behave over time in the soil environment.

In this context, a detailed quantitative analysis based on mathematical models can be carried out to comprehend the aging biochar research trends and obtain insights into the future. A new data-driven approach called bibliometrics uses statistical techniques to the outputs of research and has quantitative functions that are knowledge-oriented (Tan et al., 2021). Herein, this study was carried out to create the first baseline data on the subject for comparisons in the future and to help researchers and policymakers develop plans for using aging biochar for agro-environmental applications.

2 Methodological Approaches

2.1 Literature Survey and Selection Criteria

Forthcoming, there have been reviews in the literature exploring and compiling data on aging biochar with emphasis on aging techniques, factors (biotic and abiotic), optimization of aging techniques, characterization, soil and environmental applications, mechanisms in soil, comparison of natural and aging biochar properties, and others. Recent research that demonstrates the aforementioned includes the ones below:

(1) Effects of biotic and abiotic aging techniques on physicochemical and molecular characteristics of biochar and their impacts on environment and agriculture: a review (Murtaza et al., 2023).
(2) How does biochar aging affect NH_3 volatilization and greenhouse gases (GHGs) emissions from agricultural soils? (Feng et al., 2022).
(3) A meta-analysis of heavy metal bioavailability response to biochar aging: Importance of soil and biochar properties (Yuan et al., 2021).
(4) Biochar aging: mechanisms, physicochemical changes, assessment, and implications for field applications (Wang et al., 2020).
(5) How close is artificial biochar aging to natural biochar aging in fields? A meta-analysis (Li et al., 2019).

The aforementioned research work has focused on and reviewed by numerous researchers on the development of aging biochar for sustainable agro-environmental applications. Unfortunately, no study has reported on bibliometric methodologies that use statistical techniques. As far as our knowledge, this work is the first to offer a data-driven bibliometric analysis of aging biochar research contributions toward a comprehensive application for sustainable agriculture and the environment. Also, this paper provides a complete yet concise and brief perspective of the current situation and research developments on aging biochar over the last decade.

2.2 Data Extraction

In our initial search for comprehensive information on biochar and soil research, we discovered more than 13,000 publications in the Scopus databases. However, in keeping with the goals of the current study, we searched all the academic English publications on March 9, 2023, saved in Microsoft Soft Excel.csv, with the period set from 2011 to 2023, that were extracted from the Scopus database (www.scopus.com) and contained the keywords "Aged-biochar" OR "Aged-charcoal" OR "Aged-hydro char" AND "Soil Pollution" AND "agro-environment," etc. (Fig. 2). The Scopus database was selected because it gives more comprehensive coverage of many study areas, high-caliber research, and more reliable research data.

The content of 165 papers with a 21.15% annual growth rate in aging biochar research was retrieved using the Scopus database. Original research articles and proceedings papers comprised the areas of literature. Reviews and meta-analyses were not included in the study. These publications were contributed by 620 authors, with international co-authorship accounting for 40.61% of the total. All the relevant information about the data is presented in Fig. 3. Data extraction, analysis, and visualization were done with VOSviewer 1.6.19 and R-4.2.2 software with package Bibliometrix-Biblioshiny based on (1) annual scientific production per year, (2) average citations per year, (3) country production over time, (4) most cited countries, (5) most global cited documents, (6) most local cited authors, (7) most local cited sources, (8) most relevant affiliations, (9) most relevant authors, (10) corresponding authors countries, (11) most relevant sources, (12) most relevant words, (13) reference publication year spectroscopy, (14) sources production over time, (15) sources local impact by H index, (16) tree map of keywords, and word cloud.

