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CASE STUDY

Bibliometric analysis of biochar application for environmental management in agricultural sector

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ABSTRACT

BACKGROUND AND OBJECTIVES: Biochar has gained prominence as a sustainable solution in agriculture and environmental management, with benefits of enhancing soil fertility, improving crop yield, and mitigating the climate change. This study sought to conduct a bibliometric analysis of biochar research within the context of agricultural applications, with the objective of evaluating its progression, thematic development, and patterns of global collaboration.

METHODS: A search was conducted in the Scopus database on September 1, 2024 using a pre-determined keyword combination. The retrieved data were analyzed using the Bibliometrix package in RStudio to evaluate publication trends, research theme evolution, and international collaboration networks. The authors' keywords were employed in a co-occurrence analysis to discern principal research themes and their interrelations. The analysis on research theme evolution utilized a single time split, dividing the datasets into 2006–2021 and 2022–2025. The collaboration network was established with a minimum edge threshold of 4, and it is illustrated in a mapped format.

FINDINGS: The search using a predetermined keyword combination identified 4,402 publications related to biochar, with 2,857 focused specifically on its application in agriculture. A pronounced increase in research output was observed after 2016. China is spearheading the investigation in this domain, having produced 1,319 publications from individual countries and 564 from various international collaborations. In the second leading position, the United States has produced 382 publications, where 101 of which were published along with authors from other countries. The thematic analysis revealed a transition from the original focal points, which included carbon sequestration, to newly emerging subjects such as microbial biomass and the remediation of heavy metals.

CONCLUSION: There is an increasing significance of biochar research worldwide, where the thematic evolution and patterns of international collaborations have been successfully synthesized in this study. The thematic shifts suggest the growing interest in microbial biomass and heavy metal remediation-related themes, indicating the multiple applications of biochar in both environmental management and agricultural productivity. Given the robust framework of international research collaboration, it is essential to undertake a unified global initiative aimed at standardizing biochar application techniques, enhancing production processes, and evaluating the long-term effects of biochar usage. The production and utility of biochar in agricultural sector could be optimized through international collaboration and policy development aiming to improve soil health, and subsequently food security. The study has effectively mapped the landscape of biochar studies within the realm of environmental management, with a particular focus on its roles in enhancing microbial biomass and remediating heavy metal contamination.

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INTRODUCTION

Biochar, a carbon-rich material derived from the pyrolysis of organic biomass, has been recognized as a promising soil amendment with significant potential to enhance agricultural productivity. A meta-analysis revealed that the incorporation of biochar in agricultural practice increased the production up to 25.3 percent (%) ± 3.2% (Bai *et al*., 2022). The enhancement in productivity has been linked to the augmented soil fertility, enhanced water retention capabilities, and improved nutrient retention that result from the incorporation of biochar (Allohverdi *et al*., 2021). Studies have demonstrated that the addition of biochar can produce an average increase in crop yields of approximately 16%, with a remarkable 40% improvement observed specifically in acidic soil environments (Schmidt *et al*., 2021). As indicated in a recent meta-analysis, biochar application can lead to a significant increase in grain yield, depending on the biochar types (Schmidt *et al*., 2021). Biochars derived from poultry litter have been reported to demonstrate yield improvements of up to 28% (Schmidt *et al*., 2021). Beyond the selection of feedstock, the performance of biochar is influenced by the parameters of pyrolysis as well as the inherent properties of the soil (Gao *et al*., 2021). Earlier research has demonstrated that the efficacy of biochar produced from sewage sludge is contingent upon the temperatures at which pyrolysis occurs (de Figueiredo *et al*., 2020).The effect of biochar incorporation is not only on nutrient retention, but also various aspects of plant growth and soil health. Previously, biochar was found to increase soil water-holding capacity by up to 30%, enhance soil microbial activity, and improve soil bulk density and porosity (Adhikari *et al*., 2022; Pokharel *et al*., 2020). Recent systematic reviews and meta-analyses have consistently highlighted the positive impacts of biochar, indicating an average increase in crop yields of 16%, with some studies reporting enhancements of up to 40% in acidic soil conditions (Schmidt *et al*., 2021). Biochar has been found to enhance root growth, increasing root biomass by 32% and root surface area by 39% (Chew *et al*., 2020). These effects contribute to more effective nutrient uptake and strengthen plant resilience, particularly in soils that are low in nutrients. Moreover, biochar positively affects key physiological parameters in plants, such as the rate of photosynthesis and water use efficiency (He *et al*., 2020). Additionally, biochar's ability to sequester carbon makes it a valuable tool for carbon dioxide removal (CDR) strategies, which is beneficial for environmental management (Luo *et al*., 2023). Biochar is recognized as a sustainable solution, valued for its role in recycling agricultural waste into a useful product (Sumiyati *et al*., 2024). This examination offers valuable insights that not only pinpoint the most significant research contributions and reveal deficiencies in the existing literature but also emphasize nascent areas of inquiry, thereby influencing the trajectory of forthcoming research initiatives(Ahmad and Chiari, 2023; Zulkifli *et al*., 2023). The bibliometric analysis employs multiple, complex statistical methods, including co-occurrence network analysis and thematic evolution, to uncover publication trends, thematic development, and collaboration patterns. In the realm of co-occurrence network analysis, the frequency and relationships of terms or keywords are scrutinized, leading to the development of visual networks that elucidate the predominant concepts within the field. Thematic evolution analysis further tracks the prevalence and development of research topics over time, using techniques like latent dirichlet allocation (LDA) or non-negative matrix factorization (NMF) (Aria and Cuccurullo, 2017). This analysis provides insights that not only identify the most impactful research and highlight gaps within the literature but also draw attention to emerging fields of study, thereby shaping the direction of future research endeavors. By aligning with global trends and challenges, these findings can help researchers and policymakers focus biochar development on the most promising and impactful trajectories (Ginting *et al*., 2023; Iqhrammullah *et al*., 2023). Previously, for instance, the bibliometric analysis on microalgae research revealed the most prominent research topics such as biofuel production, wastewater treatment, and environmental sustainability (Zhang *et al*., 2020). Within agricultural studies, bibliometric methods have been utilized to investigate the impact of digitalization on agricultural practices (Bertoglio *et al*., 2021; Latino *et al*., 2022). Whilst there are review articles on biochar utility in agriculture (Wang and Wang, 2019; Xie *et al*., 2022), the bibliometric analysis has not been performed. The execution of a bibliometric analysis to methodically assess the research landscape holds significant importance, particularly due to the wide-

