



Emerging research trends on biochar application in agriculture: A scientometric analysis

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ABSTRACT

The Sustainable Development Goals (SDGs) are a comprehensive action plan for achieving world prosperity and environmental sustainability. Using biochar, a renewable and low-cost carbonaceous material produced from biomass waste, is an eco-friendly and clean technology to enhance soil health and address the energy crisis in agriculture. Hence, a comprehensive study of scientometric analysis of the use of biochar in agriculture was carried out using scientific literatures. Based on information collected from the Web of Science (WoS) database between 2001 to 2021, this work performed bibliometric visualization analysis using appropriate data sets of keywords to examine the new research trends on the application of biochar in agriculture. The number of scientific research examining the use of biochar in agriculture has significantly increased in recent years. A total of 4194 publications related to the use of biochar in agriculture were identified from the 2001 to 2021. Based on scientific data (WoS), the progress of biochar research was visualized using co-occurring analysis to identify the current scientific research trends, technological impact, and research gaps related to biochar. The scientometric study indicated that among the top 20 nations, the highest publication (44%) on biochar was produced by the People's Republic of China (PRC), followed by the USA (16%) and Australia (7%). Results showed that the majority of scientific research and development on biochar application in agriculture were accelerated after 2010 and the total research output in terms of publications was significantly increased from 42 (2010) to 882 (2021). The People's Republic of China (PRC), the United States, and Australia have published the most of the studies in the field of biochar. This paper aims to provide a thorough overview of scientific developments on the use of biochar in agriculture, notably during the past few years.

1. Introduction

Biochar is a solid organic residue formed from the pyrolysis of biomass (Jha et al., 2016; Awad et al., 2018; Oni et al., 2019). There are different types of biochar produced depending on the feedstock type and pyrolysis conditions (Brewer et al., 2014; Meyer et al., 2017; Oni et al., 2019; Wu et al., 2020; Janu et al., 2021; Hagemann et al., 2018; Verma

et al., 2023; Babu et al., 2023). There are different methods for biochar production, which include slow and fast pyrolysis, gasification, flash carbonization, hydrothermal carbonization, and torrefaction. Generally, slow pyrolysis and hydrothermal carbonization were the most popular techniques for biochar fabrication (Wu et al., 2020). Biochar is a highly porous and lightweight substance that reduces the bulk density of soil and improves the aeration and water-holding capacity of the soil.

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Biochar also acts as a soil-conditioners and liming agent which can partially replace the need for agricultural lime. When is incorporated into the soil to enhance soil quality through increasing natural rates of carbon sequestration rates (Jha et al., 2016). The application of biochar has gained in popularity in recent years as it is effective in amending acidic soils, impoverished soil by improving nutrient content and sequestering carbon (Jha et al., 2016). Biochar retains water holding capacity, increases soil pore space and soil microbial activities, and prevents the emissions of carbon dioxide and other greenhouse gases (Yu et al., 2018; Gurav et al., 2020). Biochar has the potential to solve various challenges such as biomass management, promoting renewable energy, enhancing crop productivity and quality, and mitigating the effects of climate change. Various studies showed that biochar application can also improve the nutrient-holding capacity of soil by reducing leaching losses of nitrate and phosphorus (Laird et al., 2010; Ahmad et al., 2014; Hussain et al., 2017; Yu et al., 2018; Gurav et al., 2020; Hossain et al., 2020). The application of biochar in agricultural soil also improved the response to fertilizers, especially N and P (Asai et al., 2009); moreover, it can also improve soil quality including increase in pH, organic carbon, and exchangeable cations as well as a decrease in tensile strength when applied at higher rates (Chan et al., 2007; Jha et al., 2010). According to reports (Steiner et al., 2016; Van Zwieten et al., 2010), applying biochar to acidic soils causes an increase in pH and a corresponding decrease in exchangeable Al.

There are several techniques for making modified biochar, including physical (ball milling, microwave, etc.), chemical (acid, alkali, and nanoparticles, etc.), and biological (using enzymes and bacteria, for example immobilization of microorganisms, anaerobic digestion etc.) (Wang et al., 2017, 2019; Wu et al., 2020). According to the investigation, tailored biochar made by physical or chemical alteration did a good job of adsorbing and degrading contaminants from soil and wastewater while also lowering their bioavailability (Trakal et al., 2018). There aren't many studies on biochar formed through biological modification. It is anticipated that biochar's use in wastewater treatment and soil remediation will increase with the development of microbial immobilization technologies. Before 2018, its practical application and laboratory investigations had not yet been summarized prior to 2018 (Wu et al., 2019, 2020).

Biochar used as both an adsorbent and a catalyst for a wide range of pollutants while also contributing to a reduced carbon footprint (Babu et al., 2023). It has garnered significant interest in the bio-based industry, which focuses on converting raw materials into value-added chemicals and energy. Soodesh et al. (2024) evaluated the potential of biochar and activated carbon derived from agricultural residues as catalysts for biodiesel production. Additionally, biofuels and gases produced from biochar hold promise as sources of green energy (Babu et al., 2023). The combined application of various biochar materials offers diverse benefits, including use as soil amendments, water filtration agents, livestock feed additives, pharmaceutical components, and sources of energy (Bartoli et al., 2022). The porous nature of biochar enhances its ability to trap contaminants, leading to improved water quality (Jeyaraj et al., 2024).