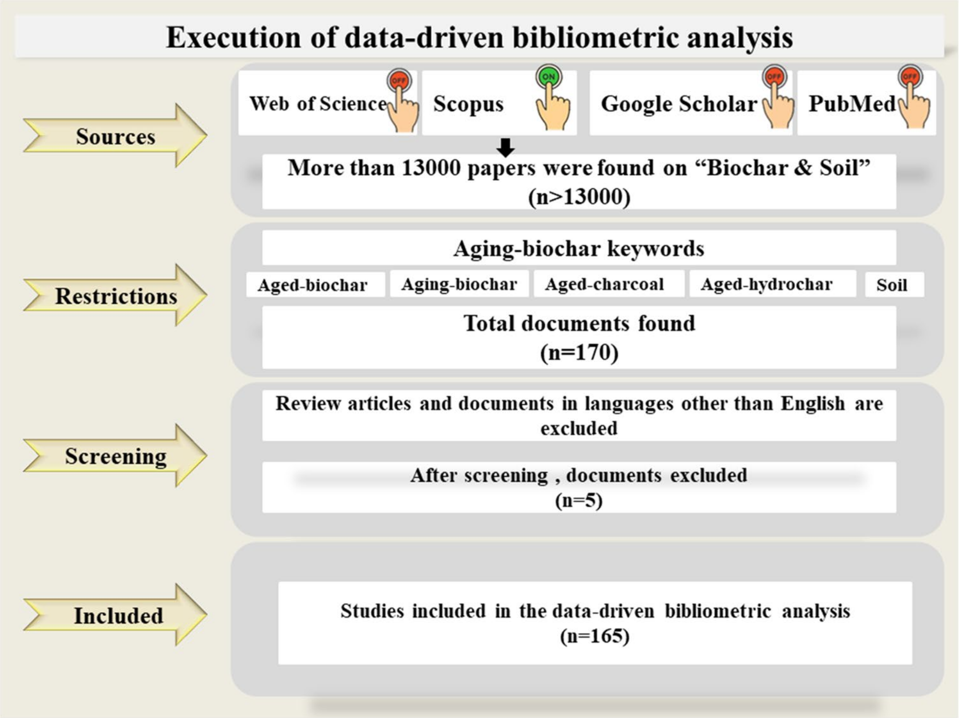


Fig. 2 Strategy for data-driven bibliometric analysis


Timespan 2011:2023
Sources 64
Documents 165
Annual Growth Rate 21.15 %
Authors 620
Authors of single-authored d 0
International Co-Authorship 40.61 %
Co-Authors per Doc 5.62
Author's Keywords (DE) 458
References 8103
Document Average Age 3.7
Average citations per doc 32.7

Fig. 3 Main information of bibliometric data extracted from Scopus on aging biochar research

3 Results

3.1 Annual Scientific Production and Average Citation per Year

The yearly publications count and average citations per year between 2011 and 2023 are displayed in Fig. 4. A considerable increase in publications occurred between 2011 and 2023, going from 1 in 2011 to 32 in 2022 and 10 up until March 9, 2023. The study of biochar aging has advanced slowly. Only one publication was published in the primary growth phase (2011–2013); following that, the research entered its medium growth phase, and the tenure can be ascribed to the years 2014 to 2017. The period from 2018 to 2022 and so on can be categorized as a fast growth phase (Fig. 4a). The bibliometric research confirms a steady growth trajectory in publications related to aging biochar studies between 2011 and 2023. Scopus data extraction reveals that most articles on aging biochar are concentrated in four primary fields: Environmental Sciences, Agricultural and Biological Sciences, Chemistry, and Toxicology.

The number of average citations per year revealed a changing tendency during 2011 and 2023, crossing a point of 24.4 over 13 citable years. After that, it displayed a declination trend, with just 9.2, 8.8, and 4.3 over 12, 11, 10, and 9 citable years (Fig. 4b). Since then, these values have generally decreased, which can be related to the fact that there have not been many publications in the field of biochar aging, and it has taken less time for publications to accumulate citations.

