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Biochar

ORIGINAL RESEARCH

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Biochar application as a green clean-up method: bibliometric analysis of current trends and future perspectives

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Abstract

Biochar has recently emerged as a cutting-edge solution for environmental remediation, distinguishing itself from traditional methods. This essay presents a comprehensive examination of the effectiveness and future prospects of biochar through innovative bibliometric analysis techniques. Since 2010, the global application of biochar as a soil amendment has surged, evolving from its conventional uses in fuel and carbon sequestration to enhancing soil functionality, a novel approach in environmental science. With over 250 research reports published during this period, biochar has demonstrated exceptional potential in improving soil properties, including water retention, nutrient cycling, and the promotion of beneficial microbial communities. However, this work identifies a critical innovation gap: the lack of a precise definition for biochar as a soil amendment in the United States, as well as the need for interdisciplinary research that bridges soil science with plant molecular biology and genetics. Our investigation not only confirms the effectiveness of biochar as a sustainable remediation method, but also suggests its potential applications in mitigating pollution and addressing climate change impacts. While current literature primarily focuses on the role of biochar in enhancing soil fertility, we have uncovered emerging trends, pointing to its use in remediating contaminated land and removing organic pollutants, which is innovative application in the field. Additionally, we highlight the novel use of advanced tools such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) to study changes following biochar application, offering a new perspective on biochar research. The versatility and effectiveness of biochar in environmental remediation make it a promising tool for sustainable soil management and pollution mitigation, underscoring the need for continued interdisciplinary research to fully realize its potential.

Highlights

- Actively using biochar in contaminated land & green construction.
- Innovating biochar production for improved efficiency.
- Utilizing biochar for carbon sequestration & climate mitigation.
- Integrating biochar with green clean-up methods for sustainability.
- Collaborating on interdisciplinary research to advance biochar use.

Keywords Biochar amendment, Green clean-up method, Bibliometric analysis, Remediation

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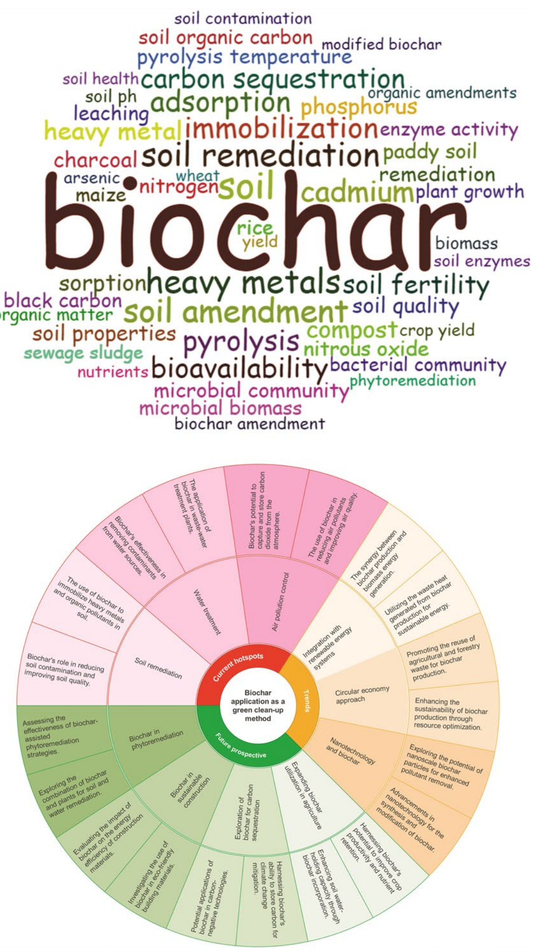
Graphical Abstract



1 Introduction

In recent years, the development of clean and sustainable technologies has gained momentum due to increasing ecological awareness and stricter waste disposal regulations. The application of biochar has emerged as a notable solution for environmental remediation and pollution control (Ren et al. 2025). Unlike activated carbon and other filtering materials, biochar is an environmentally friendly and cost-effective alternative, with diverse applications in soil amendment, water treatment, air pollution control, and waste management (Wang et al. 2023; Shanmugam Mahadevan et al. 2024; Ventura et al. 2024). Biochar enhances soil structure, increases moisture and nutrient retention, reduces acidity, and promotes fertility (Yuan et al. 2019; Wang et al. 2018; Khan 2025). Its superior sorption capacity and long-term stability make it effective in environmental remediation. In agriculture, biochar serves the dual purpose of immediate environmental clean-up and long-term land viability by slowly releasing fertilizer constituents (Pradhan et al. 2024a; Dhiman et al. 2023). These insights underscore the role of biochar in pollution remediation and its potential to enhance agricultural productivity and soil health.

As a green and sustainable technique, biochar application can clean up organic and inorganic waste in an environmentally friendly and cost-effective manner. Its efficiency in adsorbing heavy metals and organic pollutants is attributed to its porous structure and large surface area (Xie et al. 2015; De and Alkendi 2023). Furthermore, biochar has the potential to address issues such as soil pollution, greenhouse gas mitigation, wastewater treatment, and renewable energy production (Kavitha et al. 2018; Xiang et al. 2020). Additionally, it can contribute to reducing the environmental and economic burdens of waste management. For example, the thermochemical conversion of green waste into biochar, as an alternative to composting or direct landfills, can produce a valuable resource while addressing the waste management issue (Qambrani et al. 2017; Wang 2024).

Research on biochar has experienced significant growth in recent years, resulting in the publication of numerous papers and articles across various journals. However, a systematic analysis of the current status of biochar application in environmental remediation is lacking, and further investigations are needed to fully understand its potential as an effective tool for environmental clean-up. Therefore, the utilization of advanced technology such as bibliometric analysis can offer valuable insights into the existing research landscape, identify areas where knowledge is lacking, and guide future research efforts in the use of biochar for environmental remediation (Monga et al. 2022; Al Masud, et al. 2023). This approach employs quantitative analytical techniques to examine patterns in literature, providing a comprehensive understanding of research trends and the future prospects of this field (Xie et al. 2015; Ye et al. 2024). Additionally, the results can inform research policy and funding agencies in determining future research directions, helping identify successful areas of research as well as research frontiers.

Bibliometric analysis is a vital tool for evaluating research trends in various fields, including the application of biochar for environmental sustainability (Nan et al. 2023; Wu et al. 2023; Shikha et al. 2023). This method quantitatively assesses scientific literature through publication patterns, citation frequencies, and collaborations. It provides insights for exploration and resource allocation, facilitates the assessment of research impact, and aids in evaluating papers, journals, and research institutions (Lyu 2023; Fardami et al. 2023). This leads to a more efficient allocation of research funds and supports strategic decision-making.

The hypothesis of this study is that the application of biochar for environmental remediation has seen significant growth and diversification in research, with emerging trends and geographical variations influencing its adoption and effectiveness. To explore this hypothesis, the study conducted a comprehensive bibliometric analysis of current trends and future perspectives in the application of biochar as a clean-up method. This analysis provides valuable insights into the research landscape, identifies knowledge gaps, and guides future research efforts (Schwaminger et al. 2021; Khoiriyah and Syaputra 2024). The general objective was to understand the knowledge structure and research trends in biochar application for environmental clean-up. To achieve this, specific objectives were set to (1) analyze publication trends and research categories, (2) assess geographical distribution and collaboration networks, and (3) identify emerging topics and future trends in biochar application. This leads to the central question of the study: How have research trends, geographical distribution, and collaboration networks in the application of biochar for environmental clean-up evolved, and what are the emerging topics and future directions in this field? By achieving these objectives, the present study will enhance the allocation of research funds and support strategic decision-making in this area of research.

2 Materials and methods

2.1 Data source and search criteria

The literature on the subject was collected from the Web of Science Core Collection (WoSCC) database, which is operated by Clarivate Analytics and covers the period from January 2007 to December 2023. Web of Science is a highly regarded research tool that indexes and categorizes scientific literature across various fields. It serves as a reliable data source for academic research, containing a vast amount of information from influential and high-impact journals (Fig. 1). Notably, the literature for this study was exclusively sourced from the Science Citation Index Expanded and Emerging Sources Citation Index databases.

The search was performed using keywords related to biochar and its environmental effects, including:'biochar' AND ('mitigat' OR 'reduc' OR 'diminish' OR 'increas' OR 'decreas' OR 'green method' OR 'clean-up' OR 'degradat' OR 'soil' OR 'suppres' OR 'influenc') (Fig. 1). These terms were selected based on preliminary scoping reviews to ensure comprehensive coverage of biochar applications in environmental remediation. Only English-language articles were included to maintain consistency in analysis, though we acknowledge that this may exclude relevant non-English studies. After initial retrieval, records were manually screened to exclude those not explicitly addressing biochar as a green remediation method, ensuring thematic relevance. To ensure the reliability of the data, only articles written in English were included in the analysis from 01–01–2007 to 12–31–2023.

After retrieving 7659 documents, duplicates were removed using automated tools in Bibliometrix (version 4.0.0). The remaining 7095 records were screened based on title and abstract to exclude non-English articles (n = 19) and studies not explicitly addressing biochar for environmental clean-up (n = 19). Two independent reviewers conducted the screening, with discrepancies resolved through discussion (Cohen's κ = 0.85, indicating strong agreement). This resulted in 7076 articles for final analysis. Bibliometrix offers greater flexibility for custom analyses, such as thematic evolution, and integrates seamlessly with R for advanced statistical computations. On the other hand, HistCite is considered outdated, and Sci2 demands more technical expertise from its users.