Biochar can remove inorganic and organic pollutants due to its unique properties, such as high cation exchange capacity, high surface area and non-carbonized fraction combined with surface oxygen-rich functional groups. The functional groups of biochar derived from pine-needles as determined through Boehm titrations showed the removal of acidic functional groups such as carboxylic, phenolic, and lactones, while there was accumulation of basic functional groups such as ketones, pyrones, and chrome (Ali et al., 2017). Because of the presence of these and other functional groups in biochar, it is a viable and cost-effective option for removing toxins and pollutants from soils and water via sorption.

Biochar can be effectively utilized in animal production both as a feed additive and as a bedding material, offering multiple benefits. As a feed additive, biochar has been shown to enhance animal nutrition when

included in blended feed formulations. It improves feed digestibility, reduces enteric methane emissions, and supports better growth performance across various livestock species (Ayeshet & Temesgen, 2025). When applied as a bedding material, biochar helps regulate moisture, minimizes odor and ammonia volatilization, and improves the quality of composted manure (Dittmann et al., 2024).

Even though the numerous advantages of using biochar in various sectors have been demonstrated during the past 20 years (2001-2021), little research has been done on any unforeseen repercussions (He et al., 2019; Wu et al., 2020; Wu et al., 2021). Biochar has been shown to release polycyclic aromatic hydrocarbons (PAHs), hazardous hydrophilic degradable compounds and heavy metals toxic metals into the environment despite having low bioavailability and ecotoxicity (Wang et al., 2019). Furthermore, the adverse impacts of persistent free radicals (PFRs) present in biochar generated by the pyrolysis process limit the widespread use of biochar (Liao et al., 2014). To optimize biochar's use in many sectors in the future, it is necessary to investigate its effects on the environment and human health. Although several reviews have thoroughly explored biochar research, relatively few have looked into how biochar synthesis, study, and use have evolved (Wu et al., 2019; Wu et al., 2020; Wu et al., 2021). Identifying the current research horizons will be made easier by summarizing the research on biochar application. It is crucial to continue summarizing the development of biochar research beyond 2023. The purpose of this study, which was designed to analyse the trends on biochar application in agriculture, includes; i) Mapping of keyword analysis on the use of biochar in agriculture, ii) Profile the patterns in research networks at many levels, including authors, institutions, nations, and funding sources.

2. Materials and methods

2.1. Acquisition of data and search strategy

This scientometric study analyses national and international research collaborations on biochar application in agriculture using bibliometric methodology. Among the current databases of research publications, Web of Science (WoS) has been used for the collection of data for this study (Fig. 1). The Clarivate Analytics website, *i.e.*, Web of Science (WoS), is a Clarivate Analytics tool, that provides access to several publication databases (Li et al., 2018; Birkle et al., 2020; Pranckute et al., 2021). Before moving forward to the search engine, a critical analysis has been done on the keywords which will be used for collection of data. The keywords were selected in such a manner that neither unnecessary documents appeared nor relevant documents were missed. Keeping these on mind, the following keywords have been selected: biochar, biocarbon, pyrolysis, soil, agriculture, mineralization, plant, crop, GHGs and climate. From the mentioned keywords, we have formulated the search criteria such as: TI= (biochar OR biocarbon OR pyroly*) AND TS= ((Soil OR agriculture OR Mineralization OR plant OR crop) OR (GHG OR Climate change)) with filters Document Types: (Article) and Duration: 2001-2021. This main rationale behind duration filter is that since the number of research papers on the use of biochar in agriculture was in single digits in 2001 as compared to 2021 were in three digits, therefore 2001 year was chosen as the beginning point for scientometric analysis. After the collection of publication data from the WoS, the data cleaning steps have been implemented. In data cleaning steps, the unnecessary and irrelevant publications have been eliminated. Data cleaning excluded 239 publications and 4194 publications remained for the bibliometric analysis. The eliminated publications included book chapters, proceedings, review articles and irrelevant documents. The keyword selections, search criteria and data cleaning have been done based on the work domain, author opinions, and subject matter expertise. The bibliometric analysis and data visualisation have been done using WoS, Biblioshiny R-package and VoS Viewer software with selected publications. The publishing trends, top countries, top institutes, highly cited journals, top authors, and top funding agencies