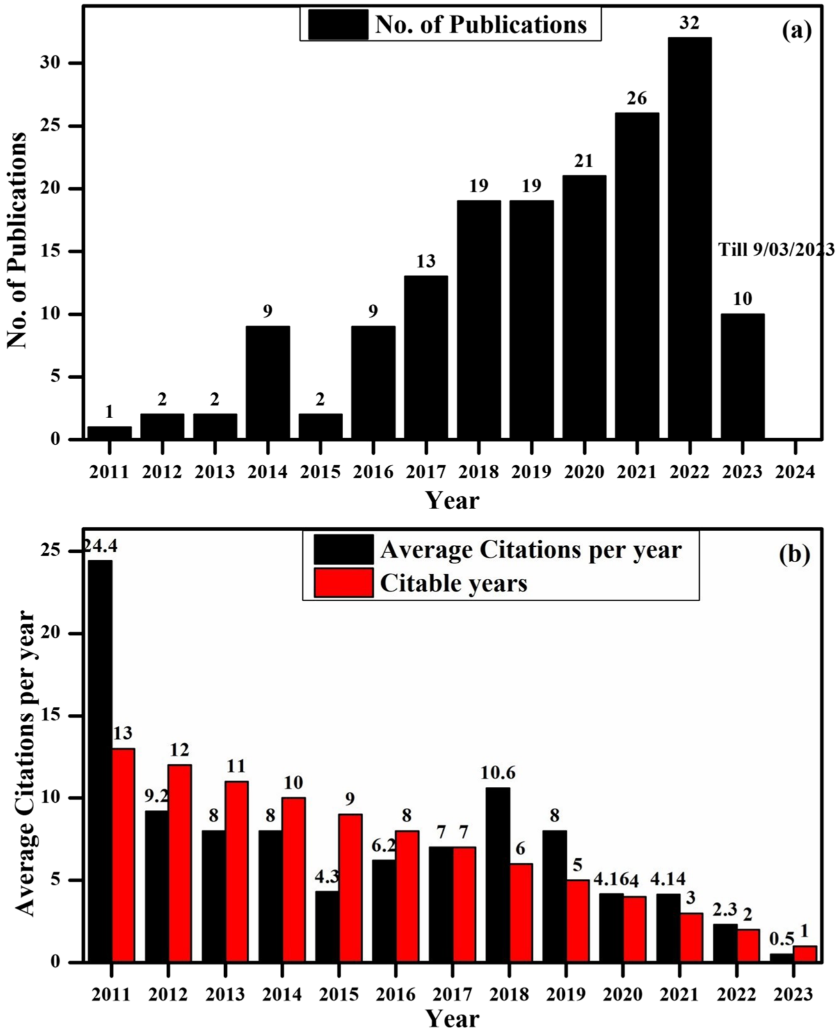


Fig. 4 Yearly publications and citations per article in aged biochar research during 2011 and 2023

3.2 Analysis of Primary Journals/Sources

According to our data, there have been 64 sources that have published on aging biochar in the previous 13 years. The data regarding the top 12 productive journals are presented in Table 1. Most of the productive journals are associated with European, England, and US journals. In terms of the total number of publications, *Science of the Total Environment* (25 publications) made the highest contributions to the number of publications, followed by *Chemosphere* (17 publications) and *Environmental Pollution* (14 publications), accounting for 15.15%, 10.30%, and 8.48% of the total number of publications (165). Regarding overall publications, there were no notable variances among the other journals.

It was interesting to note that in the field of aging biochar research, *Environmental Science and Technology* had a higher co-citation network than *Chemosphere* and *Science of the Total Environment* while having a far smaller total number of publications than *Science of the Total Environment*, which came in first, as illustrated in Fig. 5.

3.3 Network Mapping of Authors and Institutions

The co-authorship network map of authors was performed when three publications per author were chosen. The network map of authors comprised 61 authors who had 277 total link strength (TLS), resulting in 9 clusters. Nevertheless, due to overlap, several labels did not appear, as can be seen in Fig. 6. The top three productive researchers in the biochar aging field, according to research, were found to be Hailong Wang (Biochar Engineering Technology Research Center of Guangdong Province, School of Environmental and Chemical Engineering, Foshan University, Foshan, Guangdong 528000, China), Yuyan Liu (China University of Geosciences, Beijing), and Jiawei Chen (China University of Geosciences, Beijing), each with ten publications. Similarly, 90% of the institutions are Chinese, with only 10% each coming from Spain, Australia, England, and other institutions. The information on the top 10 productive authors and institutions is given in Table 2. Hailong Wang emerged as the most prolific author with 11 publications and 328

Table 1 The top 12 journals in aged-biochar-related research, as measured by the total number of articles from 2011 to 2023, are listed below

Rank	Journal title	Country	NP	IF	CS	HI	TC	PY	TLS
1	*Science of the Total Environment*	Netherlands	25	10.75	14.1	11	719	2016	2581
2	*Chemosphere*	England	17	8.94	11.7	11	647	2016	2368
3	*Environmental Pollution*	England	14	9.98	12.7	9	442	2017	1937
4	*Journal of Hazardous Materials*	Netherlands	8	14.22	14.7	5	319	2012	841
5	*Environmental Science and Pollution Research*	Germany	7	5.19	6.6	5	81	2018	894
6	*Environmental Science and Technology*	USA	5	11.36	14.8	4	549	2011	1139
7	*Geoderma*	Netherlands	5	7.42	11.1	4	109	2019	607
8	*Ecotoxicology and Environmental Safety*	USA	4	7.12	10.1	4	312	2018	235
9	*Journal of Agricultural and Food Chemistry*	USA	4	5.89	8.6	4	365	2014	643
10	*Journal of Agro-Environment Science*	China	4	Nil	1.6	2	8	2018	65
11	*Bioresource Technology*	England	3	11.88	17.4	3	86	2012	278
12	*Environmental Research*	USA	3	8.43	9.5	2	53	2020	300

NP, No of publications; *IF*, impact factor JCR-2021; *CS*, Scopus cite score-2021; *HI*, *h*-index; *TC*, total citations; *PY*, publication year start; *TLS*, total link strength