ranging applicability of biochar in numerous fields (Wang and Wang, 2019). Herein, the aim of the study was to conduct a bibliometric analysis of biochar research in agricultural sector. Results from the study are expected to offer insights into the evolution of biochar research and its potential to address the pressing challenges of modern agriculture. The study was conducted in Banda Aceh, Indonesia, in 2024.

MATERALS AND METHODS

The bibliometric analysis of biochar research in agriculture was conducted using the Bibliometrix package in RStudio. A systematic search was performed using the Scopus database with the keywords (TITLE: biochar) AND TITLE-ABS-KEY: agriculture OR crop). There were no constraints placed on the type of document or the year of publication during the search. The criteria for inclusion mandated that the document must include "biochar" in the title, as well as "agriculture" or "crop" in the title, abstract, or keywords. The retrieved data were exported from Scopus as a .csv (comma separated values) file and analyzed in RStudio using the Bibliometrix package, following the suggestion form a previous study (Aria and Cuccurullo, 2017). An assessment of publication trends was performed to elucidate the evolution and dispersion of research over time. The publication trends were also observed for each affiliation to identify the most relevant institution in this topic. Co-occurrence analysis was conducted based on the authors' keywords to identify key research themes and their interconnections. This study presents a schematic representation of the relationships between different topics in the literature, enabling the discernment of key and developing themes within the field. Thematic shift analysis was performed using a single time split, which divided the dataset into two periods (2006-2021 and 2022-2025) to track the evolution of research focus areas over time. This methodology facilitates the detection of changes in thematic emphasis and the development of novel research domains. An international collaboration map was created to illustrate global research partnerships. The analysis was conducted with a minimum edge of 4, focusing on collaborations with at least four joint publications. In Bibliometrix, co-occurrence network analysis and thematic evolution are generated by complex statistical methods. The initial step in co-occurrence network analysis involves conducting a frequency analysis, wherein the occurrences of terms or keywords within the dataset are quantified. Subsequently, a co-occurrence matrix is developed, which captures the frequency with which pairs of terms co-appear in the same documents. The matrix is then used to create visual networks using algorithms like the Force-Directed Layout, which positions nodes (terms) based on their relationships and connection strengths. Measures of centrality, such as Degree Centrality and Betweenness Centrality, are applied to ascertain the most significant terms in the network. In thematic evolution analysis, techniques like LDA or NMF are used to extract and model topics from the literature.

RESULTS AND DISCUSSION

Publication trends

ibliometric approaches were employed to analyze meta-data from a dataset comprising 5,363 entries. The publication trends concerning the application of biochar in agricultural research are represented in Fig. 1. A significant growth in the number of publications related to biochar research in agriculture over the past two decades was observed. The number of publications has increased exponentially, where the adjusted-coefficient of determination (R^2) was found to be 0.995. The remarkably elevated R^2 value indicates that the exponential rise in biochar research is not merely a coincidental phenomenon; rather, it reflects a consistent and foreseeable expansion, propelled by the growing acknowledgment of biochar's significance in agricultural practices and environmental stewardship. The data shows a gradual rise in publications from 2006 (only 2 publications) to a peak in 2023 (819 publications). By comparison, the prior bibliometric study on the utilization of drones in agricultural practices revealed a dramatic surge in publications, increasing from 108 in 2013 to 1,275 in 2020 (Rejeb *et al*., 2022). As compared to newer topics such as agriculture 4.0, the publications growth was observed to be less stable where it was only 2 studies published in 2002 and increased to 126 studies in 126 (Mühl and de Oliveira, 2022). Original research articles comprised the largest share of the documents, representing 82.1%. In contrast, reviews made up 8.2%, while conference papers and book chapters accounted for 5% and 3.7%, respectively. Other types of publications, such as errata, books, notes, retracted articles, letters, editorials, data