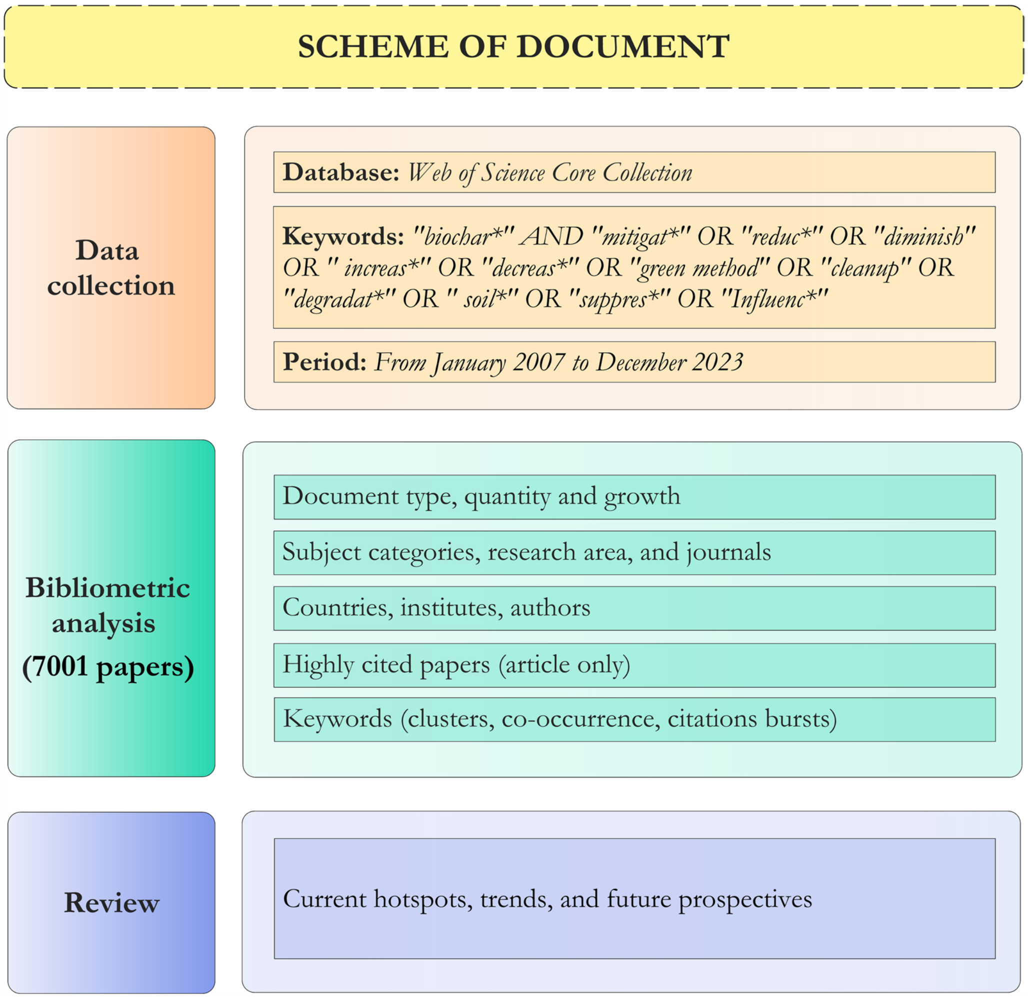


Fig. 1 A scheme of paper collection and flow chart of research framework

VOSviewer is specifically optimized for handling bibliometric data, automatically managing tasks like normalization and clustering. Gephi is a more general-purpose tool, excelling in social network analysis but requiring manual tuning for optimal results. CiteSpace specializes in creating time-sliced networks, which are essential for tracking the evolution of research fields, such as the shift in biochar research from soil remediation to carbon sequestration. Lastly, SciMAT is particularly strong in thematic mapping but may be less intuitive for analyzing dynamic trends.

Any records that did not consider biochar amendment as a green clean-up method were excluded from further analysis. Bibliometric tools were then employed to analyze the collected data from various perspectives, including authorship, keywords, journals, institutional affiliations, and citations. Finally, we examined the evolution and emergent information pathways of the research. A keyword co-occurrence network was constructed to visualize the introduction and development of each research theme in chronological order. This approach incorporates a multi-level aspect of knowledge diffusion, providing insights into changes and the validity of the intellectual structure across different time periods, which cannot be obtained through standard static network-based methods.

2.2 Analysis method: bibliometric analysis approach

The statistical results obtained from the extensive body of academic literature were visualized using the Bibliometrix (version 4.0.0), VOSviewer (version 1.6.18), and CiteSpace (version 6.2) were selected for their complementary strengths: Bibliometrix for metadata extraction, VOSviewer for network visualization (using LinLog/Modularity clustering), and CiteSpace for temporal trend analysis. These tools are widely validated in bibliometrics (Eck and Waltman 2010). To balance recency and impact, we included papers with >50 citations or published in top-quartile journals (SCImago 2023). To address database bias, we compared a subset of our data with Scopus (n =500), finding 92% overlap. Peer-reviewed articles were prioritized, but preprints were excluded to ensure reliability. Figures were generated to illustrate the data pertaining to document types, years, authors, co-cited authors, countries, institutions, journal sources, co-cited journals, keywords, and co-cited references, in order to create social network maps. Data aggregation and analysis were carried out in Microsoft Excel 2016, and the accompanying figures were created using Origin 2022 software. In particular, when determining the countries and regions from which the authors of the published records originated, numerous records were found from various countries. Additionally, cluster analysis was performed using VOSviewer software to construct social network maps.

To ensure objective and reliable findings on current hotspots, trends, and future perspectives, we assessed the following aspect in each paper: (1) Data analysis: we used Metadata with < 10% missing fields (e.g., affiliations) retained ('Excellent'/'Good' status per Bibliometrix) (Fig. S1). Review papers were excluded to focus on primary research, though their citation networks were analyzed separately to map knowledge integration; (2) Credible sources: we used well-respected sources with a proven track record of accuracy and rigorous research methods by selecting documents having more than 50 citations. Transparency in these methods facilitated understanding and replication of the findings; (3) Peer review: review paper have been excluded and subjecting the findings to peer review helped identify errors, biases, or research gaps; (4) Future perspectives: We utilized forecasting techniques based on current trends and historical data such as the thematic evolution in bibliometric software, for example, to provide future perspectives, acknowledging the inherent uncertainty in predicting the future; (5) Documentation: we thoroughly documented the research process and findings, increasing the reliability of the conclusions and allowing others to understand the approach.

2.3 Importance of using bibliometrics and VOSviewer for bibliometric analysis

2.3.1 Bibliometrics

The exponential growth of academic publishing has heightened the need for systematic methods to assess the impact of scholarly literature. Bibliometrics, the statistical analysis of publications, serves as a critical tool in this context, offering insights into research activity, citation dynamics, and academic collaboration (Kokol et al. 2021; Zheng et al. 2022). It goes beyond mere quantitative analysis, helping researchers and decision-makers navigate the vast body of academic knowledge. Key bibliometric techniques include citation analysis, which identifies influential research trends, and content analysis, which uncovers topics and themes within research bodies (Agarwal et al. 2016; Pessin et al. 2022). Co-authorship analysis reveals collaborative networks, while bibliometric indicators like the h-index and impact factor quantify research influence (Abramo et al. 2019). Manchanda and Karypis (Manchanda and Karypis 2021) suggest that innovative bibliometric approaches should integrate content-based metrics for a more comprehensive evaluation of scholarly impact.

2.3.2 VOSviewer and bibliometrix

VOSviewer excels at creating visually compelling representations of complex bibliometric data, allowing researchers to move beyond simple lists of numbers. Its capabilities include: *Network maps*: These visualizations show relationships between publications, authors, or keywords, enabling the identification of closely related research topics (Eck and Waltman 2010). This is enhanced by VOSviewer's network mapping capabilities, which allow users to visualize intricate relationships effectively. *Overlay visualizations*: VOSviewer can overlay information like publication year or citation count onto these maps, adding depth to the analysis (Pitt et al. 2021). Such visualizations facilitate a deeper understanding of interconnectedness within scientific literature, making it easier to identify emerging trends and influential works (Barbu, et al. 2024). *Diverse analysis options*: VOSviewer supports a wide range of bibliometric methods, including co-citation analysis, bibliographic coupling, co-authorship analysis, and keyword analysis. Van Eck and Waltman (2010) demonstrate its versatility in analyzing trends and connections. *Handling large datasets*: Bibliometric analyses often involve vast amounts of data, sometimes reaching thousands of publications. VOSviewer efficiently handles these large datasets, allowing researchers to analyze extensive bodies of literature and highlighting its capacity for large-scale mapping (Khoiriyah and Syaputra 2024). *User-friendly interface*: While some bibliometric tools can be challenging to navigate, VOSviewer is known for its intuitive interface, making it accessible to researchers who may not be experts in data visualization. Williams (Williams 2020) suggests that even those unfamiliar with bibliometrics can grasp VOSviewer outputs. *Open-source and accessible*: VOSviewer is an open-source software, meaning it is free to use and modify, contributing to its popularity within the research community.

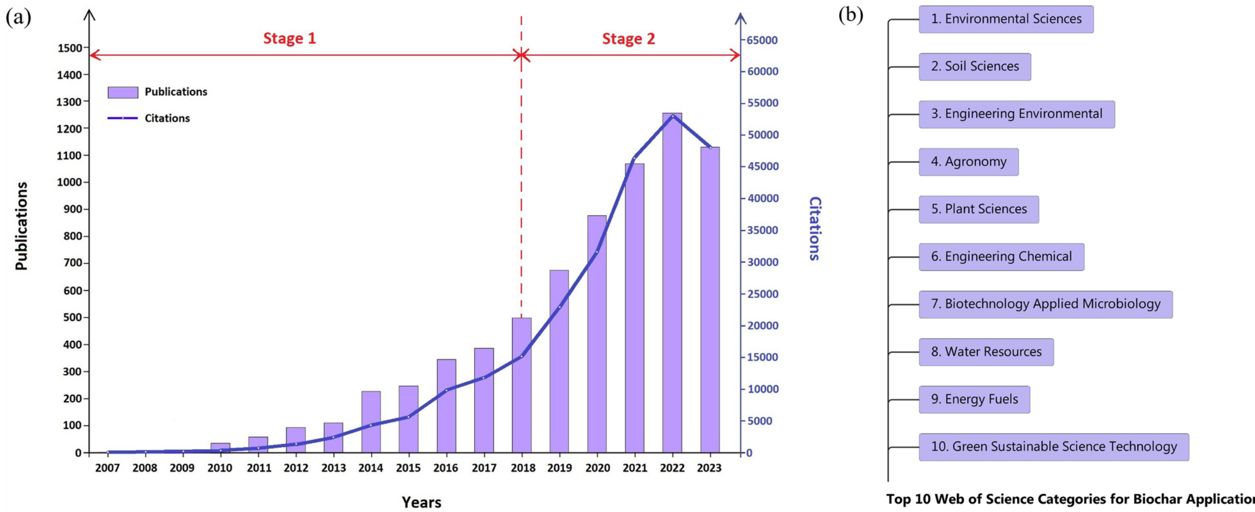


Fig. 2 Publications and citations from 2007 to 2023 (**a**) and the top 10 Web of Science categories (**b**)

2.3.3 CiteSpace

CiteSpace allows researchers to create visual representations of complex networks, such as co-citation, collaboration, and co-occurrence networks, enhancing the understanding of scientific literature. These visualizations help identify key players, research clusters, and emerging trends, offering insights into the evolution of a research field and guiding future investigations (Zhou et al. 2022). The software detects trends like citation bursts and emerging research fronts, enabling users to analyze citation patterns and centrality measures to pinpoint influential authors, institutions, and publications. This understanding of the intellectual structure aids in establishing research collaborations and conducting literature reviews.

CiteSpace also visualizes the chronological development of research fields, highlighting the emergence of new areas, the decline of older ones, and shifts in collaboration patterns (Yang et al. 2017). Its compatibility with major bibliographic databases, such as Web of Science, Scopus, and PubMed, facilitates the import and analysis of large datasets, ensuring broad coverage across various research domains. With a user-friendly interface and customizable settings, CiteSpace caters to both novice and experienced researchers, allowing tailored analyses. The software is regularly updated and supported by an active community that shares resources and best practices, keeping it responsive to the needs of bibliometric researchers (Chen et al. 2022).

3 Results and discussion

3.1 Insights from bibliometric analysis

3.1.1 Analysis of publications and research categories

Publication analysis indicates a growing interest in biochar and an expanding knowledge base in this research field. The number of scientific articles dedicated to biochar has consistently increased, reflecting its rising recognition for its importance in environmental remediation (Fig. 2). The continuous surge in scientific articles is indicative of the transition of biochar from being supported by mere anecdotal evidence to being recognized as a solution of critical importance in both academic and practical circles (Khan et al. 2021). A total of 7076 records related to biochar were identified by counting publications from 2007 to 2023. Research interest in biochar amendment began in 2007 with the first publication on biochar and has continued to increase over the years, reaching a peak of 1254 publications in 2022 (Fig. 2a).