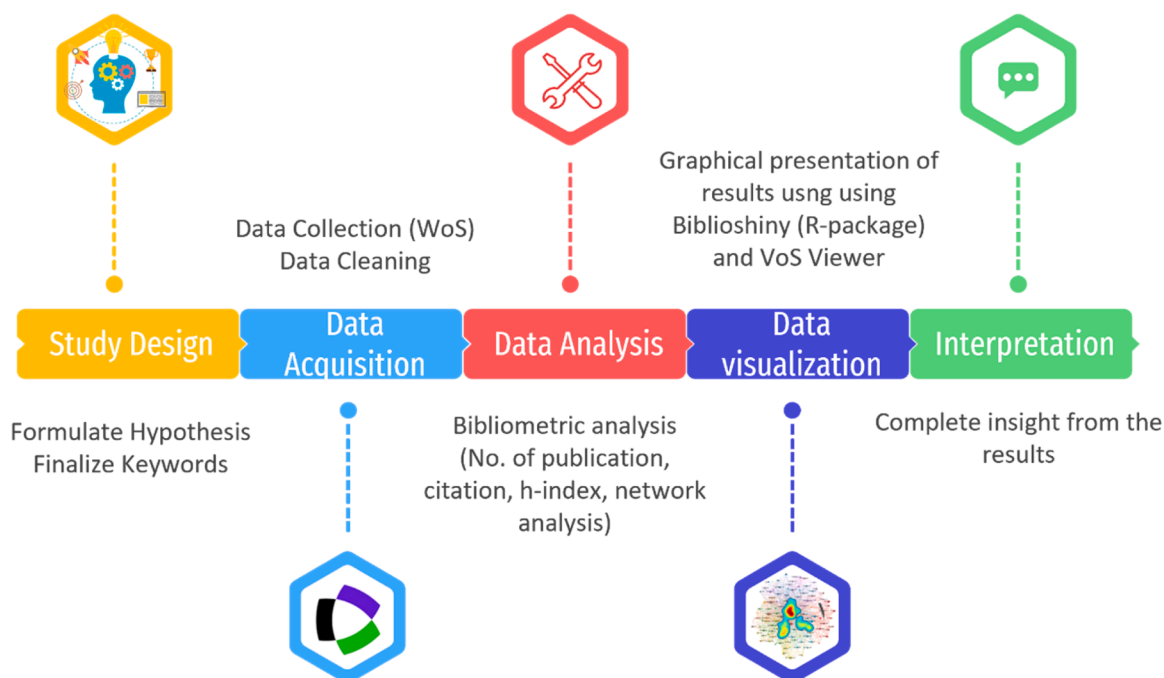


Fig. 1. Flowchart of the steps followed during the study.

and organizations during the past two decades have also been analyzed to determine the present status of this topic. In citation analysis, the total number of publications (TP), total citations (TC), average article citations per paper (ACPP), without-self citation, (WSC), h-index, and collaborating nations were calculated using WoS citation analysis. After the data analysis and data visualization, a valid and scientifically sound interpretation has been drawn to conclude about the present status and future scope of the research area “Application of Biochar in Agriculture”. The “marked list” of WoS was compiled with relevant information. The information obtained from the WoS databases were downloaded in text files, and each entry had the scientometric details.

2.2. Network analysis

Utilizing metadata obtained from the WoS, the keyword occurrence maps were created using bibliometric visualization analysis software VOS viewer version, <https://www.vosviewer.com/> (McAllister et al., 2022; Van Eck et al., 2010). In general, bibliometric network analysis is effective tool for construction of a network based on the relationships among top countries, journals, leading institutions, authors, and keywords related to find out the emerging trends in respect to biochar application in agriculture (Chen et al., 2016).

3. Results and discussion

3.1. Keywords performance

A study that co-occurs with another one may shed light on the basic ideas behind a particular line of investigation. The co-word analysis is a powerful method for identifying and expressing the connections between different research perspectives (Chen et al., 2016; Wang et al., 2012). The co-word analysis was a methodology that was based on the idea that the co-occurrence of keywords reveals the overall content of the articles. One technique for analyzing the co-occurrence of keywords and the co-word matrix was overlay visualization (Lee and Su, 2010; Liu and Mei, 2016). The idea of “keyword overlay visualization” illustrated the examination of the keywords’ co-occurrences in scientific publications made throughout the research period. In this study, various

colored networks in various sizes were developed (Fig. 2). The circumference of the circle indicates how well other keywords can build networks. The most prevalent subset of keywords, including biochar, carbon sequestration, pyrolysis, soil amendment, soil quality, soil organisms, charcoal, toxic metals, soil remediation, bioavailability, adsorption, and immobilization, etc. The prominence of keywords over time throughout particular times has been illustrated using overlay keyword visualization (Fig. 2). It is based on the number of times a keyword has been cited overall and how often it appears in papers produced in a typical year. For this study, we created an overlay visualization using the total number of citations per document published in a given year. The colorful networking represented the total citations on keywords related documents.

3.2. Research output on biochar over the years

The data with respect to total publication (TP), % total, total citation (TC), average citation per paper (ACPP), h-index, and without self-citation (WSC) on status of research on biochar over the globe between 2001-2021 was presented in Table 1. The data showed that initially the total publications on biochar research was not much (2001-2009). After 2010 the research on agricultural application of biochar gains the pace, as result the TP was improved instantaneously from 42 (2010) to 882 (2021). This was due to increasing interest of researchers on utilizing biochar as an eco-friendly amendment for remediation of agricultural soils, adsorbent, carbon sequestration and for mitigation of negative impact climate change (Wu et al., 2020; Wang et al., 2018). The Table shows that out of all TP during 2001-2021, the total TP was improved to 21.03% during 2021 from 0.19% during 2001 except decreasing trend during 2003 by 0.17%. Kamali et al. (2020) in scientometric analysis of research on biochar revealed that the publication related to biochar as an amendment was started since the 2000s but till 2008 there was no significant growth in PT. Further, they observed that after 2010, it gains rapid growth. Similarly, Li et al. (2018) observed the similar trend in biochar research. This revealed that the global researchers did not realize the importance of biochar for sustaining agricultural production under the era of global environmental pollution and energy crises situation. The remarkable increase in TP after 2017 to

Table 1

Publication and citation status of research on biochar over the years (2001–2021).