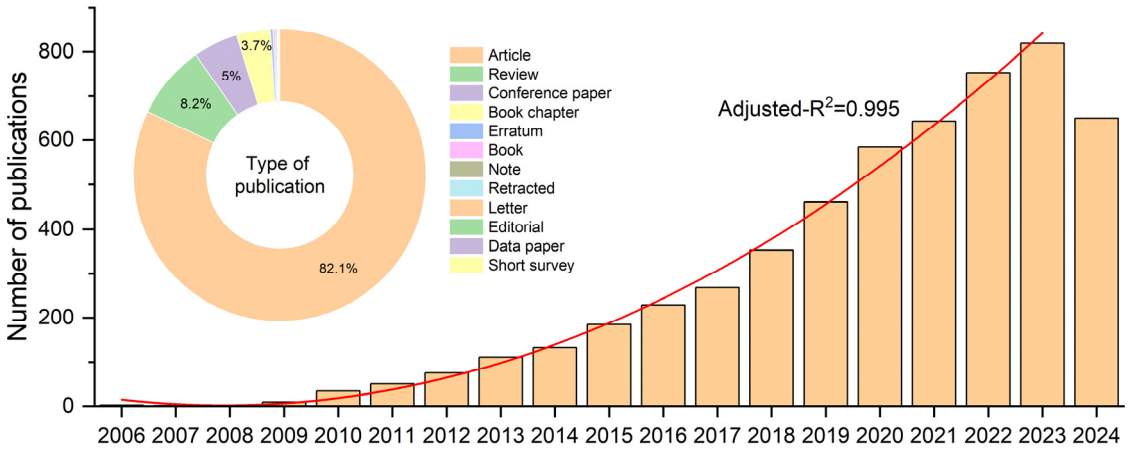


Fig. 1: Number of publications based on the publication year and type. The graph was generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al.*, 2024)

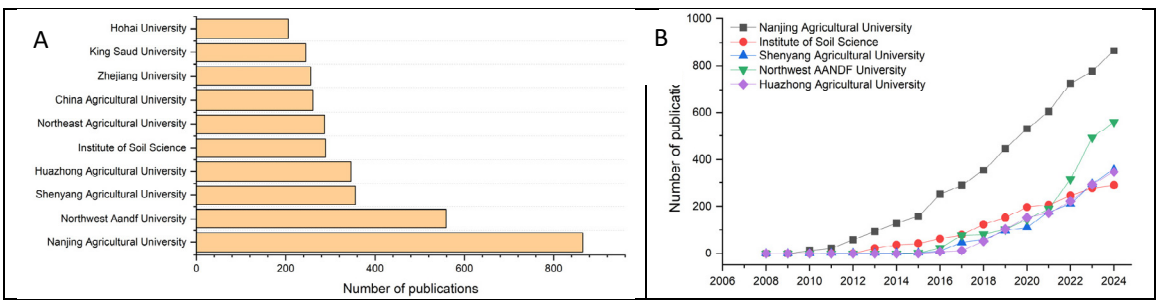


Fig. 2: Most relevant affiliations (A) and their annual publication trends (B) in biochar research for agricultural applications. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al.*, 2024)

papers, and short surveys, each constituted less than 1% of the total output.

The analysis of affiliations and publication trends are presented in Fig. 2. Nanjing Agricultural University revealed as the leading institution in biochar research for agricultural applications, with a substantial increase in the number of publications from 13 publications (in 2010) to 865 publications (in 2024). Northwest A and F University follows with 559 publications, showing a significant growth since 2016. In the year 2024, Shenyang Agricultural University, Huazhong Agricultural University, and the Institute of Soil Science have significantly advanced the field with their respective outputs of 356, 346, and 289 publications. Additionally, China Agricultural University, Zhejiang University, King Saud University, and Hohai University have published between 206 and 261 articles. The evidence presented indicates that a select group of influential institutions, notably in China, are at the helm of biochar research related to agriculture, with Nanjing Agricultural University emerging as a leader in this area.

Research trend

Research trend based on the co-occurrence of author's keywords is presented in Fig. 3. A review of the keywords relevant to biochar research in agriculture demonstrates that "biochar" is the most extensively investigated topic, with a substantial count of 2,857 publications. Other prominent keywords include "pyrolysis" (323 publications), "soil amendment" (186 publications), and "carbon sequestration" (181 publications). Topics such as "adsorption" and "soil" also appear frequently, with

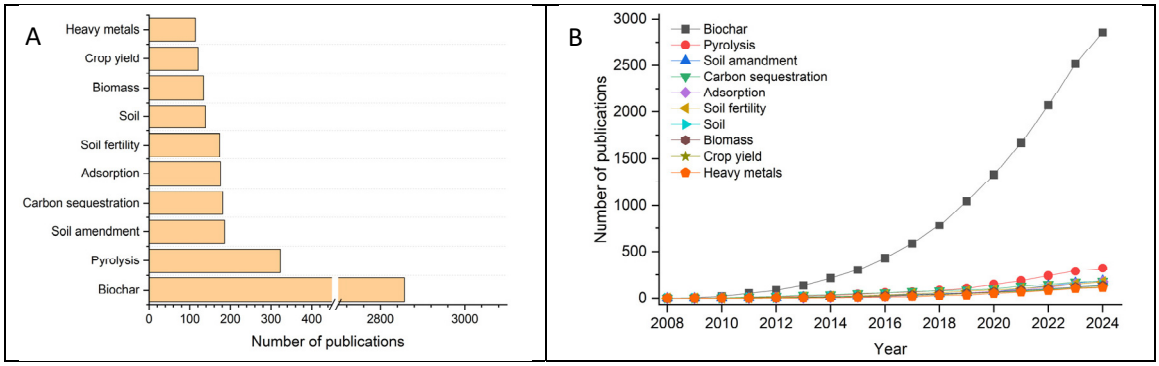


Fig. 3: Most relevant keywords (A) and their annual trend in publications (B) relevant to agricultural application of biochar research. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al.*, 2024)