The growth can be divided into two stages: from 2007 to 2017, the total publications represented only 21% of the total number of publications on biochar amendment, while from 2018 to 2023, there was exponential growth with publications accounting for 71%. Furthermore, the annual growth rate has experienced a notable acceleration. In the initial stage, from 2007 to 2017, the growth rate amounted to 125% per year, while in the subsequent stage, spanning from 2018 to 2023, to an impressive 1099% per year (Fig. 2a). This remarkable increase highlights the growing popularity and significance of research on biochar. It underscores the growing interest among researchers and practitioners in discovering the potential of this sustainable solution as green clean-up

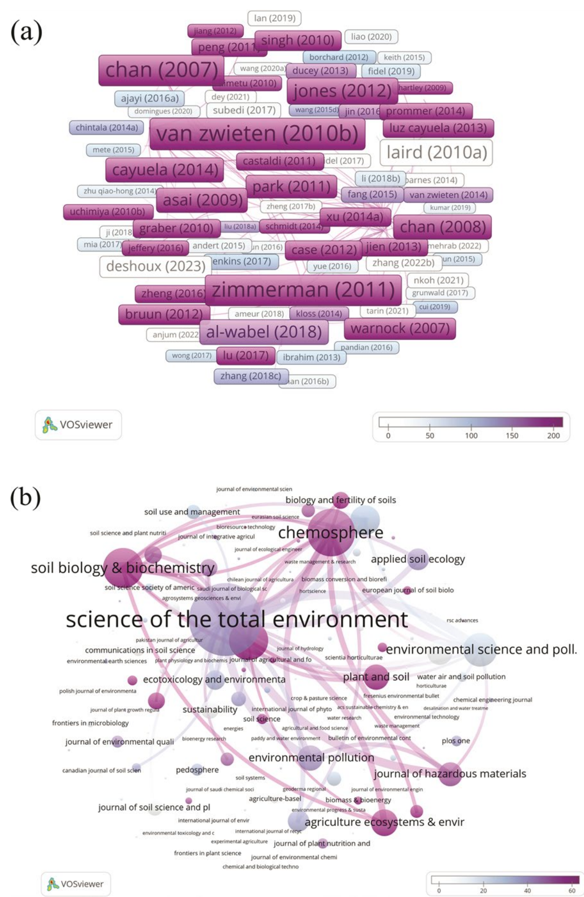


Fig. 3 The overlap visualization of the most documents cited over time (**a**) and the 10 most influential journals (**b**)

method. Our examination revealed that research on biochar spans across 95 core categories recognized by the Web of Science, suggesting its interdisciplinary nature. The 10 primary categories include environmental sciences, soil sciences, engineering environmental, agronomy, plant science engineering chemical, biotechnology applied microbiology, water resources, energy fuels, and green sustainable science technology with at least 600 publications on biochar (Fig. 2b). Diverse applications of biochar are driving a notable shift in the approach to environmental management and sustainable development among researchers and practitioners. In agronomy, for instance, the ability of biochar to improve soil structure and nutrient retention directly influences agricultural productivity and food security (Lehmann and Joseph 2015). This evidence demonstrates the appeal of biochar research due to its wide range of applications and diverse sources.

3.1.2 Most influential sources and journals contribution analysis

The contribution of journals related to biochar research was analyzed based on the total publications. Indeed, our analysis revealed that the 7076 articles have been published in 566 journals. Figure 3a presents the most influential sources in the field counting at least 5 publications. This information is valuable for researchers, as it helps them to identify appropriate outlets for sharing their work. Based on the statistical results, the top 10 journals identified include Science of the Total Environment (423 counts) followed by Chemosphere (234 counts), Environmental Science and Pollution Research (211 counts), Agronomy-Basel (157 counts), Journal of Soil and Sediments (147 counts), Environmental Pollution (133 counts), Journal of Hazardous Materials (124 counts), Journal of Environmental Management (102 counts), Geoderma (106 counts) and Sustainability (106 counts) (Fig. 3b). This finding suggests that the journal Science of the Total Environment holds the highest level of prominence within the field, accounting for 7.6% of overall contributions (Li et al. 2020; Ahmad et al. 2021). However, many journals have started to explore the topic of biochar only recently, including Soil Biology and Biochemistry, Biochar and Frontier in Microbiology (Fig. 3b). Overall, regarding the multidisciplinary field of biochar application, many highly reputed journals are available (Fig. 3b).

In terms of citations, again Science of the Total Environment revealed to be the most cited source followed by Chemosphere. Beside the predominant appearance of this journal, it started the publication on biochar in 2011 with 1 article and progressively increased publications on this subject to reach a peak of 108 publications in 2021. However, the first journal on biochar application in 2007 was Plant and Soil with regular publications on the topic from 2007 to 2023 and a maximum of 8 articles published in 2015.

3.1.3 Countries distribution and international collaboration analysis

The analysis, based on the average publication and citations per year, reveals that the 7076 original articles on biochar amendment originate from 113 countries (Fig. S2). The global distribution of research outputs on biochar, as depicted on the world map, highlights China, USA, and Germany as the primary contributors to biochar application research (Fig. S2a). China also leads in terms of single-country and multi-country publications (Fig. S2b). Factors such as funding availability, existing infrastructure, and public awareness have propelled research activities in these countries. In terms of publication and citation numbers, China stands out with 2163 articles and 69,882 citations, followed by the United

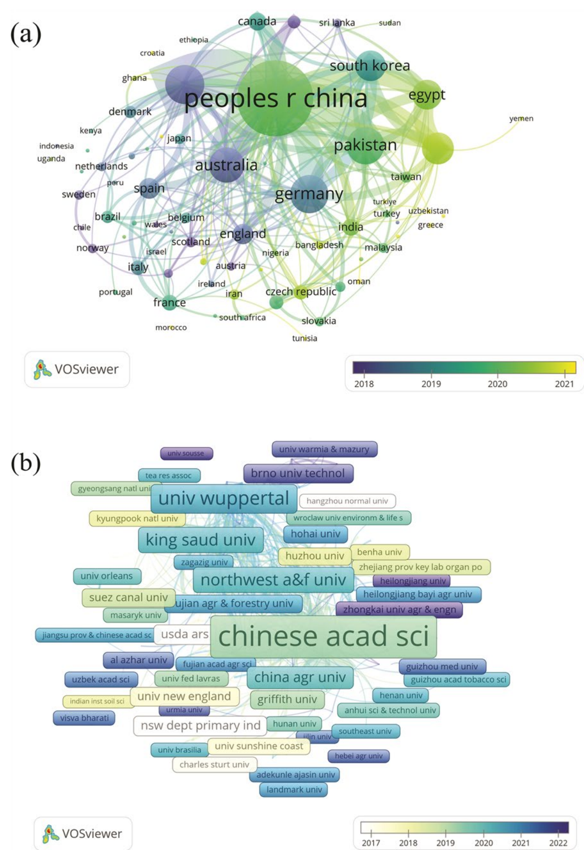


Fig. 4 The overlap visualization of the most cited country over time (**a**) and most cited institution over time (**b**)

States with 570 articles and 35,840 citations, and Australia with 312 articles and 23,455 citations (Fig. 4a). According to Leydesdorff and Wagner (Leydesdorff and Wagner 2009), while China leads in terms of volume, the qualitative impact and network influence of research from the United States of America (USA) and Australia hold substantial sway on the international stage. These findings indicate the significant interest of these countries in researching innovative remediation methods (Fig. 4a). However, among the top 10 countries, developed countries such as the USA, Australia, Germany, Canada, and Spain have a lower number of publications compared to developing countries like China, Pakistan, India, South Korea, and Egypt. Apparently, biochar research was prioritized by developing countries earlier than by developed countries.

The analysis of co-authorship between countries reveals a significant and recent relationship between China and various nations, including Pakistan, India, Saudi Arabia, Egypt, Iran, and Poland. Previously, China primarily collaborated with the United States, Australia, Germany, England, South Korea, and Spain. China has the highest number of links (61) with other countries, indicating a strong co-authorship collaboration, with a total link strength of 1345. The USA follows China with 54 links and a total strength of 495 (Fig. 4a). Thus, the total link strength represents the overall high collaborative strength of China with other countries. Based on our analysis, we can conclude that China leads the area of biochar research in terms of the number of publications, citations, and international collaborations.

3.1.4 Analysis of institutes collaboration

The analysis of co-authorship in relation to institutions was focused solely on the institutions of the corresponding author. In the current study on biochar amendment, a total of 3085 institutions around the world participated in this area of research. However, only 6 institutions, all from China, contributed at least 100 articles (Fig. 4b). Among these institutions, the Chinese Academy of Science (CAS) stands out as the most influential, with 410 publications. It is followed by the University of CAS, Zhejiang University, and Nanjing Agricultural University. The prominence of CAS can be attributed to its status as the government-supported research institution with the highest citation count in China. CAS aims to facilitate collaboration among researchers from China and around the world to address identified problems. Financial support and government policies played a crucial role in promoting the leading position of the institute (Zhang et al. 2011). These factors contribute to the institute's ability to make substantial research investments and foster an environment conducive to groundbreaking discoveries. The funding not only helps to acquire advanced technological infrastructure but also attracts top-tier talent, ensuring that CAS maintains its position at the forefront of scientific endeavors (Jacob 2023).

The top 10 productive institutes, which account for 15.85% of the total publications in the field (Fig. 4b), demonstrate an imbalance in research output. Consequently, CAS is widely acknowledged as a highly influential institution in the field of biochar amendment. For instance, the industry collaborations of CAS have greatly facilitated the implementation of biochar technologies, ensuring a smooth transition from laboratory to practical real-world applications. These partnerships have not only advanced sustainable agricultural practices but have also made significant contributions to carbon sequestration efforts. Additionally, the efforts of CAS have established new standards within the academic community and have influenced the development of policies that prioritize sustainable practices. Through collaborations with government organizations and private companies, CAS ensures the integration of biochar technologies into national strategies for environmental sustainability.

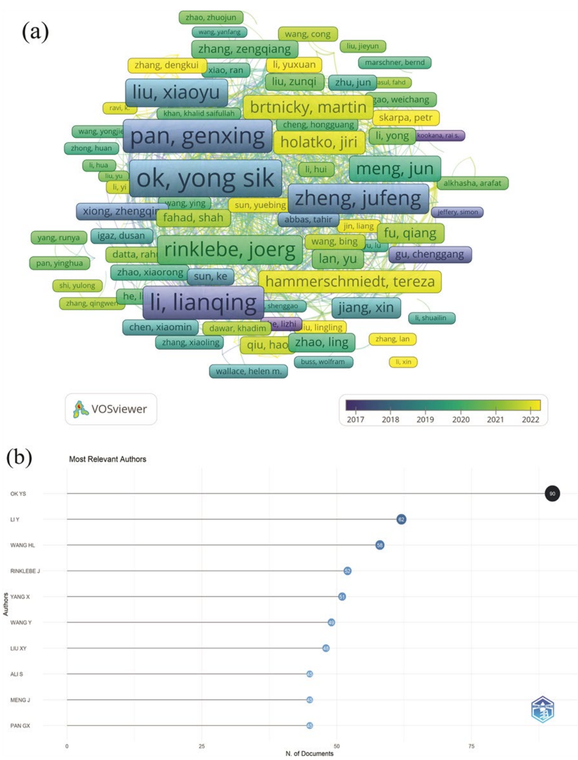


Fig. 5 The overlap visualization of average most relevant sources over time (**a**) and the top 10 of the most relevant journal sources (**b**)

3.1.5 Analysis of highly cited authors

Many influential authors have made significant contributions to research on biochar. An analysis of authorship using the"author(s)"unit of analysis and co-authorship as a type of analysis revealed that 1849 researchers have authored at least one document. Our analysis focuses on identifying the most influential authors who have published at least 5 articles (Fig. 5a). The author with the highest number of publications and citations is Ok Yong Sik, with 94 documents and 6056 citations, followed by Wang Hailong with 64 documents and 4177 citations, and Joerg Rinklebe with 48 documents and 2500 citations. Ok Yong Sik and Wang Hailong also have the highest number and strongest collaborations with other authors. Their total link strengths are 392 and 302, respectively (Fig. 5a), indicating their significant involvement in biochar research as a green clean-up solution. All of these authors share a focus on optimizing biochar production and their role in mitigating organic pollutants and heavy metals.