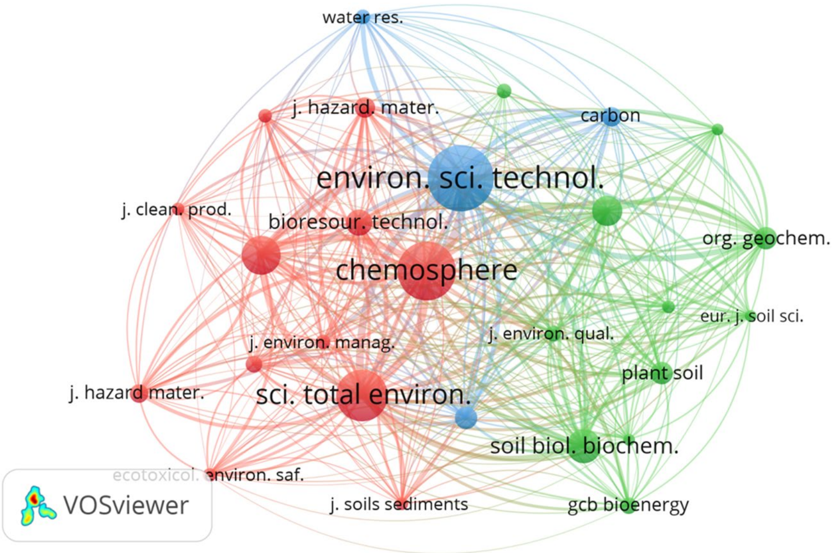


Fig. 5 The network map for journal co-citation of aging biochar studies between 2011 and 2023

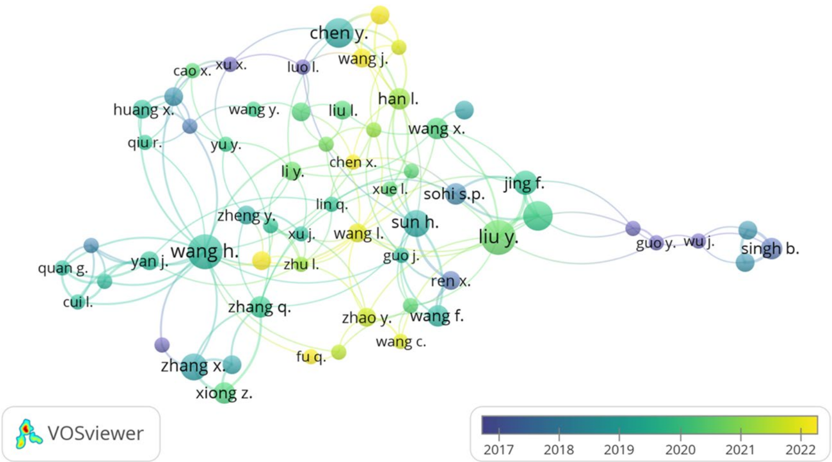


Fig. 6 The network map of co-authorship analysis of co-authors between 2011 and 2023 (frequency ≥ 3)

Table 2 Top 10 productive authors and countries in biochar-aging research from 2011 to 2022

Rank	Name	Country	Affiliation	NP	PY	TC	HI
1	Hailong Wang	China	Biochar Engineering Technology Research Center of Guangdong Province, School of Environmental and Chemical Engineering, Foshan University, Foshan, Guangdong 528000, PR China	11	2015	328	8
2	Yuyan Liu	China	State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, 100083, PR China	10	2018	256	8
3	Jiawei Chen	China	State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, 100083, PR China	8	2018	266	8
4	Yahua Chen	China	Nanjing Agricultural University, China	8	2012	102	5
5	Xi Zhang	China	Jiangsu Key Laboratory of Low Carbon Agriculture and GHGs Mitigation, College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing, 210095, China	7	2015	250	6
6	Haoran Sun	China	State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China	7	2016	206	6
7	Finqi Jing	China	State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, 100083, PR China	6	2018	234	6
8	Lucia Cox	Spain	Instituto de Recursos Naturales y Agrobiologıa de Sevilla (IRNASE-CSIC), Sevilla, Spain	5	2014	187	5
9	Balwant Singh	Australia	Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, Sydney, New South Wales, Australia	5	2014	406	5
10	Saran P. Sohi	England	UK Biochar Research Centre, School of GeoSciences, University of Edinburgh, Edinburgh, EH9 3FF, UK	5	2013	331	5

NP, no of publications; *HI*, *h*-index; *TC*, total citations; *PY*, publication year start

total citations, while the Biochar Engineering Technology Research Center of Guangdong Province, School of Environmental and Chemical Engineering, Foshan University, Foshan, Guangdong, China, was known for publishing the most documents. The second most productive author was Yuyan Liu, State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, China, with 10 publications and 256 citations.

3.4 Analysis of Countries Cooperating in Aging Biochar Research

The worldwide geographic location and co-authoring mapping knowledge domain of the producing countries are presented in Fig. 7. Research on aging biochar is being done in 38 countries globally regarding preparation, aging with biotic and abiotic variables, mechanisms research, and analysis of aging biochar usage in agro-environmental applications. China produced 107 scientific articles between 2011 and 2023, more than the USA (31) or England (14), or Australia (13).