Years	TP	% Total	TC	ACPP	h-index	WSC
2021	882	21.03	4142	4.70	21	3697
2020	708	16.88	9403	13.28	42	9090
2019	566	13.50	10991	19.42	44	10818
2018	462	11.02	12785	27.67	57	12655
2017	339	8.08	12057	35.57	54	11954
2016	313	7.46	15342	49.02	66	15243
2015	245	5.84	11433	46.67	63	11371
2014	227	5.41	16865	74.30	74	16740
2013	125	2.98	10893	87.14	57	10866
2012	86	2.05	9511	110.59	51	9487
2011	85	2.03	12415	146.06	50	12390
2010	42	1.00	11043	262.93	28	11031
2009	28	0.67	3779	134.96	21	3778
2008	12	0.29	724	60.33	9	724
2007	18	0.43	2209	122.72	11	2209
2006	12	0.29	478	39.83	9	478
2005	8	0.19	266	33.25	7	266
2004	8	0.19	330	41.25	7	330
2003	7	0.17	448	64.00	5	448
2002	13	0.31	200	15.38	8	199
2001	8	0.19	120	15.00	3	120

(PRC) contributed the highest percent of the total publications and h-index, but the Average Citation Per Publication (ACPP) is comparatively less and the record of 75.54 was recorded in New Zealand, followed by Australia, England, USA, Germany, South Korea, and Spain with an ACPP score of 69.3, 52.8, 51.55, 51.1, 43.4, and 43.2, respectively. Moreover, the People's Republic of China (PRC) is the highest contributing country in terms publication on biochar application to improve soil parameters and their impact on crop productivity and their citation and h-index. However, the impact of the USA, Australia, and Germany is also equally important on biochar research as these nations also have contributed more than 10,000 total citation in-terms of their quality research papers on different aspects of biochar (Kamali et al., 2020). Furthermore, the results indicate that much evidences of publications on biochar application and their positive impact on soil quality, water use efficiency and weed control and crop productivity are available in different parts of the world (Semida et al., 2019).

In this study, we examined the countries' cooperation based on how frequently they worked together. China demonstrated the highest levels of collaboration with the USA, Australia, Pakistan, Germany, and other nations during the study period. Country associations were depicted by colored lines (Fig. 3). Applying biochar had a number of beneficial

effects, including raising crop yield and soil fertility, lowering heavy metal contamination in soil and GHGs emissions (O'Connor et al., 2018; Mansoor et al., 2021; Blanco-Canqui, 2021; Shakoore et al., 2021). However, the impact of biochar is very site-specific. Obviously, producing and using biochar is not a panacea for all issues with the environment, soil, and food security, but it is a valuable material that requires more focus in order to meet different environmental objectives. Therefore, it is necessary for researchers from around the world to work together and conduct important studies on biochar.

3.4. Leading institutions/organizations in the biochar research

The top ten contributing institutes and organizations are listed in Table 3 and they are publishing research paper very frequently on different aspects of the biochar research. Based on paper publications, total citation and h-index, the top 10 institutes are ranked in order to find out the contribution of institutes in terms of biochar research. Impressive research finding of this analysis revealed that among the top ten organizations, 7 most prolific and productive institutions are from the Peoples Republic of China (PRC), and each institute are belongs to the USA, Egypt and Pakistan. Results indicated that another intriguing finding also appeared to be that the majority of biochar-related research appears to be concentrated in Asian Countries particularly in China. The total publications on biochar-based study have received between 17206 and 2751 citations overall of different organizations. The scientometric analysis indicated that among the top 10 institutes, Chinese Academy of Sciences from China was ranked first in the contribution of the total publication (418), total citations (17206) and h-index (65) on different aspect of biochar and contributed almost 10% of the total publications on biochar and followed by the United States Department of Agriculture (USDA) from USA which contributed about 163 total publication and 9602 total citations with the highest Average Citation Per Publication (58.91) and with self-citation (9286). Besides, the university of Chinese Academy of Sciences (TC, 6641; ACPP, 48.83; h-index, 43; WSC, 6465), Nanjing Agricultural university (TC, 6275; ACPP, 47.90; h-index, 43; WSC, 5968) and Institute of soil science (TC, 5640; ACPP, 45.85; h-index, 35; WSC, 5429) also prominently focused on biochar-based research. The findings show that these institutions contributed more than any other organization to the study of biochar and its effects on the quality of soil and crops. The data on biochar-based systems serves as a useful indication of current institutional development research and highlights the patterns of influence and collaboration among them.

The Fig. 4 presents a country-wise collaboration network in biochar research over the last two decades, based on co-authorship patterns from

Table 2

Top 20 countries who published research papers on biochar during last two decades.