To gain a deeper understanding of the effectiveness of research conducted by these influential authors, we performed a threefold analysis based on the 20 most cited references, authors, and keywords (Fig. 5b). The results confirmed that Ok Yong Sik, Pan Genxing, and Joerg Rinklebe have the highest links with keywords and references. This indicates that these authors can be considered pioneers in this field of research, as their research is related to keywords such as biochar, soil remediation, bioavailability, soil amendment, carbon sequestration, heavy metals, soil fertility, compost, and charcoal (Fig. 5b). Despite their significant contributions, these authors are not among the authors of highly cited papers. This finding highlights that reliable authors are not always the fastest and most cited, as their research may be specialized within a specific field or they may have been engaged in interdisciplinary research at the time of publication.

3.1.6 Analysis of tree plot

Numerous publications have been retrieved on the topic of biochar amendment, resulting in a wide range of citation levels highlighting the link between cited references, authors and keywords (DE) (Fig. 6a), as well as countries, affiliation and cited sources (Fig. 6b). The number of citations a document receives can serve as an indicator of its reliability and relevance in the field. Generally, the more a document is cited, the more important, accurate and trustworthy the information it provides. Upon analyzing the most cited documents, several notable titles stand out (Fig. S3). Woolf et al. (Woolf et al. 2010) authored a document titled "*Sustainable biochar to mitigate climate change,*" which has gathered 1503 citations. Chan et al. (Chan et al. 2007) contributed "*Agronomic value of green waste biochar as a soil amendment*," which has received 1192 citations. "*Biochar impact on nutrient leaching from a midwestern agricultural soil*" by Laird et al. (Laird et al. 2010) has obtained 997 citations. "*Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils*" by Zimmerman et al. (Zimmerman et al. 2011) has been cited 966 times. Novak et al. (Novak et al. 2009) investigated the "*Impact of biochar amendment on the fertility of a south earthen coastal plain soil*" and has gathered 864 citations. Beesley et al. (Beesley et al. 2010) delved into the "*Effects of biochar and green waste compost amendments on the mobility, bioavailability, and toxicity of inorganic and organic contaminants in a multi-element polluted soil*," receiving 845 citations. Lastly, Park et al. (Park et al. 2011) examined how "*Biochar reduces the bioavailability and phytotoxicity of heavy metals*" and has been cited 805 times. All of these documents were published during the initial research stage of biochar, suggesting that their findings have established a standard for future research in the field. Consequently, these documents have received the highest number of citations over time.

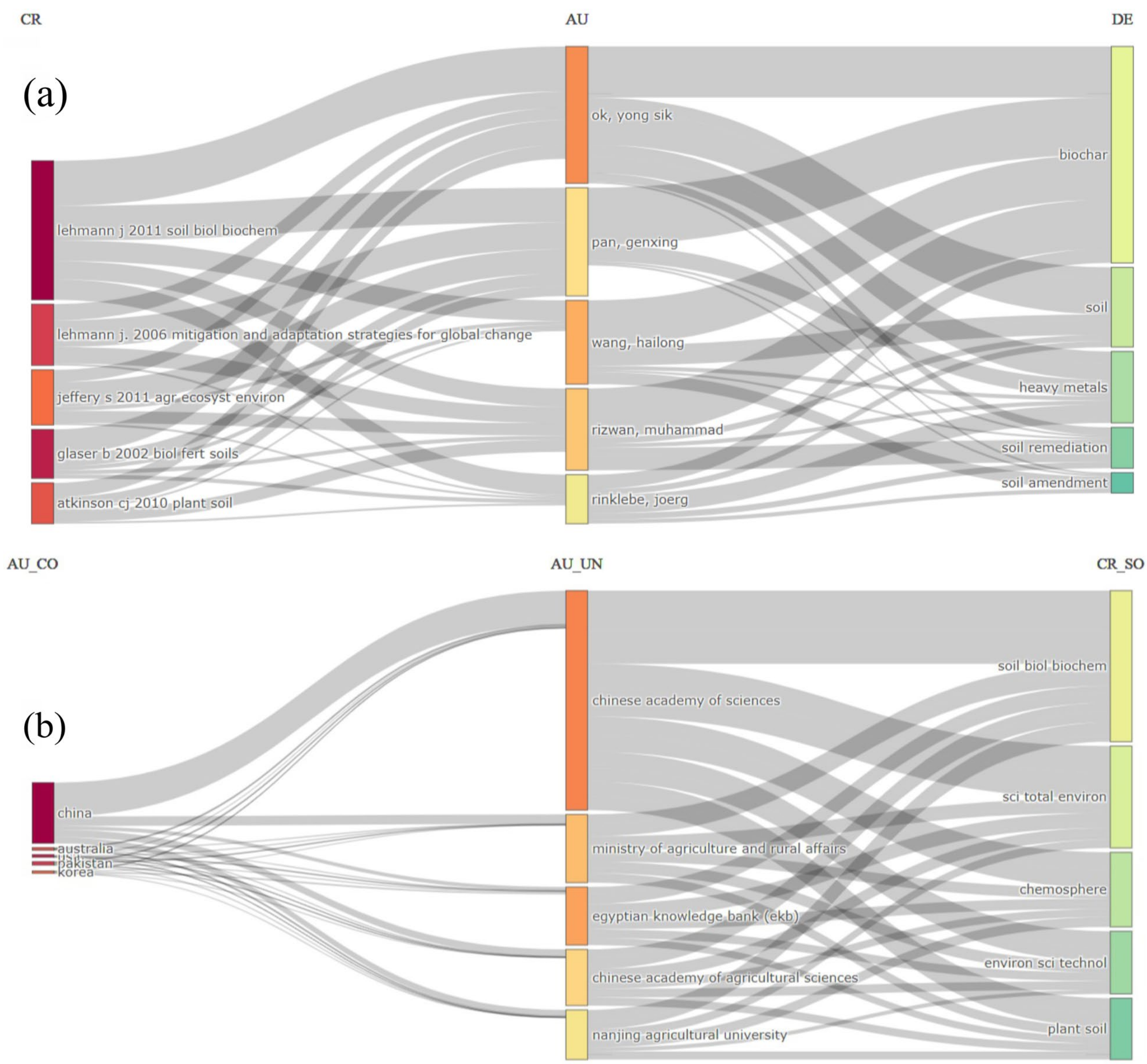


Fig. 6 Tree-field plot of the overlap visualization of interconnection between: **a** cited references (CR), authors (AU), and keywords (DE); and **b** between countries (AU_CO), Affiliation (AU_UN), and cited sources (DE)

3.1.7 Analysis of keywords and research progress

The analysis conducted in this section utilized all the collected keywords from the articles, including authors' keywords and keywords plus (additional keywords that are identified and included in article metadata to enhance the discoverability of the article) (Fig. 7a). The purpose of this analysis was to identify research trends and establish future directions in order to enhance search precision. The primary keywords with the highest occurrences and citations associated to biochar were carbon followed by black carbon, absorption, impact, amendment, heavy metals, growth, organic matter, nitrogen and bioavailability (Fig. S4a). These keywords indicate that global research on biochar focuses on its sources, the role in pollution mitigation, and environmental impact of its production. Additionally, the keyword analysis revealed that during the earlier stages of research, studies were dominated by keywords such as charcoal, mineralization, sorption, adsorption, impact, nitrogen, water, and productivity (Fig. S4b), indicating a strong research interest in characterizing biochar materials and their sorption and adsorption capacities (Yadav et al. 2018; Barbhuiya et al. 2024). In later years, the terms black carbon and cadmium emerged, indicating a shift towards

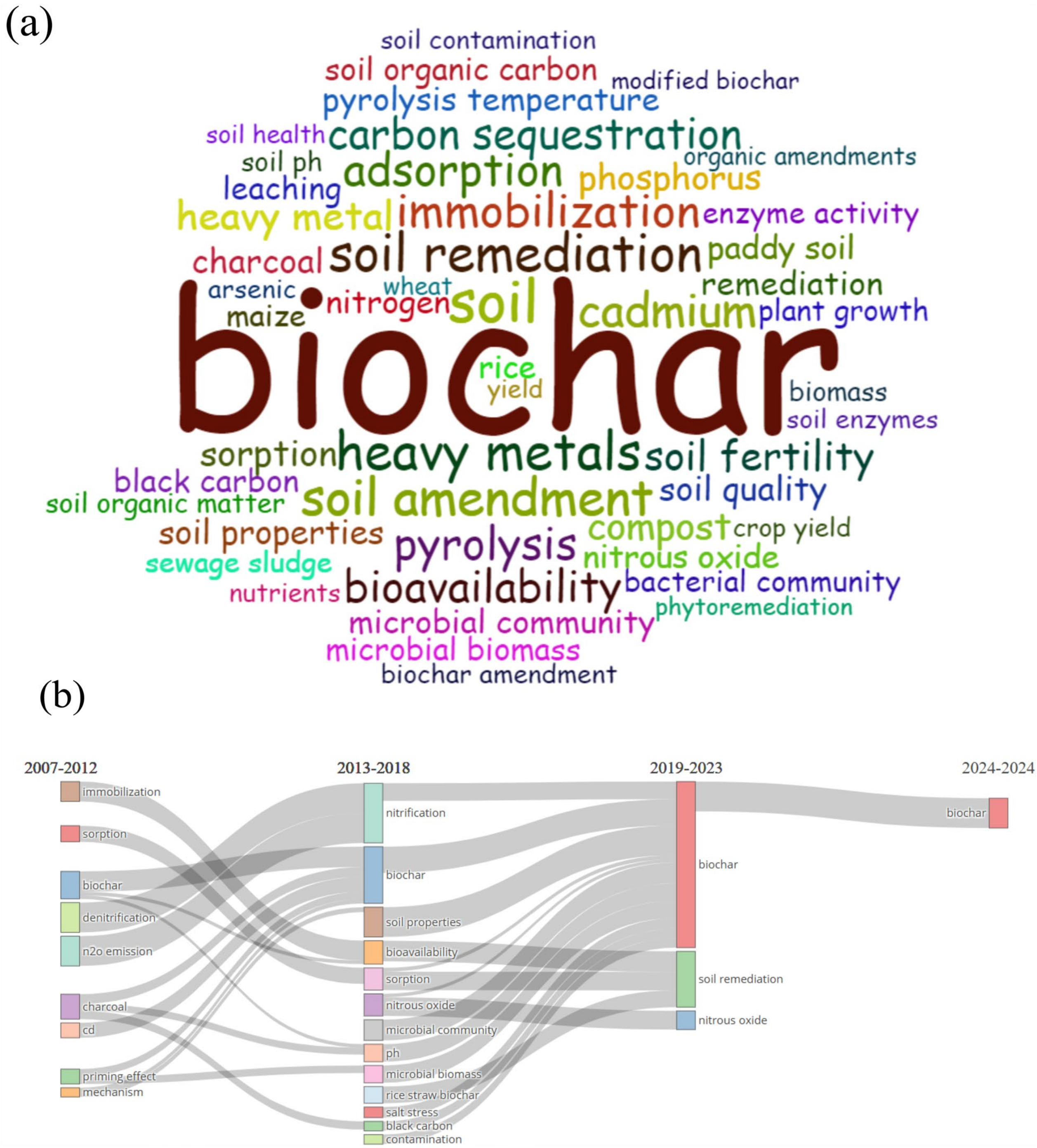


Fig. 7 The visualization of the most frequently cited keywords spanning from 2007 to 2023 (**a**); and keywords evolution including three periods: 2007–2012, 2013–2018, and 2019–2023 (**b**)

investigating the effects of biochar in heavy metal remediation, particularly cadmium (Fig. S4b). Overall, the analysis allowed us to identify three research hotspots in the field.