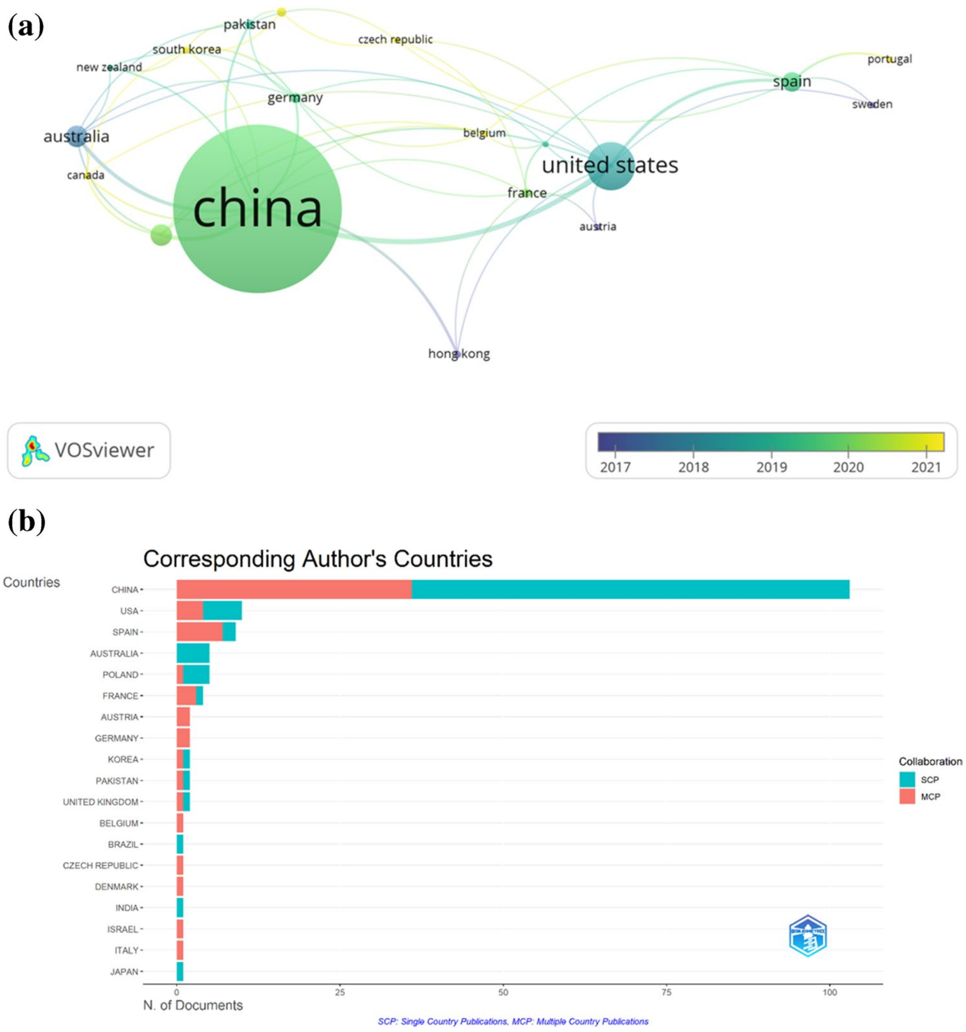
The node in Fig. 7a represents a distinct country, and the different colors correspond to the various clusters based on the co-authoring matrix of the associated countries. The size of the node represents the country's overall population and scientific outputs. The line's thickness, which connects two nodes, reveals how much their knowledge is collaborative. It could seem to reason that the stronger the connection between two nodes, the closer the two nations will interact and work together. China and the USA collaborate the most frequently, followed by the USA and Spain, China and Hong Kong, and China and Pakistan. There is no doubt that other countries have made significant contributions and worked together to advance aging biochar research, but future trends demand more diverse development and international cooperation.

The countries of the corresponding authors are represented in Fig. 7b, along with their collaboration. As can be seen, China is with the most corresponding author publications with single country publications (SCP) compared to multiple country publications (MCP). The USA is next with the same publication trend (SCP>MCP), followed by Spain (MCP>SCP), Australia with only SCP, Poland with SCP>MCP, France with (MCP>SCP), and Austria and Germany with only MCP.