Rank	Countries	TP	%Contribution	TC	ACPP	h-index	WSC
1	Peoples R China	1834	43.73	56034	30.55	105	45850
2	USA	687	16.38	35413	51.55	89	33366
3	Australia	305	7.27	21134	69.29	70	20072
4	Germany	261	6.22	13342	51.12	59	12753
5	Pakistan	273	6.51	7812	28.62	48	7240
6	Spain	222	5.29	9597	43.23	47	9193
7	Canada	182	4.34	5201	28.58	40	5032
8	India	159	3.79	3722	23.41	35	3498
9	South Korea	169	4.03	7333	43.39	52	6968
10	Egypt	145	3.46	3782	26.08	36	3519
11	England	133	3.17	7022	52.80	41	6891
12	Italy	144	3.43	5580	38.75	39	5377
13	Brazil	142	3.39	2930	20.63	29	2811
14	Saudi Arabia	123	2.93	3434	27.92	32	3262
15	Iran	107	2.55	1190	11.12	17	1102
16	Poland	103	2.46	1907	18.51	25	1789
17	France	97	2.31	3117	32.13	32	3012
18	Japan	81	1.93	2963	36.58	22	2911
19	New Zealand	72	1.72	5439	75.54	29	5327
20	Turkey	71	1.69	1523	21.45	21	1453

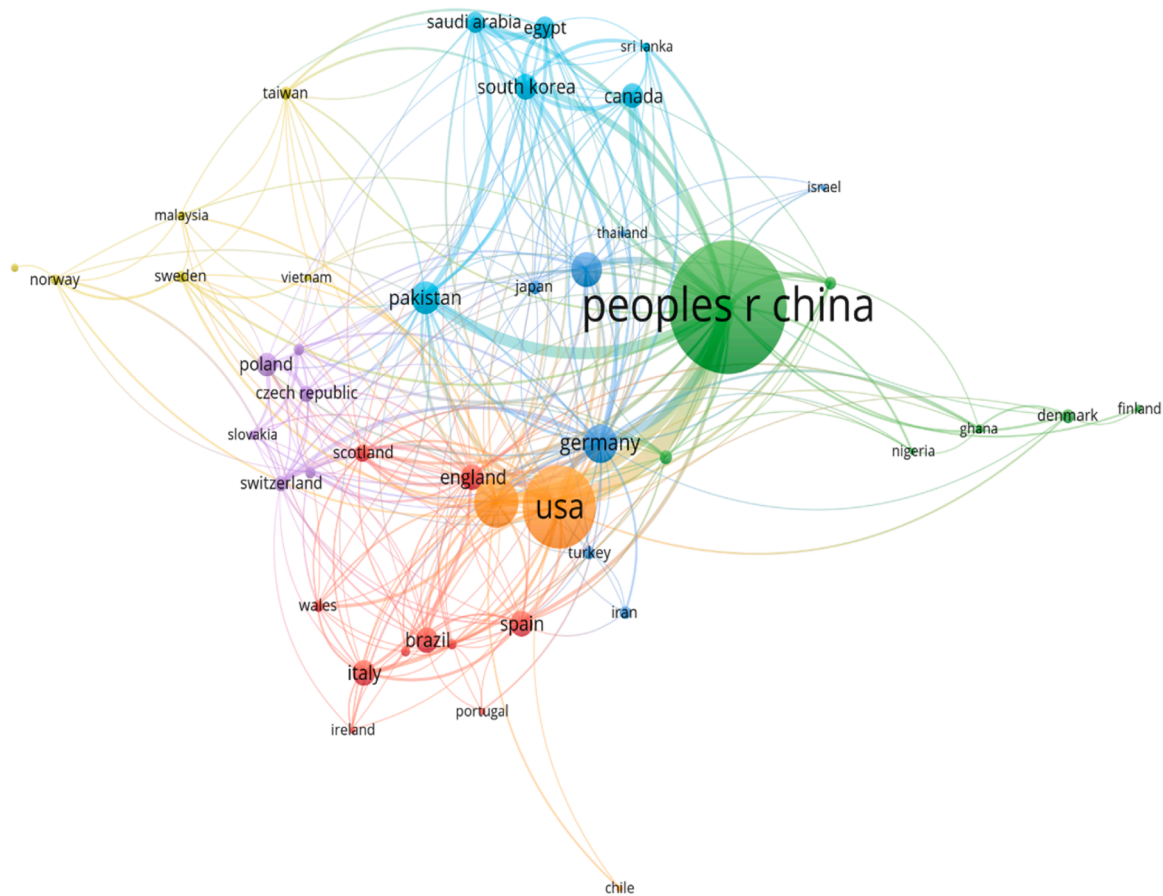


Fig. 3. Geographical collaboration between countries during the study (2001-2021) and the colored scale represented the frequency of articles published by various countries.

Table 3

Top 10 institutes/organizations who published research papers on biochar during last two decades.