From 2007 to 2012, keywords such as straw, feedstock type, corn, zea mays, compost, pyrolysis, soil amendments, fertilizer manure, bioavailability, activated carbon, and biomass dominated the research (Fig. 7b). These keywords are related to biochar production, its application to soil, and its potential in soil remediation. During 2013 to 2018, the research focus shifted to keywords such as water retention, pH, salt stress, amendments, nitrous dioxide, indicating increasing interest in using biochar for water remediation (Fig. 7b). Research in this period of time was aimed to investigate the effectiveness of biochar in removing specific organic pollutants, such as polychlorinated biphenyls, which are classified as persistent organic pollutants. Also keywords such as metals, specifically Cd, Pb, Zn, Cu, also emerged during this period. These organic pollutants and metals are considered harmful to human health and the interest in studying the potential of biochar in removing them from water aligns with global research goals and sustainable development objectives related to improving access to clean drinking water (Majumder et al. 2023; Ahmed et al. 2016).

From 2019 to 2023, keywords such as CH_4, N_2O, and greenhouse gas emissions took prominence. These keywords are mainly related to air pollution, indicating that research aimed to investigate the effectiveness of biochar in improving air quality (Fig. 7b). Furthermore, keywords such as heavy metals, nanoparticles, temperature sensitivity, microbial community, and mineralization were highly used and cited. In this context, the implication of biochar in air pollution extends beyond its production through pyrolysis, which can produce greenhouse gases like CH_4 and N_2O. More importantly, researchers explored the use of biochar to mitigate air pollution through processes such as adsorption, desorption, and association with nanoparticles. This research has gained significant interest in recent years as a means of reducing environmental pollution through eco-friendly methods.

3.2 Current hotspots in biochar application

3.2.1 Biochar use as soil amendment

The primary global application of biochar has been as a soil amendment, aligning with its definition as a carbon-enriched substance applied to the soil to enhance its functionality. The initial study investigating biochar as a soil amendment was published in 2007, and since then, over 250 articles have been recorded in this field by the Web of Science. The analysis of the yearly publication numbers over the past two decades reveals a clear upward trend in interest in biochar as a soil amendment since around 2010. This result suggests a potential shift from the traditional use of biochar as fuel and soil carbon sequestration strategy towards its adoption as a soil amendment in the past ten years. This paradigm shift is primarily driven by a growing body of field studies demonstrating the effectiveness of biochar in improving various soil properties, including water retention, nutrient cycling, and the promotion of beneficial microbial communities (Vijay et al. 2021; Qian et al. 2015).

Furthermore, biochar is widely acknowledged as a soil amendment for enhancing soil quality. However, there is currently no precise definition of biochar as a soil amendment product in the United States (Novak et al. 2014). This lack of clarity may present challenges for individuals seeking to utilize biochar in their soil amendment products. Despite this constrain, Jha et al. (Jha, et al. 2010) provided foundational evidence that biochar may extend beyond conventional soil amendment roles by potentially interacting with plant molecular genetics. Surprisingly, the plant genetics literature pays little attention to the use of biochar as a soil amendment. This highlights a gap between the fields of soil science and plant genetics, particularly regarding the understanding of how biochar addition activates specific genes in roots. This knowledge could contribute to the development of plants capable of adapting to harsher environmental conditions.

On the other hand, soil science predominantly focuses on the nutrient effects of biochar and its potential impact on greenhouse gas or ammonia emissions from manure (Lyu et al. 2022). In terms of geochemistry, there are relatively few articles that specifically address biochar as a soil amendment. However, the application of biochar was reported to significantly enhance soil geochemistry, particularly in terms of nutrient retention, water holding capacity, and microbial activity (Yu et al. 2013; Giagnoni and Renella 2022) with particular emphasis on the effects of biochar amendments on soil nutrient composition and microbiology. However, the geochemical literature seems to have overlooked the long-term effects of the soil amendment efficiency of biochar in recent years, which presents an opportunity for new research ideas. Overall, biochar soil amendment research has the potential to greatly benefit those working in the field of environmental science, as it has the potential to integrate genomics, geochemistry, and plant nutrition related to biochar amendment research into a comprehensive system in future.

3.2.2 Biochar use for water treatment

The utilization of biochar for wastewater treatment is a recent and evolving area of research. The application of biochar has demonstrated the potential to enhance water quality and reduce treatment costs by providing a suitable medium for microorganisms to degrade organic matter and pollutants present in wastewater (Novak et al. 2016). There are currently two primary methods of biochar application in wastewater treatment: the suspended biochar system and the fixed-bed biochar system. In the suspended biochar system, biochar is finely ground and mixed into a slurry, which is then utilized as a filter medium in the treatment of wastewater (Fig. S5).

Conversely, in the fixed-bed biochar system, biochar is packed into a filter bed and wastewater is allowed to percolate through it (Inyang and Dickenson 2015; Enaime et al. 2020).

Randomized trials have consistently demonstrated that the inclusion of biochar in wastewater treatment processes leads to improved removal rates of pathogens and organic compounds, surpassing those achieved through traditional treatment methods. The effectiveness of biochar can be attributed to its porous nature, which provides an increased surface area for the adsorption of pollutants. As a result, what was once regarded as waste biomass now presents itself as a valuable resource for initiatives focused on ecological sanitation (Enaime et al. 2020). For example, Gupta et al. (Gupta et al. 2022) elucidated that biochar fosters a favorable environment for microbial communities within wastewater systems, thereby expediting the breakdown of volatile fatty acids, a problematic pollutant in untreated water. Future research efforts in this area may concentrate on optimizing the design of biochar systems and enhancing treatment efficiency.

The establishment of a detailed range of optimal operating conditions for different wastewater parameters is crucial, particularly considering the advancements in characterization techniques and numerical simulation (Faisal et al. 2023). These contemporary methodologies have revolutionized the manner in which engineers determine the ideal operating conditions required to meet regulatory standards and achieve sustainable waste treatment goals.

3.2.3 Biochar use in air pollution control

In air pollution control, biochar can be used to remove organic pollutants from industrial and domestic wastewater and in controlling gaseous pollution. Current research has been focusing on defining the suitability of different biochar types in adsorbing organic gases and particulate matter from air. Previous studies have reported the effectiveness of biochar in absorbing gases such as methane, ammonia, and hydrogen sulfide. Gwenzi et al. (Gwenzi et al. 2021) delineated how specific variants of biochar demonstrate exceptional proficiency in adsorbing organic gases and particulate matter, thereby purifying air to a remarkable extent. Chandra and Bhattacharya (Chandra and Bhattacharya 2019) indicated that when biomass undergoes pyrolysis at carefully calibrated temperatures, the resulting biochar exhibits increased porosity along with a greater surface area–characteristics essential for maximizing adsorption efficiency.

On the other hand, it was highlighted that the surface acidity of biochar can act as a key factor in the removal of ammonia gas, with the biochars containing the highest acidic functional groups showing the highest ammonia retention over time. According to Chen et al. (Chen et al. 2021a), these functional groups comprising mainly carboxyl and hydroxyl groups engaged in hydrogen bonding and electrostatic interactions with ammonia molecules. This engagement not only facilitates the initial adsorption of ammonia onto the biochar surface but also contributes to its long-term sequestration. As a result, biochar may present a low cost and environmentally friendly alternative to waste management since it can be produced from waste biomass and has the potential to be used in gas purification, with the added benefit of reducing biomass waste through pyrolysis. The increasing number of patents relating to the use of biochar. includes methods for producing biochar and bio-oils, as well as apparatus for gasifying biomass to produce biochar. The number of patents for the use of biochar in pollution and emissions control is also increasing, *e.g.,* for reducing and preventing air pollution and treating food processing wastewater using biochar (Kumar and Bhattacharya 2021).

3.2.4 Biochar use in agricultural applications

The use of biochar in agriculture is one of the most widely researched areas, and many review articles focus on this topic (Dwibedi et al. 2023; Rombola et al. 2022; Wang et al. 2022). Biochar can be used as a soil amendment, and in recent years, there has been increasing interest in integrating biochar with fertilizer application to improve the nutrient retention capacity of the soil. The impacts of biochar on soil physical properties, chemical properties, microbial activities, and greenhouse gas emissions from soil, as well as plant productivity and the economics of biochar in agricultural practices, have been extensively studied (Wang et al. 2022). These studies showed that biochar amendment improves the water holding capacity, and increases the cation exchange capacity of the soil, which is crucial for nutrient retention in the soil and nutrient supply to plant roots. Furthermore, Rombel et al. (Rombel et al. 2022) conducted an experiment that supports the idea that combining biochar with conventional fertilizer formulations not only enhances soil fertility, but also improves crop yield through better nutrient management practices. This finding highlights the important role of biochar in advancing sustainable agricultural methods that balance productivity gains with ecological stewardship, aligning perfectly with global efforts to reduce the environmental impact of agriculture while meeting the food demand of an increasing world population. Both field and laboratory experiments have been conducted in this area, and the physico-chemical properties of the applied biochars are usually thoroughly characterized. Research on the water retention capacity of soil demonstrated that biochar addition can significantly increase the ability of soil to retain water (Kumar and Bhattacharya 2021). This may be due to the high porosity of biochar, which increases soil water holding capacity, while the hygroscopic nature of biochar allows water absorption and slow release to the surrounding soil due to the water-repellent surfaces of biochar particles, and the good connectivity of pore spaces in biochar (Chen et al. 2021b; Verheijen et al. 2022).

3.2.5 Biochar for waste management and bioenergy production

Typical waste in modern society, such as municipal solid waste, industrial waste, and hazardous waste, can be classified as organic or inorganic. Organic waste contains carbon, while inorganic waste mainly consists of minerals such as metals, glass, and plastics. Over 60% of the annual waste in the world is organic (Wilson et al. 2015). When organic waste is buried in landfills, it undergoes anaerobic digestion by microorganisms, leading to the release of methane, a harmful greenhouse gas (Ragazzi et al. 2017; Zulkepli et al. 2017). This process contributes to global warming and causes water pollution due to the production of leachate. Biochar provides a practical solution for managing organic waste. As a form of carbon produced by heating organic material at high temperatures without air (pyrolysis) it can be used in conjunction with anaerobic digestion processes, thereby increase the biogas yield by up to 30% (Zhao et al. 2021). This improvement directly enhances the efficiency and viability of biogas as a renewable energy source, addressing environmental concerns and the need for reliable alternatives to fossil fuels. The increased efficiency of biogas production could result in more operational anaerobic digestion plants, leading to better management of organic waste that is currently not economically viable to treat, thereby also introducing new revenue streams.