3.5 Analysis of Keywords

The essential ideas, organizational framework, and frontier of the academic field of biochar or aging biochar can be described through the co-occurrence analysis of keywords. The line width of each node indicates the strength of its associations, and the keywords of related study areas are grouped with the identical colors (Qin et al., 2022). The five core clusters of aging biochar research are shown in Fig. 8a with 6558 links and total link strength of 16,952. The entire

Fig. 7 Mapping knowledge domain of **a** co-authoring and **b** corresponding-authoring countries in aging biochar-associated research



core clusters are interconnected and ascribed to (1) production and aging of biochar with biotic (microorganisms and organic molecules) and abiotic factors (freeze-thaw, temperature, moisture, chemical activation, etc.), (2) application of aging biochar for agro-environmental sustainability in terms of climate change mitigation (carbon sequestration in soil), enhancing nutrient (mostly nitrogen, phosphorus, and potassium) pools in soil, and contaminated soil remediation, (3) characterization (XRD, XPS, SEM, EDX, TEM, FTIR, etc.) of pristine and aging biochar, (4) mechanisms involved in the process of climate change mitigation, soil pollution remediation, and enhancing nutrient pool, and (5) overall crop production as confirmed by the TreeMap in Fig. 8b.

4 Discussion

This study identified a notable increase in research papers on aging biochar over the past decade, following international warnings to reduce the excessive use of synthetic chemical fertilizers and pesticides for maximum crop productivity. The excessive use of these agrochemicals and other unsuitable practices can harm the soil, water, and agricultural biodiversity (Kumari and Chauhan, 2023; Rahim et al., 2021). To address these challenges, countries, institutions, and research organizations have been promoting research and innovation in green, organic, and sustainable agriculture, aiming to develop new technologies and management systems (Hossain et al., 2023; Raihan, 2023; Xu et al., 2023). Sustainable agriculture strives to limit environmental harm while remaining economically viable, a challenging objective. To mitigate the detrimental impacts of land intensification, researchers are investigating several protective agricultural practices (Liu et al., 2023), and the application of biochar as a soil conditioner stands out as one of the sustainable, environmentally friendly, and green techniques (Dwibedi et al., 2023). While there is some disagreement on the short-term (fresh biochar) and long-term (aged biochar) effects of biochar on soil quality, it is evident that biochar significantly influences soil quality (Uras et al., 2012). This