Rank	Institute	TP	%Contribution	TC	ACPP	h-index	WSC
1	Chinese Academy of Sciences	418	9.97	17206	41.16	65	16281
2	United States Department of Agriculture, USDA	163	3.89	9602	58.91	41	9286
3	Egyptian Knowledge Bank EKB	143	3.41	3731	26.09	36	3469
4	University of Chinese Academy of Sciences, CAS	136	3.24	6641	48.83	43	6465
5	Chinese Academy of Agricultural Sciences	134	3.20	3235	24.14	31	3092
6	Nanjing Agricultural University	131	3.12	6275	47.90	43	5968
7	Zhejiang University	124	2.96	4756	38.35	36	4616
8	Institute of Soil Science, CAS	123	2.93	5640	45.85	35	5429
9	Northwest A F University China	104	2.48	4193	40.32	30	4057
10	University of Agriculture Faisalabad	92	2.19	2751	29.90	28	2635

scientific publications. Each node represents a country, with the size of the node corresponding to the volume of publications from that country. Edges between nodes indicate research collaborations, where thicker edges represent stronger cooperation between two countries. China is the most dominant country in biochar research. It serves as a central hub in the network, with strong collaborations with multiple countries, particularly the USA, Australia, and European nations. The USA follows as the second-leading contributor. It has significant collaborative ties with China, the United Kingdom, and Canada. Australia has formed a robust research network with China, the USA, and European countries, reflecting its active role in agricultural and environmental applications of biochar. Canada, Brazil, and India are emerging players, with growing research output and strong partnerships with major research hubs. If examine the regional research clusters, many strong regional collaborations can be noticed. China, India, South Korea, and Japan form a regional network, with China acting as the main hub. Germany, France,

the UK, and the Netherlands show strong intra-European research partnerships while also collaborating with China and the USA. The USA, Canada, and Brazil display close collaboration. Australia and New Zealand have a strong research collaboration, with connections extending to China and the USA.

The authors contributions to scientific publications related to use of biochar for soil amendment and their results of the scientometric parameters analysis are depicted in Table 4. Among the top leading authors in the field of biochar research, the ‘Ok YS’ (Yong Sik Ok) from South Korea is contributing the highest the Total Publications (TP, 84), total citations (5479) and h-index (44). However, ‘Joseph S’ from Japan is the top performer globally in the field of biochar research in terms of total citation (TC, 6417), Average Citation Per Publication (ACPP, 164.54) and with self-citation (WSC,6340). The results indicated that ‘Ok YS’ and ‘Joseph S’ both are actively involved in the field of biochar research and their work on biochar preparation, application as soil

Table 5
Top 10 highly cited journals on biochar during last two decades.

Journal	TP	% Contribution	TC	ACPP	h-index	WSC
Science of The Total Environment	320	7.63	11091	34.66	57	10654
Chemosphere	186	4.43	10258	55.15	55	9990
Environmental Science and Pollution Research	148	3.53	3391	22.91	28	3299
Geoderma	117	2.79	7698	65.79	43	7482
Journal of Soils and Sediments	111	2.65	3451	31.09	31	3352
Agronomy Basel	96	2.29	806	8.4	15	744
Journal of Hazardous Materials	90	2.15	3164	35.16	30	3091
Environmental Pollution	85	2.03	3699	43.52	30	3638
Journal of Environmental Management	81	1.93	2561	31.62	29	2533
Soil Biology Biochemistry	77	1.84	9159	118.95	42	8963

which Netherland and United Kingdom each occupies 30% of journal published. Li et al. (2018) studied the comprehensive scientometric approach in biochar research from 1998 to 2017 found that United Kingdom occupies first place, taking up 40.0% journal publication. All the top ten journal publishing countries are developed countries, which indicate that developing countries has go long to bring the top journal that can publish research papers on biochar research. As regard to TC, h-index and WSC the top three journals followed the sequence as Science of the Soil Biology and Biochemistry (9159, 57 and 10654) > Chemosphere (10258, 55 and 9990) > Science of the Total Environment (11091, 42 and 8963). In contrast to this although Soil Biology Biochemistry contributed least TP; but still the journal is at third position with respect to TC, h-index and WSC still it occupies first position with respect to ACPP (118.95).

Based on the analysis of results top 10 research supporting/funding institutes are identified. It is observed from Fig. 5 that these top 10 funding institute supported about 1974 research publications. The National Natural Science Foundation of China (NSFC) alone supported 1089 (55.17 %) publications in the field of biochar research and being on top among all other institute. The National Key Research and Development Program of China and Fundamental Research Funds for The Central Universities are second and third major funding institute for

the biochar research respectively. These three institutes are followed by European Commission (108, publications), China Postdoctoral Science Foundation (80, publications), United States Department of Agriculture USDA (79, publications), National Basic Research Program of China (74, publications), Chinese Academy of Sciences (73, publications), Spanish Government (69, publications), China Scholarship Council (69, publications) in the funding direction of biochar research. These results are based on the data collected from Web of science may have some difference in funded publication and rank of funding institute as the funding source may appear with some changed names (in form of abbreviation, punctuation and format) at other places or databases (Begum and Lewison, 2017).