In addition to its environmental benefits, the byproduct of biochar production, referred to as bio-oil, can serve as renewable fuel. Sharma et al. (Sharma, et al. 2019) emphasize the importance of adopting thermal cracking and esterification processes, which effectively minimize the presence of free radicals and unwanted acidic compounds in bio-oil. This transformation not only enhances the stability and combustion efficiency of bio-oil, but also expands its applicability across various industrial sectors. Zacher et al. (Zacher et al. 2014) outlined a range of feasible approaches for refining bio-oil, not only to alleviate its inherent drawbacks, but also to maximize its usefulness as a sustainable energy source. Furthermore, biochar serves as a co-product alongside bio-oil and syngas, providing an additional source of renewable energy (Iwuozor et al. 2023). Such endeavors not only hold the potential for a decrease in waste generated through biochar production but also signify efforts towards diversification of fuel supply by environmentally sustainable alternatives.

3.2.6 Integration of biochar with other green clean-up methods

The integration of biochar with other green clean-up methods can address environmental contamination and promote sustainable remediation practices. This approach combines biochar with techniques such as phytoremediation or microbial degradation to maximize contaminant removal efficiency while minimizing negative environmental impacts (Lyu et al. 2022; Inyang and Dickenson 2015). By targeting multiple pathways of contaminant degradation and immobilization synergistically, this integrated approach enhances overall remediation effectiveness. Additionally, the use of biochar in conjunction with other green clean-up methods contributes to the restoration and improvement of soil functionality, including nutrient cycling and water retention (Yuan et al. 2019; Ahmad et al. 2014). One significant benefit of integrating biochar with other green clean-up methods is its potential to enhance soil carbon sequestration (Xia et al. 2023). The high carbon content of biochar facilitates soil carbon storage, which helps mitigate climate change by counteracting the increase of atmospheric carbon dioxide levels. By combining biochar with phytoremediation or microbial degradation, contaminated sites can be remediated, while also achieving long-term carbon sequestration in the soil (Inyang and Dickenson 2015; Wang et al. 2024). This aligns with broader goals related to environmental contamination and climate change mitigation (Anand et al. 2022).

Integrating biochar with phytoremediation enhances contaminant removal and improves soil quality also by providing a habitat for beneficial microbes that complement the uptake and degradation of contaminants by plants (Yang et al. 2021). The porous structure of biochar enhances nutrient availability to plants, promoting their growth and remediation effectiveness. The relationship between chemical compositions, structural properties, and reactivity in biochar is important for advancing its use in environmental remediation (Qin et al. 2022a). Structural attributes such as pore size distribution and specific surface area are crucial as they directly affect the accessibility of these active sites to pollutants (Wan et al. 2020). For instance, biochars with well-developed micropores facilitate the adsorption of small organic molecules, while those with meso- and macropores are better suited for trapping larger entities or providing habitat space for microbial communities involved in biodegradation (Qin et al. 2022a; Zheng 2020). The synergy between biochar and microbial degradation provides an additional avenue for effective clean-up. Microorganisms play a key role in the degradation of contaminants, and biochar provides a conducive environment for the microbial community to carry out degradation processes (Zhu et al. 2017). According to Waqas et al. (Waqas et al. 2021), biochar acts as a scaffold for microbial communities, providing not only a large surface area for adhesion, but also hosting essential nutrients that support microbial growth. The porous structure of biochar also provides sites for attachment and localization of the degrading microorganisms, thereby enhancing their activity and promoting contaminant degradation.

3.2.7 Biochar production techniques and characterization

Biochar is a carbon-rich product derived from biomass materials through pyrolysis under oxygen-limited conditions. Its physical and chemical properties are influenced by the pyrolysis temperature. At lower temperatures, increased hydrogen bonding enhances the ability of water to support diverse functional groups for ecological and biochemical processes (Akiya and Savage 2002). Conversely, higher temperatures weaken these bonds, resulting in reduced oxygen solubility and increased pH levels (Howes et al. 2015). Surface area and pore volume generally increase with pyrolysis temperature up to a certain threshold, beyond which they decrease. Intermediate pyrolysis, within a temperature range of 400 °C to 600 °C, maximizes bioenergy recovery while producing biochar as a byproduct (Kazawadi et al. 2021). By avoiding the decrease in yield and quality observed at higher temperatures (Manyà et al. 2018), bioenergy can be efficiently extracted and biochar can achieve an optimal structure, with a superior surface area and suitable pore volume for applications as soil amendment. Residence time and heating rate are also important considerations.

Advanced techniques such as microwave and hydrothermal pyrolysis improve the quality of biochar for specific applications. Microwave biochar has a high surface area and an ordered, porous structure, while hydrothermal biochar exhibits a lower surface area and a higher degree of carbonization compared to conventional biochar produced at the same pyrolysis temperature (Paramasivan 2022). These techniques open up new possibilities for the use of biochar in various applications. Analytical techniques such as Fourier-transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), nuclear magnetic resonance (NMR) spectroscopy, Brunauer–Emmett–Teller (BET) surface area analysis, XRD, SEM, Raman spectroscopy, transmission electron microscopy (TEM), and scanning transmission X-ray microscopy (STXM) are used to characterize biochar (Donne and Appendix 2. 2017; Ngan et al. 2019). For example, Raman spectroscopy provides information on the degree of graphitization in biochar, which is important for its electrical conductivity properties and its potential use in energy storage devices. Collectively, these methods offer a comprehensive understanding of the structural composition and thermal stability of biochar, which are key factors in determining its suitability for environmental remediation projects or as an effective soil amendment.

3.3 Emerging topics in biochar use for environmental clean-up

To evaluate emerging topics and future trends, we assessed the timeline, development and relevance of subject categories, keywords, author's keywords, title words, and abstracts (Fig. S6 and S7). Understanding the niche of biochar amendment helps identify specific areas where it may be most effective. Analyzing emerging trends allows us to anticipate future demand and potential growth of this green cleanup method. Our modularity and silhouette score confirmed the objectivity and reliability of the results obtained (Fig. S6). The modularity Q value measures the strength of network division into clusters or modules. According to Thébault (Thébault 2013) and Song and Yang (Song and Yang 2024), a higher Q value indicates a better network structure and ensures the reliability of conclusions drawn from complex network studies. Our results showed a modularity of 0.8812 (Fig. S6). Furthermore, the silhouette score measures the similarity of an object to its own cluster compared to other clusters (Thrun 2018). A higher silhouette score indicates a well-defined and coherent cluster structure. Our study achieved a silhouette score of 0.9715, indicating that the data points within a cluster are more similar to each other than to those in other clusters, effectively demonstrating robust internal cohesion (Shahapure and Nicholas 2020). Figure 8 provides an overview of the current hotspots, trends, and future prospects.

Niche themes indicate major shifts when they gain broader recognition. For instance, niche themes in previous studies reveal the role of biochar in enhancing soil fertility and sequestering carbon, particularly beneficial in agricultural settings where soil quality directly impacts productivity (Pandey 2023). Emerging themes, on the other hand, represent innovative concepts that are gaining momentum and serve as early indicators of significant future impacts across various industries (Al Masud et al. 2023). Basic themes, in contrast, provide foundational knowledge that remains consistent over time but evolves gradually, forming the basis for new trends. Meanwhile,

Fig. 8 Current hotspots, trends, and future prospectives of biochar application as a green clean-up method. Data from VOSviewer, Bibliometrix, and CiteSpace were used to generate this representation. The prominence of soil remediation, water treatment, and air pollution control as current hotspots highlights proven effectiveness of biochar in these fields. This aligns with the global need to address soil and water contamination. The emergence of renewable energy, circular economy approaches, and nanotechnology as key trends is interesting, as it shows the expanding scope of biochar applications beyond traditional remediation, in line with broader sustainability goals. The future prospects of carbon sequestration, biochar in sustainable construction, and phytoremediation are particularly exciting, as they indicate a shift towards more sophisticated and tailored biochar materials with enhanced functionality

motor themes are influential drivers of change within a thematic network.

3.3.1 Emerging research areas in biochar application

The present analysis reveals that the majority of publications focus on soil application, followed by studies on the role of biochar in water treatment, air pollution control, and waste management (Fig. 8). However, there is a rapidly changing trend with emerging research areas in biochar application (Fig. S6 and S7). For instance, there is increasing research interest in using biochar to remediate contaminated land. Another promising area of research is exploring the ability of biochar to remove emerging contaminants, such as pharmaceuticals and personal care products. Furthermore, there has been noticeable biochar research in the fields of engineering and environment, where engineers and environmental scientists are collaborating to uncover the potential of biochar in addressing environmental pollution (Das et al. 2023; Qin et al. 2022b; Meng et al. 2024).

Additionally, research interest is shifting towards field-based or pilot studies, indicating a greater focus on the practical aspects of biochar application and its long-term effects. Moreover, advanced research techniques, like SEM and XRD enable researchers to investigate the molecular and elemental composition of soil after the application of biochar (Faheem et al. 2020). In this context, the use of SEM provides a magnified visual representation of the interaction between biochar and soil particles, revealing how this carbon-rich amendment can modify pore structure and potentially enhance water retention capabilities of the soil (Faheem et al. 2020; Buss et al. 2020). Simultaneously, XRD analysis offers a complementary perspective by identifying chemical changes within soil matrices, including shifts in mineral composition that may directly impact nutrient uptake by plants (Faheem et al. 2020; Buss et al. 2020). This integrated approach, combining imaging and analytical technologies, equips scientists with a powerful toolkit to systematically understand the complexities associated with the impact of biochar. Lastly, recent research explores the use of biochar as an additive in green construction materials, such as cement and asphalt, which holds significant potential in reducing the carbon footprint of these materials (Singhal 2023; Chaturvedi et al. 2023).

3.3.2 Innovative techniques for biochar production

Various innovative biochar production methods such as co-pyrolysis (Fig. S5) have been discussed in literature. This method involves the simultaneous thermal decomposition of biomass with another organic material under an inert atmosphere, resulting in a higher quality biochar alongside other valuable by-products such as bio-oil and syngas (Ahmed and Hameed 2020). Impregnating raw material with a chemically ionized substance in an electrical field can create a 'pre-char' with enhanced electrical conductivity for microwave absorption that can be used for microwave heating to generate biochar. The pre-char efficiently absorbs the microwave irradiation and facilitates the heating process, leading to improved efficiency and output in biochar production (Wang et al. 2021; Wang et al. 2020a; Wang et al. 2020b). While this research primarily focuses on biochar production from organic waste, other studies have explored similar approaches for producing biochar from contaminated soil. Ongoing research is also conducted to enhance the effectiveness of traditional biochar production methods (Fig. S6). For example, Inyang and Dickenson (Inyang and Dickenson 2015) suggested the use of physical and chemical activation techniques, as well as embedding material on the surface of biochar to enhance the effectiveness of traditional biochar production methods. These advancements in biochar engineering have opened up new possibilities for the treatment of a wide range of organic contaminants in aqueous systems.

Moreover, the higher temperature observed at the center of reactors used for biochar production aligns with the actual production process (Liu et al. 2017). In this context, the use of hydrothermal carbonization offers a promising solution for biochar production, as it requires less energy compared to other thermochemical treatment processes. Additionally, a new method called plasma-arc pyrolysis has attracted considerable attention (Fig. S7). This approach involves generating a high-temperature plasma field through strong electrical discharge between two electrodes (Hazra et al. 2019; Tripathi et al. 2016). Under elevated temperatures and an oxygen-free environment, biomass is decomposed and converted into gas and biochar. One significant advantage of plasma-arc pyrolysis is its speed, with extremely high heating rates reaching several tens of thousands of degrees per second from ignition to arc establishment.