176 and 139 publications, respectively. A total of 174 publications have incorporated the keyword "soil fertility," reflecting its widespread relevance in academic discourse. In comparison, the areas of "biomass" and "heavy metals" have been the focus of 134 and 114 publications, respectively, indicating a lower frequency of study. The analysis also reveals that there are at least 121 publications focusing on the effect of biochar amendment, as indicated by the occurrence of keyword "crop yield". As for keyword "plant growth", indicative to agricultural crop growth, was identified in 73 publications. The trend analysis from 2008 to 2024 shows a significant increase in publications related to biochar, with a marked rise after 2016. The increase in interest underscores the rising appreciation for the environmental and agricultural benefits that biochar offers. Historically, the term "charcoal" was widely utilized, especially in contexts related to fuel and metalworking. However, as research shifted toward environmental sustainability and soil management, "biochar" became the preferred term, emphasizing its role as a soil amendment and its potential for carbon sequestration. Although there has been a notable rise in the number of publications addressing areas such as pyrolysis, soil amendment, and carbon sequestration, this growth has occurred at a more measured pace compared to the accelerated development of studies focused on biochar. These findings indicate a strong and growing interest in biochar and its applications, with related topics experiencing steady, albeit slower, growth. This trend indicates the shifted focus of biochar research from its general applications to the specialized and environmentally significant role of biochar in agriculture.

The co-occurrence network reveals several distinct clusters, each representing interconnected research themes (Fig. 4a). The green cluster is predominantly focused on environmental themes, including "greenhouse gas," "nitrogen fertilizers," and "soil carbon," highlighting the role of biochar in mitigating emissions and improving soil nutrient management. Centered around agricultural applications, the blue cluster features keywords including "crop yield," "fertilizer," and "soil moisture." This highlights a considerable interest in exploring the influence of biochar on enhancing agricultural productivity and improving soil health. The red cluster addresses technical aspects, such as "pyrolysis," "adsorption," and "surface area," which are critical for understanding the production and physical properties of biochar. Finally, the purple cluster is concerned with pollution and remediation, emphasizing biochar's potential in addressing soil contamination and environmental cleanup (Fig. 4a). This thematic plot additionally organizes these themes by their progression and importance, wherein the produced plot is illustrated in Fig. 5a. "Biochar," "charcoal," and "soils" are identified as motor themes, which are both well-developed and central to the field, driving much of the research activity. Conversely, themes such as "soil pollution" are categorized as fundamental themes, essential to the discipline yet lacking in specialization. Niche themes, including "adsorption" and potential of hydrogen ("pH") represent highly specialized areas that, while important, are less central to the broader research community. The concepts of "crop yield" and "carbon sequestration" reflect emerging

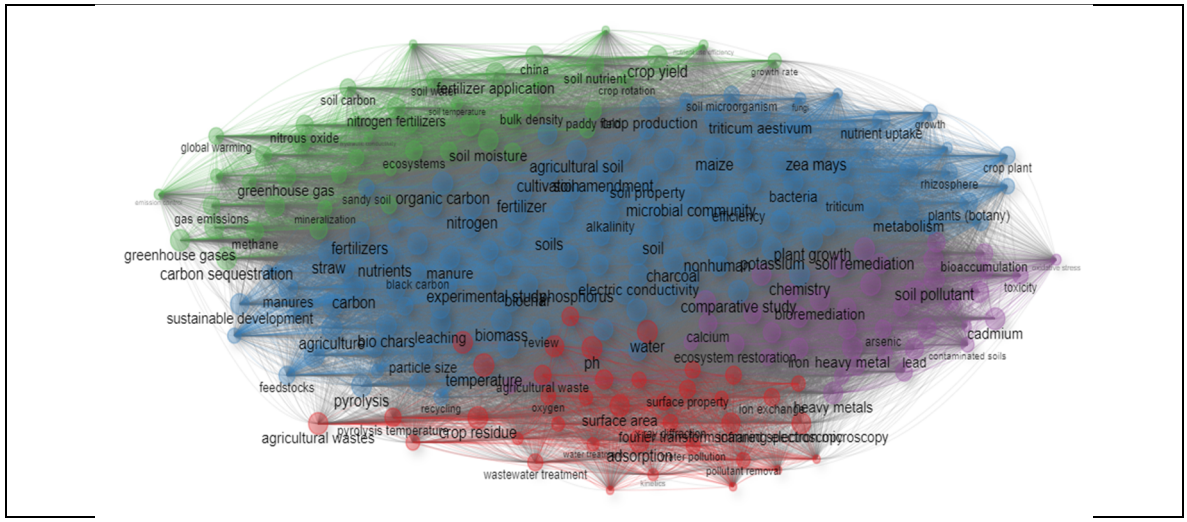


Fig. 4: Co-occurrence network (a) of research on biochar application in agriculture. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al*., 2024)

or diminishing trends, pointing to domains that are undergoing significant transformations, either increasing in importance or fading from prominence.