3.6. Highly cited studies on on biochar

The frequency of citation of research paper is the most important tool to assess the impact and quality of the research. Table 6 depicts the highly cited research papers that have been published on biochar over the past two decades. It showed that the research article entitled ‘Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)’ authored by Keiluweit et al. (2010) published in Environmental Science and Technology was found most cited article in Clarivate Web of Science (WoS) (1722) and Google Scholar (GS) (2004). The article’s primary focus was on characterizing aromatic carbon in biochar formations at the molecular level. The research area with the highest citation implies that the scientific community is interested in studying biochar at the molecular level, which has resulted in the publication of several research articles in a related field of biochar research. During the similar time, researchers also start to use the biochar as sustainable management option for climate change mitigation. The research paper entitled ‘Sustainable biochar to mitigate global climate change’ authored by Woolf et al. (2010) published in Nature Communications was found most cited article in WoS (1276) and GS (1386). Thereafter, several researchers documented the potential environmental benefit of biochar due to removal atmospheric carbon dioxide for longer period. Furthermore, the researchers also explored the aspects of soil fertility and ameliorative benefits of use of biochar in agriculture. Among the top cited articles published on this aspect, the research papers authored by Chan et al. (2007) and Van Zwieten et al. (2010) receive the most citation 1098, 1078 and 1271, 1192 citation as found in WoS and GS respectively. Later on, similar area of research has gained the momentum as many research publications got tremendous citation. For example, Yuan et al. (2011) (WoS- 1070 and GS- 1333), Zimmerman et al. (2011) (WoS- 864 and GS- 954), Novak et al. (2009) (WoS- 787 and GS- 977), Beesley et al. (2010) (WoS- 768 and GS- 866), Laird et al. (2010) (WoS- 757 and GS- 940) and Laird et al. (2010) (WoS- 739 and

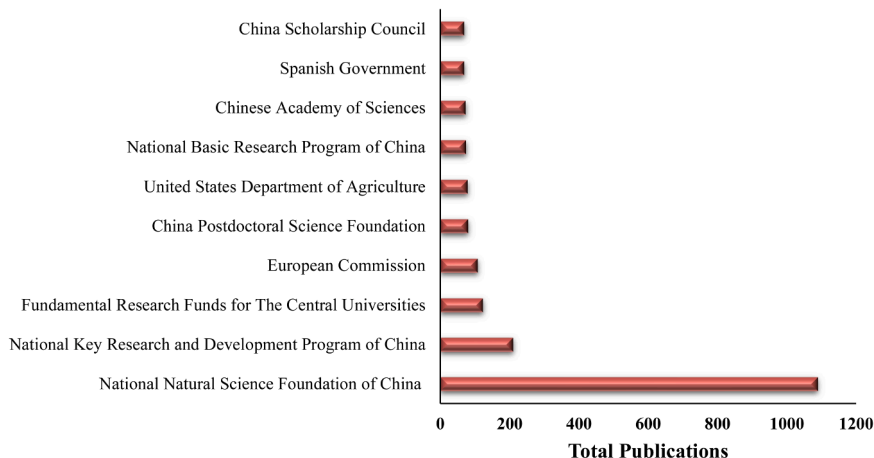


Fig. 5. Top 10 funding agencies/ organizations working in the area of biochar during last two decades.

Table 6

Top 10 highly cited research publications on biochar during last two decades.

Title of the paper	Author and year	Affiliation of corresponding author	Journal	Journal title and IF (2022)	Citations	
					WoS	GS*
Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	Keiluweit et al., 2010	Oregon State Univ, Dept Crop & Soil Sci, Corvallis, OR 97331 USA	Environmental Science & Technology	11.357	1,722	1904
Sustainable biochar to mitigate global climate change	Woelf et al., 2010	Pacific NW Natl Lab, Div. Chem & Mat Sci, Richland, WA 99352 USA	Nature Communications	17.694	1,276	1,383
Agronomic values of greenwaste biochar as a soil amendment	Chan et al., 2007	Dept Primary Ind, Richmond, NSW 2753, Australia	Australian Journal of Soil Research		1,098	1271
Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility	Van Zwieten et al., 2010	NSW Dept Primary Ind, 1243 Bruxner Highway, Wollongbar, NSW 2477, Australia	Plant and Soil	4.993	1,078	1192
The forms of alkalis in the biochar produced from crop residues at different temperatures	Yuan et al., 2011	Chinese Acad Sci, Inst Soil Sci, State Key Lab Soil & Sustainable Agr, POB 821, Nanjing, Peoples R China	Bioresource Technology	11.889	1,070	1333
Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	Zimmerman et al., 2011	Univ Florida, Dept Geol Sci, 241 Williamson Hall, POB 112120, Gainesville, FL 32611 USA	Soil Biology & Biochemistry	8.546	864	954
Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil	Novak et al., 2009	USDA ARS, Coastal Plain Soil Water & Plant Res Ctr, Florence, SC USA	Soil Science	1.692	787	977
Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil	Beesley et al., 2010	Liverpool John Moores Univ, Fac Sci, Liverpool L3 3AF, Merseyside, England	Environmental Pollution		768	866
Impact of biochar amendments on the quality of a typical Midwestern agricultural soil	Laird et al., 2010	ARS, USDA, Natl Lab Agr & Environm, 2110 Univ Blvd, Ames, IA 50011 USA	GEODERMA		757	940
Biochar impact on nutrient leaching from a Midwestern agricultural soil	Laird et al., 2010	ARS, USDA, Natl Lab Agr & Environm, 2110 Univ Blvd, Ames, IA 50011 USA	GEODERMA		739	891

* Google scholar

GS- 891). Surprisingly, most of the top cited research papers were found to be published before the year 2010. Moreover, most of the researchers they given emphasis on research related to soil fertility, climate change, carbon sequestration etc. So, these topics of research were found to be emerging areas of research during 2000-2020.