3.3.3 Expanding biochar utilization in agriculture

With the global population constantly increasing, there is a growing demand for food production worldwide. Unfortunately, intensive farming practices have led to a range of environmental issues, such as soil erosion, fertility loss, nutrient runoff, water pollution, and greenhouse gas emissions. As a result, modern agriculture is shifting towards more sustainable practices in order to minimize its environmental impact while maintaining productivity. One such sustainable practice is the use of biochar as a soil amendment. The addition of biochar to agricultural soil has numerous benefits, including increased nutrient retention, enhanced microbial activity, and reduced greenhouse gas emissions (Kavitha et al. 2018; Lyu et al. 2022; Wang et al. 2022). For instance, it can improve soil water holding capacity, thereby reducing water and nutrient leaching, and safeguarding surface and ground water (Major et al. 2012). Additionally, biochar has a high liming capacity, making it effective in stabilizing acidic soils and enhancing soil quality (Saleem et al. 2022). Moreover, its porous nature promotes the abundance of beneficial microbes and improves nutrient cycling in the soil. Furthermore, biochar, being a recalcitrant form of organic carbon, has the ability to sequester carbon and mitigate greenhouse gas emissions from agricultural soil (Zhang,, et al. 2023). These multiple benefits highlight the potential of biochar in solving environmental challenges posed by current farming practices.

3.3.4 Biochar as a carbon sequestration tool

Biochar has demonstrated efficacy in carbon sequestration, owing to its high carbon content, resistance to degradation, and porous structure (Fig. S6 and S7). Numerous studies revealed that both laboratory-produced and field-produced biochar can effectively serve as carbon sinks in diverse soil types (Shackley et al. 2016). Laboratory-produced biochar generally exhibits a more controlled and uniform quality as a result of regulated production parameters (Li and Tasnady 2023). This ensures consistent effectiveness in carbon retention. In contrast, field-produced biochar offers benefits in terms of adaptability and suitability for various environmental applications. This is due to the use of diverse input materials and production conditions that reflect local ecosystems (Li and Tasnady 2023; Tan 2019). Recognizing these distinctions between biochars produced under different settings confirms their complementary capabilities as carbon sinks but emphasizes the need to tailor application methods to optimize their potential in mitigating climate change through soil carbon enhancement.

Research on the carbon sequestration associated with biochar production primarily focuses on assessing its lifespan. While there is significant emphasis on quantifying measures like mean residence time (MRT), there is a lack of understanding regarding how soil–biochar interactions and external environmental factors affect these dynamics (Leng et al. 2019). This perspective is crucial as it goes beyond evaluating the general long-term carbon storage ability of biochar and instead assesses its real-world effectiveness under different environmental conditions (Zhang et al. 2019). There is a need for a comprehensive understanding of the lifespan of biochar in various environments. It is evident that the desired characteristics of biochar will vary depending on its intended use. Future investigations must go beyond traditional boundaries to fully comprehend the role of biochar in sustainable management practices and climate change mitigation efforts (Downie 2011). Therefore, establishing a robust scientific foundation and practical regulatory framework for monitoring biochar quality in all approaches related to its application is of utmost importance.

3.3.5 Biochar in sustainable construction and development

Biochar may be utilized as an alternative to cement or asphalt in construction. The concrete industry is a major producer of CO_2 emissions due to the energy-intensive production process and release of large amounts of CO_2 into the atmosphere (Adesina 2020). Incorporating biochar into the production process can extend the lifespan of concrete while absorbing CO_2, due to its porous network acting as a sink for trapping partially oxidized organic materials. Specifically, biochar can act as a lightweight aggregate that improves the thermal resistance of material and reduces permeability, two key factors that substantially contribute to its durability (Barbhuiya et al. 2024). This reduces the need for cement, thereby extending the lifetime of structures like bridges and walls. This highlights that biochar can provide a more sustainable construction model by effectively reducing the carbon footprint linked to cement production.

3.3.6 Life cycle assessment

Life Cycle Assessment (LCA) is a widely utilized method for assessing the environmental impacts of production, product systems, and services (Fig. 8). It covers the entire lifespan of a product, from the acquisition of raw materials to its final disposal (Ingwersen et al. 2014). A crucial element of LCA is its systematic examination of the environmental consequences throughout the entire lifecycle. Changes in land use resulting from biochar amendment can have various effects on climate, greenhouse gas emissions, soil system and ecosystem services (Roberts et al. 2010; Matuštík et al. 2020). These alterations subsequently influence the net emission profile by affecting emission sources and sinks identified in LCA inventories. Therefore, evaluating the systemic impacts of these scenarios on different emission sources and sinks can offer valuable insights into the overall environmental sustainability and carbon footprint of agricultural practices. However, limited research has been conducted on various land use change scenarios, such as converting pastures into energy crops due to biofuel markets or shifting from conventional arable crops to energy crops or corn stover, with or without N_2O emissions from fertilizers. Additionally, studies on the effects of adding biochar to arable lands without changing the crop type within GHG cycling studies are lacking.

Another significant application area for biochar is its potential use as an alternative to coking coal in metallurgical processes, specifically steel manufacturing. While biochar and coke have similarities in structure, there are differences in reactivity and ash mineral composition that may significantly influence environmental burdens. Currently, there is no peer-reviewed LCA comparing traditional coking coal with biochar in this industry.

Conducting such comparative studies presents a worthwhile opportunity to bridge this gap and gain valuable insights. On the other hand, the use of green hydrogen is a significant step towards achieving environmental sustainability and meeting market demands for cleaner products (Souza Filho et al. 2022). By moving away from fossil fuels, which contribute to high CO_2 emissions, the steel sector can reduce its environmental impact.

3.3.7 Circular economy approach

The concept of the circular economy has gained significant attention in recent years, both in academic literature and policy documents (Fig. 8). It offers a means to reconcile economic development with environmental protection (Kurniawan et al. 2023). An exemplification of the zero-waste lifecycle is biochar production, where its by-products are effectively recycled back into the economy. This process has positive impacts on both, economies and ecosystems. Previous studies have examined the efficiency of the biochar production cycle and demonstrated successful integration of circular economy principles. This reflects the emergence of a "bio-materials-extensive" economy that promotes local eco-industries and facilitates decentralization. For example, Singh et al. (Singh et al. 2022) highlights how the reintegration of biogases and other by-products generated during pyrolysis of biochar transforms potential waste into valuable resources, thus embodying the sustainability promise of biochar manufacturing. It is recommended to expand the introduction to the circular economy approach and its compatibility with biochar into a dedicated section to encourage further discussion and research in the field.

Creative collaborations should be encouraged with various sectors, including material science, agricultural products, and geography, to investigate sustainability from both economic and environmental perspectives. There is significant potential for transitioning from the current linear economy to a circular model, characterized by minimal waste and the repurposing of bio-waste for diverse applications (Vasiljevic-Shikaleska et al. 2017). Consequently, policy intervention is crucial to promote the adoption of a circular economy approach in biochar production and utilization. Both regulatory and economic policy measures should be implemented to enhance the feasibility of implementing this approach. For instance, governments could provide tax incentives or subsidies to assist farmers and stakeholders in embracing the innovative biochar technology and the concept of circular economy.

3.4 Future trends in the use of biochar for environmental clean-up

3.4.1 Interaction between biochar with plant molecular biology and soil microbiomes

The interaction between biochar and plant molecular biology offers a promising approach to enhancing the effectiveness of biochar in environmental remediation. Biochar improves soil health and nutrient retention while fostering plant resilience and growth. However, its impact is also due to the complex biological mechanisms it influences within plant-soil systems. While the contribution of biochar to soil health and nutrient retention is well documented, Polzella et al. (Polzella et al. 2019) observed minimal direct effects on plant growth and soil nutrients under certain conditions, highlighting its dependence on intricate biological mechanisms. Biochar can alter root morphology and modify signaling pathways related to stress responses, enabling plants to adapt more effectively to adverse environmental conditions. Furthermore, biochar influences molecular signaling pathways crucial for plant adaptation to abiotic stresses (Gorovtsov et al. 2020). Biochar-mediated changes can regulate gene expression related to nutrient uptake and stress response, reinforcing plant vigor. It can stimulate specific enzymes and enhance root exudation, encouraging beneficial microbial interactions that improve nutrient cycling. According to Minofar et al. (Minofar et al. 2025), biochar significantly influences the activity of key enzymes like P. stutzeri N_2OR (PsN2OR) from *Pseudomonas stutzeri*, which plays a crucial role in nitrogen cycling. This interaction underscores the contribution of biochar to fostering beneficial microbial networks and its indirect yet profound impact on plant growth and adaptation mechanisms under stress conditions.

The interaction of biochar with soil microbiomes offers a dual benefit: enhancing soil health and fertility while serving as a green method for environmental remediation. Yadav and Ramakrishna (Yadav and Ramakrishna 2023) highlight that biochar significantly influences soil microbial communities, causing shifts in the balance between bacterial and fungal populations. This recalibration stems from the porous structure of biochar, which facilitates microbial habitation and fosters beneficial microbial communities (Brtnicky et al. 2021). These shifts amplify ecological resilience, improve nutrient cycling, and suppress pathogenic organisms, ultimately leading to improved soil fertility and health. The enhanced microbial activity boosts nutrient availability and enzymatic activities essential to soil health. Beyond its biological benefits, biochar exhibits a remarkable adsorptive capacity, allowing it to sequester heavy metals and organic pollutants, immobilizing toxins that disrupt soil ecosystems as well as plant–microbial–soil interactions and threaten agricultural productivity. The dual action of fostering beneficial microbial communities and immobilizing contaminants makes biochar a cornerstone in sustainable agriculture and environmental remediation. The effects of biochar on soil microbiomes are complex and influenced by factors such as time and geographic site (Liu et al. 2017). Nonetheless, significant shifts in microbial composition that underscore ecological resilience have been consistently observed. Therefore, by merging biological enhancements with contaminant immobilization, biochar demonstrates its potential as a powerful tool for environmental detoxification.

3.4.2 Economic feasibility for biochar implementation

The economic feasibility of biochar implementation is a complex issue, influenced by a variety of factors. At the forefront of these considerations are the initial investment costs for biochar production, which can vary significantly depending on factors such as feedstock availability, technological infrastructure, and regional market conditions (Patel and Panwar 2024). These costs, along with market-specific variables, are crucial in determining the minimum selling price (MSP) of biochar (Downie 2011). However, such upfront costs can be counterbalanced by potential revenue streams, most notably through carbon credits. Joseph et al. (Joseph et al. 2015) highlight that carbon credits represent a vital mechanism for offsetting initial production expenses. These credits function as a way to valorize the environmental benefits of biochar, particularly its ability to sequester atmospheric carbon dioxide and mitigate climate change. The ability of biochar to sequester carbon not only provides environmental merit, but also aligns with global carbon trading frameworks, offering an income stream that can help offset production expenses (Price et al. 2024). Indeed, opportunities for revenue generation through carbon credits have increasingly been acknowledged as a pivotal financial lever in promoting sustainable agricultural practices. The monetization of environmental contributions of biochar, especially its carbon sequestration capabilities, incentivizes sustainable practices, making the technology economically more viable (Majumder et al. 2019; Galinato et al. 2011). Therefore, while initial investment costs are a significant consideration, the potential for financial return through carbon credits is key to the successful and widespread implementation of biochar.