Evolution of key research themes in biochar studies from 2006-2021 to 2022-2025 was illustrated in a Sankey diagram and presented in Fig. 5b. The extent of the bands that associate themes throughout various periods illustrates the comparative importance and ongoing nature of these themes. The wider the band, the more significant and consistent the theme is across the periods. Biochar consistently exhibits the widest band, which statistically indicates its unchanging prominence in research. Conversely, topics such as nitrous oxide and carbon sequestration display more restricted ranges as they progress into the 2022-2025 timeframe, indicating a potential decrease in research emphasis or their assimilation into broader, emerging themes. The appearance of new themes with significant band width in the 2022-2025 period (such as microbial biomass, soil moisture) suggests a statistically significant shift in research priorities, indicating new or evolving areas of interest within the field of biochar research. In the earlier timeframe spanning from 2006 to 2021, the prevailing themes encompassed “biochar,” “nitrous oxide,” “carbon sequestration,” “adsorption,” and “pyrolysis.” As research has progressed into the 2022-2025 period, there has been a noticeable shift and expansion in focusAlthough “biochar” remains a predominant subject of study, recent investigations have expanded to encompass new topics such as “microbial biomass,” “soil moisture,” and “heavy metals.” In addition, “maize” has surfaced as a critical area of focus, highlighting the rising interest in the utilization of biochar in relation to specific crop production systems. Themes like “carbon sequestration” and “nitrous oxide,” which were prominent in earlier years, appear to have been integrated into broader studies or have shifted focus as indicated by their reduced prominence in the current thematic landscape. This shift in research themes illustrates the evolving landscape of biochar investigation, marked by an enhanced attention to its biological implications and its practical applications within the realms of agriculture and environmental management.

Collaboration trends

The analysis of publication data reveals that China is leading the biochar research with a significant number of publications, totaling 1,319 from single-country studies and 564 from international collaborations (Fig. 6a). Following closely is the United States, which has generated 281 publications from research conducted independently and 101 from collaborative projects. India also exhibits significant research productivity, contributing 236 publications from single-country research and 63 from collaborative endeavors. Other