3.7. Techno-economic analysis of biochar

Biochar is derived from biomass (agriculture waste, wood, municipal sludge), making it low-cost compared to metal-based catalysts. Biochar can be mass-produced from waste feedstocks, reducing dependency on expensive rare metals (Do Minh et al., 2020). Biochar is less energy-intensive to produce than synthetic catalysts, but it may require modifications (metal doping, acid treatment, or functionalization) to improve catalytic properties (Wan et al., 2020). On the other hand, biochar is highly effective in wastewater treatment and CO₂ capture, serving as a competitor to activated carbon and zeolites (Shafawi et al., 2021). In the present context, Biochar production sequesters carbon, providing financial incentives in carbon markets. However, Biochar is a cost-effective, sustainable, and versatile catalyst, particularly in wastewater treatment, biofuel production, and environmental applications. While it may not completely replace metal catalysts in high-end applications, modifications (e.g., metal/acid doping) can significantly enhance its efficiency (Babu et al., 2023.)

Furthermore, biochar is widely used as a catalyst material because of its excellent catalytic properties in many different areas like agriculture, environment, and energy, for biodiesel production, tar removal, waste management, production of syngas, production of chemicals, and removal of contaminants, etc.(Yaashikaa et al., 2020). The large surface area of biochar is important for its catalytic activity coupled with presence of large group functional groups on its surface. Oleszczuk et al. (2012) reported that due to presence of O-H functional group the adsorption of norfloxacin was more. Also a catalyst, biochar finds vast application such as biodiesel production, energy production, and removal of tar, waste management, syngas production, and electrodes in microbial fuel cells, production of chemicals and removing environmental contaminants. For hydrolysis of biomass there are numerous

catalytic agents like enzymes, mineral acids, and solid acids, have been employed (Cao et al., 2017). However, the enzymatic hydrolysis of biomass is slow and costly, and the hydrolysis of biomass by mineral acids usually produces various environmental hazards. In contrast to this biochar-based solid acid is a promising alternative to mineral acid in biomass hydrolysis and dehydration due to its high reaction activity, recyclability, and low cost (Lee et al., 2017). Besides this biochar is also catalytically active in cracking tar because of its presence of inorganic elements including Fe and K (Hervy et al., 2017).

4. Conclusion

Biochar is a low-cost, solid carbonaceous substance that is the main product from biomass pyrolysis, which is basically the heating of organic biomass in an oxygen-stress environment. It has the ability to encapsulate pollutants in soil, sequester carbon, reduce greenhouse gas emissions, and enhance soil quality. Besides, it has several other ancillary benefits, like improvements in soil structure, water holding capacity, bulk density, and nutrient availability for crop plants. Due to the fact that the use of biochar as an eco-friendly and clean technology has been emerging in recent years. Therefore, a comprehensive scientometric study was performed using scientific literature in order to map the research trends of biochar application in agriculture. Information was collected from the Web of Science (WoS) database between 2001 and 2021. The present scientometric analysis suggested that the majority of scientific research and development on biochar application in agriculture were accelerated after 2010 and increasing trend of publications on biochar is expected in the near future. The People's Republic of China (PRC) ranks first among the nations publishing papers on biochar studies. Among the top and active journals, "Science of the Total Environment" has published highest papers on biochar research. The recent publication on biochar shows that biochar application in agriculture has great potential to improve crop yield and soil quality and plays an important role in climate change mitigation. Considering the overall implications of biochar on soil health and crop productivity, it is desirable that future studies explore the issues of biochar application in agriculture to achieve the Sustainable Development Goals (SDGs).

CRedit authorship contribution statement

B.P. Meena: Writing – review & editing, Visualization, Supervision. **Dinesh K. Yadav:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Md Yeasin:** Software, Formal analysis, Data curation. **A.O. Shirale:** Writing – review & editing, Writing – original draft, Validation. **Priya P. Gurav:** Writing – original draft, Visualization, Supervision. **K.C. Shinogi:** Visualization, Supervision. **Deviden Yadav:** Writing – review & editing, Visualization, Methodology. **Subhash Babu:** Writing – review & editing, Supervision, Resources. **M. Saha:** Writing – original draft, Methodology, Data curation. **S. Lenka:** Writing – review & editing, Validation, Supervision. **Abhijit Sarkar:** Writing – original draft, Methodology, Conceptualization. **M.V. Coumar:** Writing – review & editing, Supervision, Methodology. **Abhishek Patel:** Writing – original draft, Data curation. **B. Lal:** Visualization, Software, Investigation. **P. Jha:** Writing – review & editing, Supervision. **S.K. Behera:** Visualization, Validation, Supervision.

Declaration of competing interest

This is to certify that the manuscript entitled “**Emerging Research Trends on Biochar Application in Agriculture: A Scientometric Analysis**” authored by B.P. Meena, Dinesh K. Yadav, Md Yeasin, A.O. Shirale, Priya P. Gurav, Shinogi K.C., Deviden Yadav, Subhash Babu, M. Saha, S. Lenka, Abhijit Sarkar, M.V. Coumar, Abhishek Patel, B. Lal, P. Jha and S.K. Behera is based on the scientometric analysis and no part of the manuscript has been submitted in any other journal for publication. All authors have reviewed the revise manuscript before submission in the journal and **there is no conflict of interest between the authors about the publication of this manuscript.**

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Data availability

Data will be made available on request.

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