3.4.3 Policy implications for biochar large-scale adoption

To maximize the benefits of biochar for climate mitigation and agriculture, policymakers should adopt a comprehensive strategy that combines economic incentives, regulatory frameworks, and collaborative partnerships, supported by robust monitoring systems (Xia et al. 2023; Gurwick et al. 2013). Offer phased subsidies for biochar producers and users, prioritizing smallholder farmers and early adopters through tiered grants based on farm size or production volume, as well as input-linked subsidies covering 30–50% of production costs, and performance-based payments tied to verified carbon sequestration outcomes (Zhang et al. 2016; Pourhashem et al. 2019; Chiaramonti and Panoutsou 2019). Expand fiscal incentives beyond generic carbon credits by integrating biochar into climate policy frameworks, developing standardized methodologies for biochar carbon sequestration under the Paris Agreement, offering tax exemptions for biochar-related equipment, and partnering with development banks for low-interest loans in high-emission agricultural regions.

Establish regionally co-funded biochar hubs to pilot decentralized production models, provide government-backed loan guarantees to de-risk private investments, and mandate agri-food corporations to allocate a percentage of carbon offset budgets to biochar projects to ensure stable market demand (Karim 2020; Latawiec et al. 2017). Set national biochar quality standards aligned with international certifications to define feedstock purity, pyrolysis protocols, and contaminant limits, and link biochar use to existing regenerative agriculture programs to streamline adoption. Encourage farmer participation by indemnifying against unintended consequences, such as soil pH shifts (Ma et al. 2009). Address knowledge gaps through train-the-trainer programs, deploying agronomists as regional biochar ambassadors, focusing on marginalized communities, and allocating up to 40% of training slots to women farmers. Provide digital decision-support tools offering localized application guidelines. Track the impact of biochar on soil organic carbon over 5–10-year cycles, implement third-party verification of sequestration claims, and conduct biannual stakeholder forums to refine policies based on data (Phillips et al. 2020; Pradhan et al. 2024b). Align biochar policies with national climate goals and pilot programs in high-potential regions like degraded soils in Southeast Asia to demonstrate feasibility before scaling.

By anchoring these measures in localized evidence and iterative learning, governments can transition biochar from a niche innovation to a cornerstone of climate-resilient agriculture, ensuring equitable access, environmental integrity, and long-term scalability. To facilitate large-scale adoption of biochar, policy frameworks should incentivize production and use, promote research and development, and ensure equitable access for all farmers (Pourhashem et al. 2019). Implement subsidies and corrective taxes to make biochar production economically feasible and environmentally prominent, addressing financial barriers to encourage private sector participation (Verde and Chiaramonti 2021). Fund technological advancements in pyrolysis processes and application techniques to enhance the cost-effectiveness of biochar (Manyà 2012) and ecological impact across different agricultural systems (Li et al. 2023). Ensure all farming communities, especially marginalized groups, have access to biochar through cost-sharing schemes and educational outreach initiatives to prevent exacerbating existing disparities in agricultural productivity and climate resilience (Pourhashem et al. 2019; Jansen and Drivers 2023). By integrating tools that promote inclusivity alongside technological advancements, biochar can realize its full potential as a climate mitigation tool, reflecting a commitment to both social equity and environmental restoration.

3.4.4 Longevity and stability of benefits of biochar: persistent effects on soil geochemistry and water retention

Long-term benefits of biochar, particularly its positive impact on soil geochemistry and water retention, highlight its potential in sustainable agriculture and environmental management. Research shows that its advantages do not fade over time. The porosity and chemical stability of biochar enable it to maintain structural integrity, ensuring consistent benefits for soil health and agricultural productivity (Li et al. 2021). Razzaghi et al. (2020) indicated that resilience allows biochar to persist in the soil, improving nutrient dynamics and microbial ecosystems. This interaction stabilizes essential elements like nitrogen and phosphorus and fosters an environment conducive to agricultural productivity. Additionally, biochar increases cation exchange capacity, enhancing nutrient availability and reducing the leaching of potassium and magnesium. It also significantly enhances soil water content, especially in free-draining environments (Atkinson 2018). The porous structure of biochar captures and gradually releases water, supporting plant growth and mitigating drought stress. In conclusion, the stability and benefits of biochar establish its critical long-term role in sustainable agriculture and environmental stewardship.

Recent research highlights the stability, decomposition, and adsorption efficiency of biochar, which significantly affect soil health and crop productivity (He et al. 2021). The interaction of biochar with soil ecosystems depends on its long-term stability, but environmental variations and soil types can accelerate decomposition, compromising its integrity and functionality. This can diminish beneficial effects of biochar and its capacity to retain essential nutrients. While initial applications can enhance crop productivity by improving water retention and microbial activity, these benefits may wane due to changing conditions. The adsorption efficiency of biochar influences soil structure and function over time, with vineyard-pruning biochars benefiting specific soil types and straw biochar being more effective for overall soil quality (Burrell et al. 2016). Aller et al. (2018) pointed out that biochar can provide immediate benefits to soil structure, but these may not last. As decomposition increases and environmental interactions change biochar properties, adjustments to application strategies become necessary.

3.4.5 Regulatory frameworks and innovative economic models for biochar production and application

The adoption of biochar is hindered by fragmented regulations and a lack of economic incentives. Existing sustainability frameworks can be adapted to regulate biochar production, ensuring alignment with environmental protection standards (Pourhashem et al. 2019; Thengane et al. 2021). These frameworks should encompass both production and application phases, guided by principles of environmental accountability and resource efficiency. This includes responsible biomass sourcing to prevent harmful land-use changes and oversight of production technologies to minimize pyrolysis emissions. These models should focus on unique properties of biochar while addressing its environmental implications. For instance, regulatory policies could mandate collaboration between agricultural sectors, research institutions, and local governments to ensure biochar use is tailored to specific soil conditions and regional climate needs (Rittl et al. 2015). In parallel, economic models that prioritize innovation are crucial for mainstream adoption. Subsidies for farmers to reduce upfront costs and performance-based incentives, such as carbon credits, would position biochar as a key element in climate change mitigation through carbon sequestration (Salo et al. 2024; Mohammed et al. 2024). Furthermore, integrating biochar into broader circular economy strategies, where agricultural waste is repurposed, enhances resource optimization and contributes to soil regeneration. These policies would create a structured pathway for the integration of biochar into agricultural systems, embedded within a framework of sustainability.

3.4.6 Enhancing pollutant adsorption with nanotechnology-infused biochar

The integration of nanotechnology with biochar significantly enhances pollutant adsorption efficiency by increasing its surface area and reactivity. Nanotechnology allows precise structural modifications at the molecular level; it amplifies the porosity of biochar, creating a network of adsorption sites that can effectively trap various contaminants, including heavy metals and organic pollutants (Rajput, et al. 2024). These nanoscale adaptations improve the interaction of biochar with pollutants by enhancing electrostatic attraction and balancing hydrophilic and hydrophobic properties. For example, nanoparticles within the biochar matrix act as catalytic centers, facilitating reactions that break down complex pollutants into less harmful compounds while also immobilizing toxins (Liu et al. 2020). Tan et al. (2016) found that this tailored porous framework significantly enhances the adsorption capacity for heavy metals and organic pollutants by providing high-affinity binding sites within the biochar matrix. This engineering increases surface area and accessibility, maximizing contaminant interaction and retention. This dual functionality adsorption and degradation marks a significant advancement over traditional remediation materials, which often exhibit limited specificity or adaptability.

Furthermore, integrating nanomaterials with biochar not only improves pollutant capture but also enhances long-term environmental stability through increased durability and reusability (Nosratabad et al. 2024; Zhang et al. 2024). This synergy arises from enhanced thermal and chemical resistance, allowing the hybrid material to withstand cyclic regeneration processes without a significant loss of efficiency. Additionally, Zhang (Zhang et al. 2024), incorporating nanoparticles within the biochar matrix, boosts physical adsorption via an expanded porous structure while augmenting chemical reactivity by introducing functional groups that facilitate specific interactions with various contaminants. The nanostructured modifications foster stronger electrostatic interactions and enhanced π-π stacking, enabling the effective capture of recalcitrant pollutants such as polycyclic aromatic hydrocarbons (PAHs) and heavy metal ions (Yadav and Mishra 2025). This increased reactivity is further supported by the catalytic properties of embedded nanomaterials, such as zero-valent metals and metal oxides, which promote the in situ transformation of pollutants into less hazardous substances.

3.4.7 Biochar as a solution for energy and carbon management

The unique properties of biochar make it valuable for both energy storage and carbon capture. Its porous structure, created through pyrolysis, provides a large surface area that enhances energy retention and transfer in advanced storage systems. This high thermal stability and microporous surface area are particularly useful in technologies like lithium-ion batteries and supercapacitors, improving ionic conductivity and charge retention, and ultimately boosting efficiency and lifespan (Jung et al. 2019). Additionally, the porous structure of biochar increases energy retention capacity and provides a stable framework for integration into advanced electrochemical storage technologies, enhancing energy density and stability (Liu et al. 2022). Biochar also acts as a significant carbon sink, immobilizing atmospheric CO_2 into stable carbon forms that can remain sequestered for centuries when applied to soils or other reservoirs. This carbon sequestration ability, combined with its energy storage potential, makes biochar a key element in global climate mitigation strategies. It connects renewable energy advancements with long-term carbon management, allowing for practical and scalable integration with existing technologies (Osman et al. 2022).

3.5 Limitations of the study

This study on biochar application as a green clean-up method has some limitations. The analysis primarily relies on bibliometric data, which may not capture all nuances of research trends and impacts, particularly those not reflected in publication metrics. The focus on highly cited authors and journals might overlook significant contributions from less prominent sources, potentially introducing bias. Additionally, the scope of this study is limited to publications indexed in the Web of Science, possibly excluding relevant research from other databases. The emphasis on quantitative metrics, such as publication counts and citations, may not fully represent the qualitative impact and practical applications of biochar research. Furthermore, the study does not explore the long-term environmental and social impacts of biochar use, which are essential for a holistic understanding of its sustainability.

4 Conclusions

Biochar research has grown significantly since 2007, with a marked increase in publications until 2017, reflecting rising interest in its potential applications. It has become a central focus in addressing environmental pollution and contaminants across various disciplines. Key areas for future exploration include biochar characterization, its impact on greenhouse gas emissions, its lifespan in soils, and its role in nutrient availability for plant growth. To capitalize on these advancements, the following actionable recommendations are proposed: First, develop standardized methods for characterizing biochar to ensure consistency and comparability across studies. Second, conduct comprehensive studies to quantify the impact of biochar on greenhouse gas emissions, considering both direct emissions from production and indirect effects on soil carbon sequestration, as well as methane and nitrous oxide emissions. Third, undertake long-term field studies to determine the longevity of biochar in different soil types and environmental conditions, providing insights into its stability and effectiveness over time. Fourth, focus on research examining how biochar influences nutrient availability for plant growth, including interactions with soil microorganisms and impacts on nutrient cycling and plant uptake. Finally, foster collaboration among researchers from various disciplines such as environmental science, agriculture, chemistry, and engineering to facilitate a holistic understanding of benefits and limitations of biochar.

Abbreviations

BET	Brunauer–Emmett–Teller
CAS	Chinese Academy of Science
GHG	Greenhouse gases
LCA	Life Cycle Assessment
MRT	Mean residence time
NMR	Nuclear magnetic resonance
SEM	Scanning electron microscopy
STXM	Scanning transmission X-ray microscopy
TEM	Transmission electron microscopy
USA	United States of America
WoSCC	Web of Science Core Collection
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction

Supplementary Information

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Supplementary material 1

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Author contributions

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Data availability

Data available on request from the authors.

Declarations

Competing interests

The authors declare no competing interests.

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