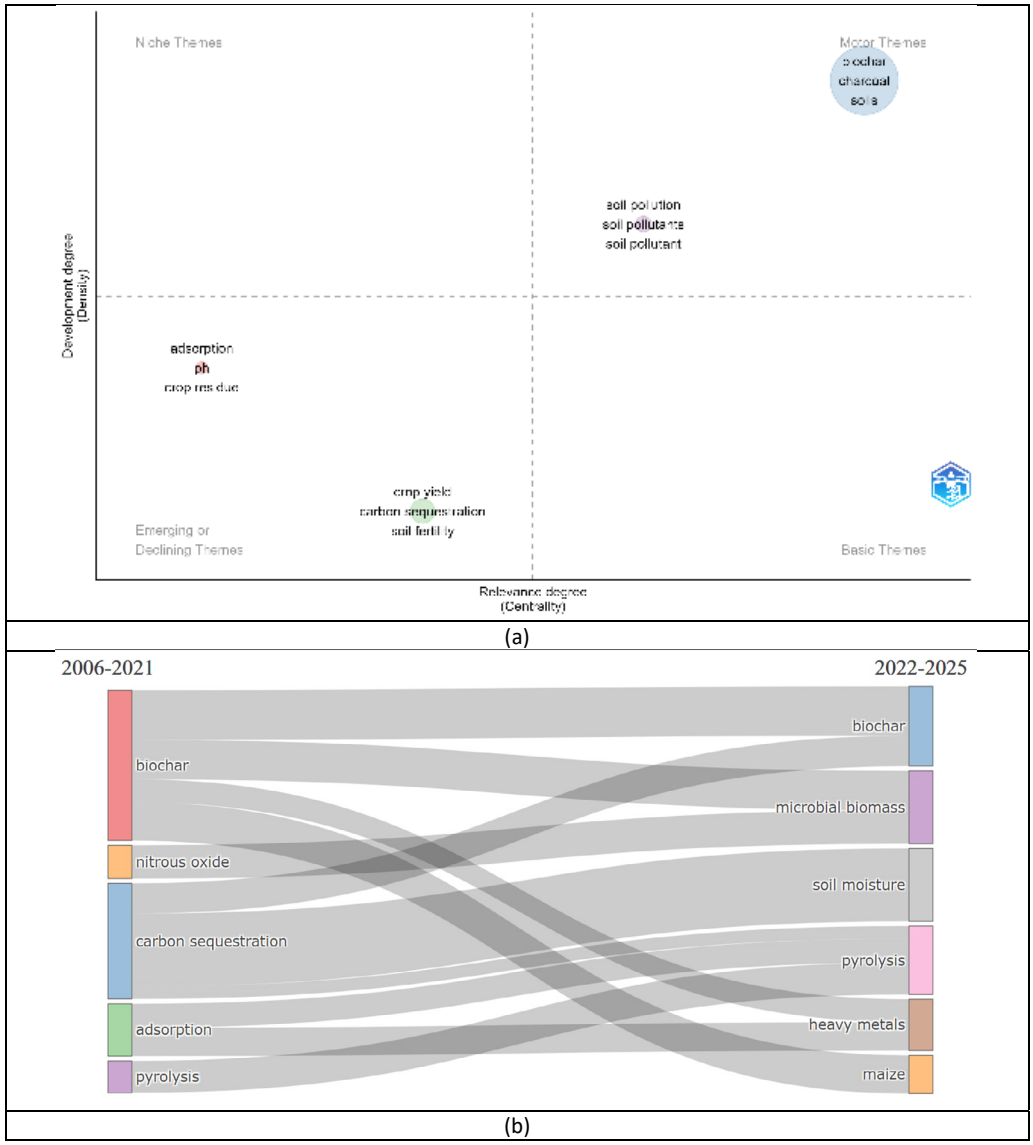


Fig. 5: Thematic plot (a) and thematic evolution plot (b) of research on biochar application in agriculture. The graphs were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al.*, 2024)

countries with notable contributions include Pakistan, Italy, and Australia, which have higher proportions of publications from international collaborations compared to their single-country outputs. Particularly in Pakistan, the collaborative publications exceed single-country publications. In contrast, countries like Indonesia, Nigeria, and Thailand have a higher focus on single-country research, with limited international collaboration. For example, Indonesia has 80 single-country publications and only 6 collaborative ones. Another example, Thailand has 47 single-country publications and just 6 collaborative ones (Fig. 6a). According to a previous bibliometric study focused on biochar research, China emerged as the dominant contributor, with 227 published studies, which constituted 51.01% of the total number of publications (Wang *et al.*, 2024). The map of global research collaborations in biochar studies reveals a

dense network of international partnerships, with China and the United States emerging as central hubs (Fig. 5b). China, with 564 international collaborations, notably collaborates frequently with the United States (190 collaborations), Australia (142 collaborations), Korea (60 collaborations), and Saudi Arabia (70 collaborations). The United States demonstrates robust collaborative relationships with a variety of nations, having established 101 partnerships with China, 56 with Canada, 29 with Germany, and 29 with Australia. Other countries such as Australia, the United Kingdom, and Germany also play significant roles in fostering international research partnerships, contributing to a globally interconnected research landscape. To illustrate, Australia boasts 101 collaborative initiatives with the United States, 28 with Korea, and 24 with Saudi Arabia. Conversely, Germany has 48 partnerships with China and 29 with the United States. Countries like Pakistan, with 123 collaborations, India (63 collaborations), and Brazil (43 collaborations) also demonstrate active participation in global research networks, often collaborating with leading research