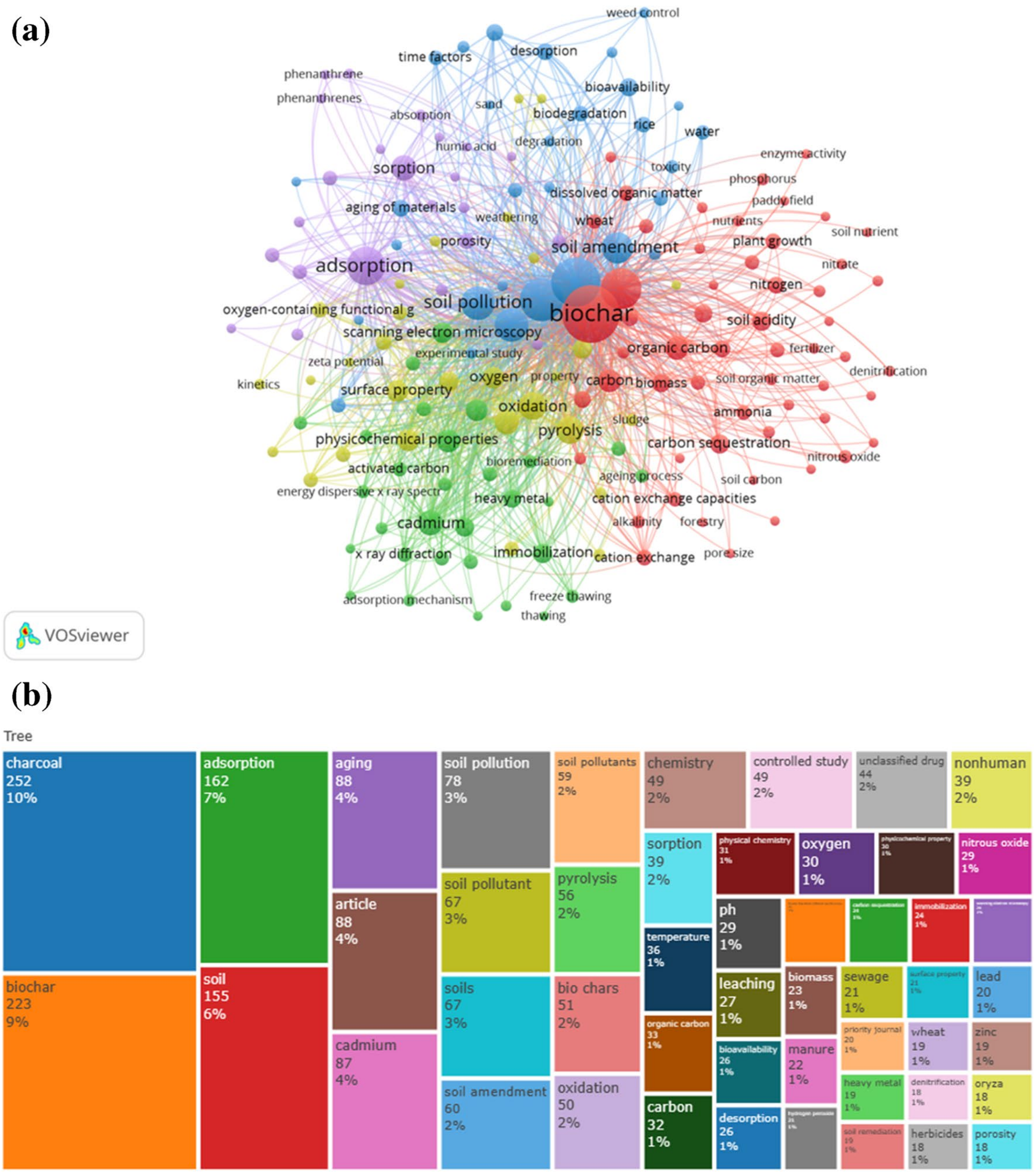


Fig. 8 Co-occurrence network of **a** keywords and **b** TreeMap in aging biochar research

study's data analysis focused on multiple aspects: (1) production and aging of biochar with biotic (microorganisms and organic molecules) and abiotic factors (freeze-thaw, temperature, moisture, chemical activation, etc.); (2) application of aging biochar for agro-environmental sustainability, encompassing climate change mitigation (carbon sequestration in soil), enhancement of nutrient pools in soil (mostly nitrogen, phosphorus, and potassium), and remediation of contaminated soil; (3) characterization of pristine and aging biochar; (4) mechanisms involved in climate change mitigation and soil pollution remediation; and (5) the primary research trend and hotspot in aging biochar research, focusing on overall crop production. According to the results of the current study, aging biochar production and development occur in three stages: the primary, medium, and fast growth phases.

In the primary growth phase (2011), just one excellent study was published in the *Journal of Environmental Science and Technology* by Hale et al. (2011), who found that activated carbon and biochar aged by physical, chemical, and biological processes demonstrated maximal sorption capacity for pyrene in soil and under harsh aging. The aging of biochar via physical, chemical, and biological processes mainly takes place by subjecting fresh biochar to alternating freeze-thaw and wet-dry cycles, treating biochar with chemical reagents, and incubating biochar with nutrient solutions, organic molecules, or microbes (Zeba et al., 2022). Commonly reported effects of biochar aging include a drop in pH, an increase in O content, and an increase in O-containing functional groups on the surface of aged biochar compared to un-aged biochar. This suggests that the aging of biochar, both naturally and artificially, causes changes to its elemental composition and surface chemistry. Furthermore, these changes have been shown to affect the properties of biochar, such as sorption and cation exchange capacity (Mia et al., 2017, Yi et al., 2020, Singh et al., 2016, Cheng et al., 2006).

Interest in aged biochar grew during the medium growth phase, prompting scientists to conduct more in-depth investigations on the characterizations. Singh et al. (2014) performed high-demand characterizations such as NEXAFS and XPS to gain insights into the surface functional groups of fresh and aged biochar. They reported that after 1 year of aging in soil, the carbon functional groups in biochars remained unchanged. However, after 2 years of aging, XPS results revealed a rise in carboxyl groups. In a similar study, Singh et al. (2016) utilized diffuse reflectance Fourier transform infrared (DR-FTIR) spectroscopy, X-ray diffraction (XRD), and chemical and isotopic analyses to characterize the light fraction of four contrasting soils (control and biochar amended soils) and determine changes in biochar properties after aging. The DR-FTIR spectra of the light fraction revealed discrete absorption bands reflecting native soil organic C, biochar C, and mineral components present in the soils. The mineral bands aligned with the XRD data of the four soils' clay fractions. Another study investigated the influence of fresh and aged biochar on water use efficiency and plant available water. The results indicated that biochar type and age have varying effects on plant available water and water use efficiency, suggesting that biochar amendments can improve soil water relations and crop development under water-limited conditions for some soils but not all (Aller et al., 2017).