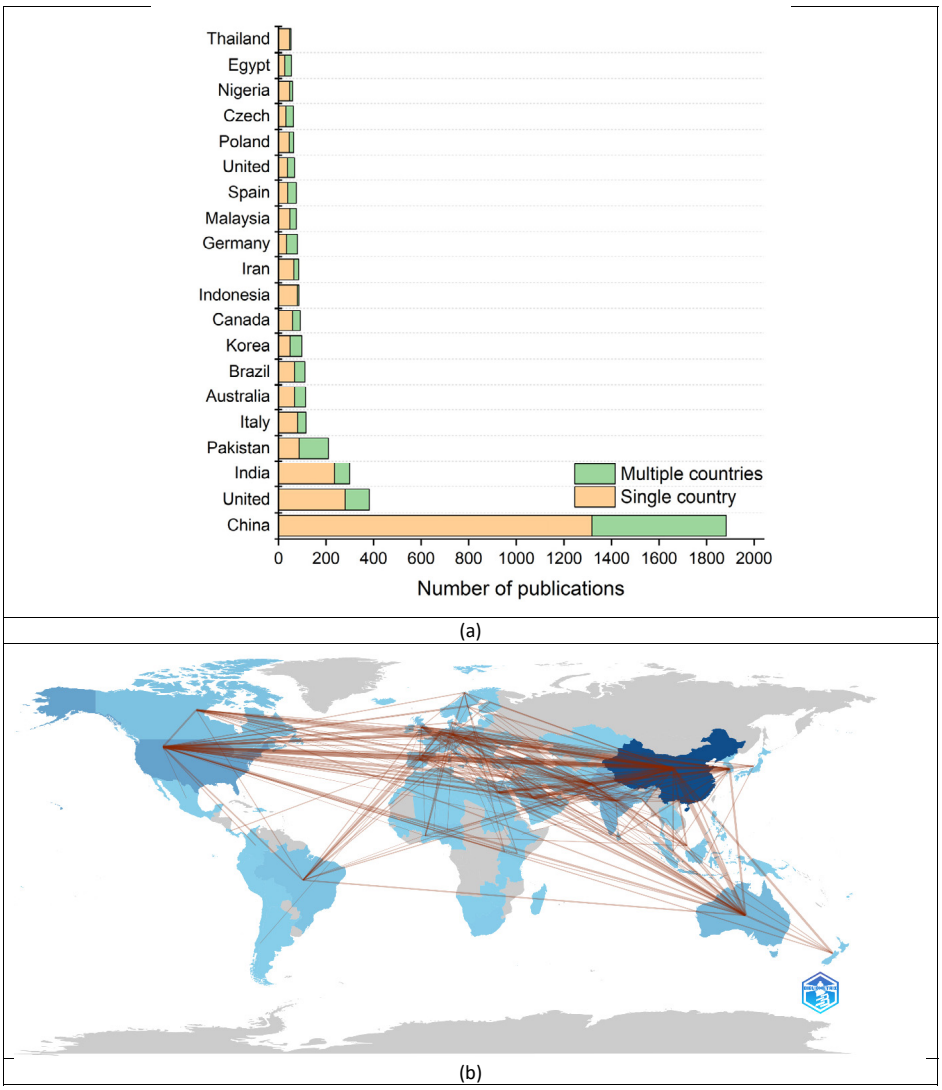


Fig. 6: Number of publications from each corresponding author's country (a). The collaboration between countries as illustrated in a map (b). The graph and collaboration map were generated using meta-data from 5,363 publications identified from Scopus database (Chiari *et al.*, 2024)

nations. Collaborative research network of China is 5.6 times larger than that of Indonesia and 3.5 times larger than that of Pakistan. China's collaboration rate of 29.9% signifies a harmonious balance between leveraging domestic research strengths and fostering international partnerships. Meanwhile, the United States, with a collaboration rate of 26.4%, demonstrates a similar pattern, although it shows a slightly stronger inclination towards domestic research efforts (Fig. 5b).

Trends in the biochar research and their implications

The bibliometric analysis of biochar research within the context of agricultural applications has demonstrated a notable surge in academic publications, especially following the year 2016, characterized by an exponential growth in the volume of research output. This growth reflects the increasing recognition of biochar's potential to address pressing challenges in agriculture, such as soil fertility, carbon sequestration, and environmental sustainability. Findings from the present study align with previous literature that highlights biochar's ability to improve crop yields, enhance soil properties, and mitigate climate change through CDR (Neogi *et al*., 2022). In the agricultural domain, the requisite quantity of biochar generally falls within the range of 5 to 30 tons per hectare, influenced by the intended improvements in soil attributes and the resultant crop yield (Bai *et al*., 2022). Biochar improves soil fertility through its high surface area and porous structure, which increases soil aeration and water retention. This structure also provides a habitat for beneficial microorganisms, enhancing microbial activity and nutrient cycling. Furthermore, biochar contributes to an increase in the cation exchange capacity of soil, facilitating the retention of key nutrients including potassium, calcium, and magnesium, which are critical for optimal plant development (Allohverdi *et al*., 2021). The impact of biochar addition to the soil has been previously highlighted to alter the presence of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) contents in the soil (Shalini *et al*., 2021). Biochar plays a significant role in curbing greenhouse gas emissions by interfering with the nitrification and denitrification processes present in the soil ecosystem (Neogi *et al*., 2022; Shalini *et al*., 2021). By acknowledging the trend in biochar research focused on reducing greenhouse gas emissions, related stakeholders can develop practical guidelines for such purposes. A recent meta-analyses have shown that biochar can increase crop yields by up to 16%, with even greater effects in acidic soils (Schmidt *et al*., 2021). Specifically, the increased yield has been reported in various crops such as maize (Liu *et al*., 2021), legumes (Farhangi-Abriz *et al*., 2021), and rice (Liu *et al*., 2022). This current study illustrates a significant transformation in the thematic focus of biochar research, demonstrating a temporal shift towards emerging areas of interest, including microbial biomass, soil moisture, and heavy metal interactions. The transition from earlier research themes, such as nitrous oxide and carbon sequestration, reflects an enhanced understanding of the complex roles that biochar plays in soil ecosystems. The shifted focus is driven by the motivation to study applicability of biochar in which becoming more evident. These emerging themes align with global priorities in combating soil degradation and pollution, which are often linked to funding opportunities from both governmental and international agencies. Initially, research centered on the fundamental properties and environmental benefits of biochar, such as its ability to sequester carbon and reduce greenhouse gas emissions. As the discipline evolved, scholars started to investigate more targeted applications and interactions within soil ecosystems. This shift resulted in the development of themes concerning the biological effects of biochar, including its role in increasing microbial biomass and its utility in regulating soil moisture and addressing heavy metal contamination. Recent publications have reported that biochar could increase the soil microbial biomass (Li *et al*., 2020). Morever, studies revealed that the effectiveness of biochar is dependent to the soil moisture levels (Dissanayake *et al*., 2022). In its intersection with heavy metal, biochar application has been reported to stabilize the lead (Pb) content, thus preventing its translocation to the crops (Boostani *et al*., 2021). In the context of sustainable agriculture, biochar serves a vital function by enriching soil fertility, enhancing the capacity for water retention, increasing microbial biomass, and mitigating the effects of heavy metal pollution. Based on the bibliometric findings, these benefits are evidenced by the thematic shifts in research focus towards biochar's application in improving soil health and addressing environmental contamination, reflecting its growing importance in sustainable

agriculture and environmental management. Herein, the analysis of global collaboration trends indicates that both China and the United States serve as pivotal centers in the field of biochar research, participating in a multitude of international partnerships. China, with 564 collaborations, and the United States, with 101 collaborations, frequently partner with each other and other countries, fostering a globally interconnected research network. These patterns can be explained by the strategic importance of biochar research in addressing global challenges like food security and climate change, which necessitates collaborative efforts across borders. The development of these collaborative networks is likely influenced by the imperative to share resources, expertise, and information, thereby empowering researchers to more effectively confront complex, multidisciplinary problems. Countries with emerging economies, such as India and Brazil, are increasingly participating in these networks, contributing to the global knowledge pool and benefiting from the collaborative research environment. In previous research, the leading countries in the research include China and the United States (Chiari *et al*., 2022; Puspita *et al*., 2022; Pratama *et al*., 2024). Within the field of agricultural studies India and Brazil have emerged as leaders in research development, as reflected by the substantial increase in publication output, especially in the case of Brazil, which has experienced a particularly swift escalation (Bertoglio *et al*., 2021; Rejeb *et al*., 2022; Mühl and de Oliveira, 2022).

Limitations

Interpretation of the findings from the present bibliometric analysis should consider of its several limitations. Initially, the scope of the analysis was confined to publications listed in the Scopus database. While this database is comprehensive, it may not encompass all pertinent research, especially that which originates from non-English-speaking countries or smaller regional journals. Second, the study did not evaluate the quality or impact of the publications, instead prioritizing the quantity of publications and the nature of collaborative efforts. Finally, the thematic evolution was based on keyword analysis, which might oversimplify the complexity of the research themes. A more nuanced approach, possibly involving full-text analysis, could provide deeper insights into the evolution of biochar research.

CONCLUSION

The bibliometric analysis has successfully elucidated the evolution and current state of biochar research in agricultural applications. A unique contribution of this study does not only include the growth mapping and thematic shifts in biochar research since 2016 but also by revealing the impact of international collaborations on advancing biochar technologies. The study demonstrated a significant escalation in the number of publications, particularly since 2016, along with a thematic evolution from core environmental benefits like carbon sequestration to more targeted applications, such as the enhancement of microbial biomass and the remediation of heavy metals. The study reveals the central roles of China and the United States in driving global research collaborations, while also illustrating the expanding involvement of emerging economies like India and Brazil. The findings underscore the scientific value of international research networks in facilitating innovations in biochar technology and its application in diverse contexts. The findings of this study demonstrate that biochar is increasingly viewed not just as a method for improving soil conditions and crop yields, but also as a significant contributor to overarching environmental sustainability goals, which involve climate change mitigation and the restoration of ecological systems.. The thematic shift observed in the study underscores the dynamic nature of biochar research, with emerging focus areas such as soil moisture management and pollution remediation reflecting the evolving challenges in agricultural and environmental managementAs the scope of research broadens, the imperative to understand the long-term consequences of biochar use in diverse ecological and agricultural contexts intensifies. Researchers are encouraged to engage in interdisciplinary collaborations that integrate scientific, economic, and social perspectives, ensuring that biochar technologies are both effective and equitable. It is imperative to conduct more research on the socio-economic ramifications of biochar applications, particularly in smallholder farming contexts and resource-limited areas, to facilitate the equitable distribution of biochar's benefits across all communities. This bibliometric analysis yields findings that are crucial for policymakers, allowing them to keep pace with global trends and challenges in sustainable agriculture. Such insights are essential

for the formulation of policies that support the development of biochar technology along suitable pathways. It ensures that policy decisions are informed by the latest research, supporting the adoption of biochar in practices that address critical environmental and agricultural needs. According to the findings, it is projected that governmental support will play a crucial role in promoting the development of biochar research. Supportive policies and targeted funding are essential to scale up biochar applications, particularly in regions vulnerable to soil degradation, food insecurity, and climate change impacts. Governments should consider integrating biochar into national and regional sustainability strategies, promoting its use as part of broader efforts to achieve carbon neutrality and enhance soil resilience. Moreover, the facilitation of international collaborations via strategic policy frameworks and dedicated research funding can significantly harness global expertise. This strategy is essential for advancing innovation and ensuring that biochar research is aligned with addressing environmental challenges on both local and international scales.

AUTHOR CONTRIBUTIONS

B.A. Bakar contributed in the conceptualization, investigation, and writing of the original manuscript. Idawanni contributed in the conceptualization, investigation, and writing of the original manuscript. Yardha, contributed in supervisión, validation, and writing of the revision. R. Purba contributed in supervision, validation, and writing of the revision. S. Abdullah, contributed in supervision, validation, and writing of the revision. Jonharnas contributed in supervision, validation, and writing of the revision. A. Azis contributed in formal analysis, data presentation, and writing of the revision. S. Kurniawati contributed in formal analysis, data presentation, and writing of the revision. Y. Giamerti contributed in data presentation and writing of the revision. D.R. Mustikawati contributed in data presentation and writing of the revision. W. Chiari contributed in investigation. E.A. Wikurendra contributed in investigation and formal analysis.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
AND	Boolean operator to limit the search
Bibliometrix	An RStudio package for bibliometric analysis
CDR	Carbon dioxide removal
CH_4	Methane
CO_2	Carbon dioxide
CSV	Comma separating value
Fig.	Figure
LDA	Latent dirichlet allocation
NMF	Non-negative matrix factorization

N_2O	Nitrous oxide
OR	Boolean operator to expand the search
Pb	Lead
pH	Potential of hydrogen
R^2	Coefficient of determination
Rstudio	A software used to compute R programming language
Scopus	Journal indexing database
TITLE	The search on the titles of published articles
TITLE-ABS-KEY	The search on the titles, abstracts, and keywords of published articles

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