In the fast growth stage, aged biochar research garnered remarkable attention and was extensively studied for various applications, including (1) the remediation of pollutants in soil and constructed wetlands (Khan et al., 2023), such as mercury (Zhang et al., 2019), aluminum, (Lin et al., 2018), cadmium (Jing et al., 2018), zinc (Kumar et al., 2018), copper (Gonzaga et al., 2020), lead (Raeisi et al., 2020), and herbicides (Gámiz et al., 2019b), (2) mitigation of greenhouse gases emissions such as nitrous oxide, carbon dioxide, and methane (Liao et al., 2021; Wang et al., 2021; Wu et al., 2019), (3) improved microbial and enzyme activities in soil (Yadav et al., 2019) and enhanced soil organic carbon content (Quan et al., 2020), and (4) nutrients availability and uptake by plants (Karimi et al., 2020) and ultimately, plant growth (Haider et al., 2015; Rahim et al., 2020). Wang et al. (2024) conducted a pot experiment to explore the effects of fresh biochar (FBC) and freeze-thaw cycled aged biochar (FTC-BC) on di(2-ethylhexyl) phthalate (DEHP)-contaminated soils. After freeze-thaw cycles, the specific surface area of FBC increased from 145.20 to 303.50 $m^2 g^{-1}$, and the oxygen-containing functional groups increased from 1.26 to 1.48 mol g^{-1}, considerably improving DEHP adsorption in the soil. FTC-BC outperformed FBC in terms of protecting normal pak choi plant growth and enhancing soil properties. Furthermore, biochar treatment increased the diversity and number of bacteria in DEHP-contaminated soil and altered the composition of the soil bacterial community. Similarly, several studies reported that biochar aging improved the physical properties of soil by decreasing bulk density, increasing porosity, improving aggregation, and enhancing water retention. Soil chemical parameters such as pH, cation exchange capacity, organic matter, soil carbon sequestration, soil nutrient content, and soil biological properties were also found to be improved. These changes in soil physiochemical and biological characteristics enhance soil fertility, plant growth, and development (Murtaza et al., 2023, Xia et al., 2023, Yue et al., 2023, Nyambo et al., 2023, Védère et al., 2023).

5 Conclusions

In the present work, the data from the Scopus database was extracted to conduct a bibliometric analysis of aging biochar. A total of 165 documents have been reported, with the first aging biochar article published in 2011. The majority of these documents—roughly 70%—had been published during the previous 3 years, and almost all of them—about 95%—were original research articles. According to a keyword analysis, the most popular method for producing biochar is pyrolysis, while the primary processes for aging biochar are freeze-thawing and natural weathering. Furthermore, aging biochar was primarily used to improve soil nutrient pools, remediate contaminated soil, promote plant growth, and mitigate climate change (carbon sequestration in soil). Hailong Wang emerged as the most prolific author, while China was known for publishing the most documents. The authors' extensive network connections reflect well-established international scientific communication channels. *Environmental Science and Technology* received the most citations, while *Science of the Total Environment* published the most documents.

6 Significance of the Study and Future Research Trend

This study's analysis of the aging biochar research trend for agro-environmental applications has significant implications for various stakeholders and academic disciplines. This study promotes the implementation of sustainable agricultural practices concerning the Sustainable Development Goals of the United Nations about climate change, sustainable agriculture, and environmental sustainability by concentrating on aging biochar, a particular type of biochar. The results show how aging biochar can help with urgent agro-environmental issues such as carbon sequestration, soil nutrient dynamics, and restoration of multi-polluted soils and sediments. The paper also identifies prospective research areas, promoting multidisciplinary cooperation and promoting the use of various biomass resources. Overall, this novel data-driven bibliometric analysis offers insightful information about the research possibilities and future potential of aged biochar for agro-environmental applications making it relevant to academics, decision-makers, and professionals looking for efficient and eco-friendly approaches to sustainable agricultural development. However, there are still some gaps in the literature that are crucial to be addressed in the future:

(1) Application-specific aged biochar can be prepared, tested in complex soil systems, and screened for predicting the life-cycle environmental impact of aged biochar using improved machine learning models, e.g., artificial intelligence, data-driven machine learning, and artificial neural network modeling.
(2) Life cycle assessment (LCA) is crucial to guarantee agro-environmental sustainability, determine the fate of aged biochar compared to fresh biochar, and determine potential ecological and health effects.
(3) Even if the study has examined the bibliometric analysis of all the crucial links of aged biochar, there are still ways to further its promotion. There is a tremendous opportunity for doing an in-depth research due to the different activation and aging variables and processes that affect biochar.
(4) Future bibliometric analyses might also look at the trends of a wide range of feedstocks used to make raw biochar to recommend suitable biomasses rich in lignocellulosic molecules for the development of high-yielding aged biochar that is suitable for a particular use.
(5) It is critical to understand how the effects of aging biochar on soil quality and plant growth compared to those of fresh biochar. To gain an in-depth understanding of its effects, we plan to do a meta-analysis of the 165 publications' data currently provided in this bibliometric data analysis.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest The authors declare no competing interests**.**

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