

REVIEW

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Trends and hotspots in biochar research for soil quality improvement in tropical and semi-arid regions based on bibliometric analysis

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Abstract

Intensive agriculture, deforestation and climate change have caused soil degradation, making environmental degradation a silent yet critical threat in tropical and semi-arid regions. In this context, biochar produced by the pyrolysis of biomass under oxygen-limited conditions has gained significant prominence in soil science over the past decade. This study aimed to analyze global research trends, scientific collaboration networks, and key thematic focuses related to the use of biochar for soil quality improvement in tropical and semi-arid regions, covering the period from 2009 to 2024, including scientific articles and reviews based on a Web of Science search using the terms “biochar for soil quality improvement in tropical and semi-arid regions,” resulting in 666 articles. After applying eligibility criteria and screening procedures, 505 records were retained for bibliometric analysis. The data were analyzed using the Bibliometrix (RStudio) and VOSviewer software, applying techniques such as co-authorship analysis, co-citation, and keyword co-occurrence. Furthermore, the results show a continuous growth in publications, particularly after 2014, with China leading the way (183 articles and 7257 citations) in a global collaboration network, followed by the United States and Pakistan. Although these countries are not entirely characterized by tropical or semi-arid climates, the retrieved studies specifically focused on dryland, tropical, and semi-arid agroecosystems, according to the environmental descriptors adopted in the bibliometric search strategy. The collaboration networks show strong internationalization, with China acting as the main scientific hub. The thematic analysis revealed three main research areas: carbon sequestration, agricultural productivity, and soil remediation, as well as emerging trends related to bioremediation and mitigation of abiotic stresses. Keyword co-occurrence and thematic evolution analyses revealed increasing scientific attention toward biochar applications associated with water retention, nutrient cycling, and soil sustainability in vulnerable agroecosystems. It is concluded that biochar has high potential as a sustainable technology; however, its advancement depends on interdisciplinary approaches to consolidate biochar as a technology



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in sustainable agriculture and on strengthening international collaborations in the development of applied studies under real field conditions, especially in vulnerable environments.

Highlights

Scientific output on biochar has shown continuous and significant growth from 2009 to 2024, with China leading globally in terms of the number of articles (183 publications) and citations.

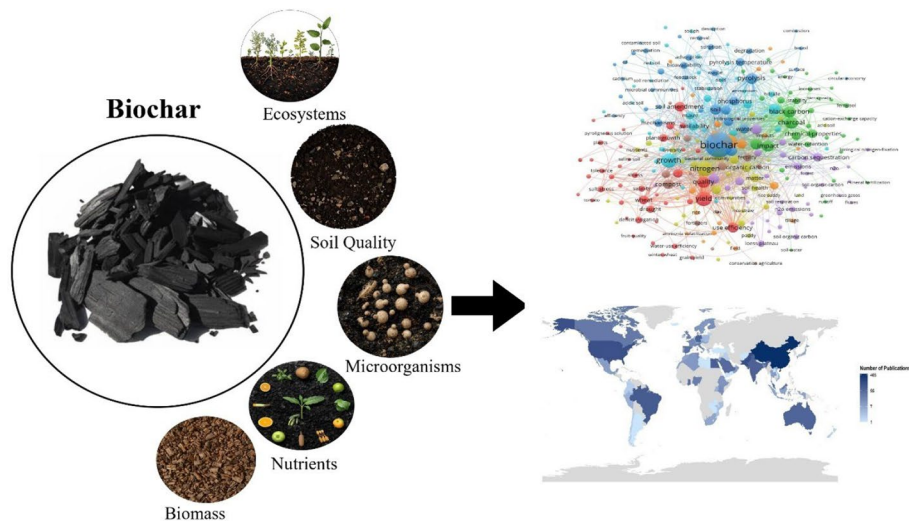
Studies focus on three central themes: carbon sequestration, agricultural productivity (yield), and soil remediation (including heavy metals).

Keyword co-occurrence and thematic analyses revealed growing scientific interest in biochar applications related to water retention, nutrient cycling, and soil sustainability.

Large-scale adoption faces the challenge of an urgent lack of long-term data on the material's persistence and the need for methodological standardization.

Keywords Biochar, Soil degradation, Bibliometric analysis, Sustainability

Graphical Abstract



1 Introduction

Soil degradation, driven by intensive agricultural practices, deforestation, and climate change, advances as a silent threat, particularly affecting tropical and semi-arid agroecosystems, where soils are naturally fragile and climatic conditions impose additional challenges [47]. In this context, biochar has emerged as a promising alternative. Produced through the pyrolysis of residual biomass, this carbonaceous material has been extensively investigated for its ability to improve key soil attributes, such as nutrient retention, water holding capacity, provision of microbial habitat, and stable carbon sequestration [42, 58, 66].

Studies in agricultural contexts have shown that biochar application can increase crop productivity in degraded soils, reduce fertilizer leaching, and contribute to climate change mitigation through long-term carbon sequestration [16, 33, 67]. These characteristics are especially relevant in tropical and semi-arid regions, where soils often exhibit low organic matter content, high susceptibility to nutrient leaching, and recurrent water stress limitations that biochar can help mitigate [14, 50]. However, the effectiveness of

biochar is not uniform: its effects vary depending on multiple factors, including feed-stock type, pyrolysis temperature, application rate, and, crucially, the edaphoclimatic conditions of the application site [6, 34].

Despite the growing volume of publications on the topic—ranging from agronomic efficiency studies to investigations of physicochemical mechanisms and environmental impacts—the knowledge generated remains fragmented. To date, there is no quantitative synthesis that systematically maps research trends, scientific collaboration networks, and key topics related to the use of biochar specifically in tropical and semi-arid systems. Unlike traditional narrative reviews, which rely on subjective literature selection and qualitative interpretation, bibliometrics enables an objective, systematic, and replicable assessment of scientific production at scale [21, 75]. Through the analysis of metadata from hundreds or thousands of publications, it is possible to identify collaboration patterns among institutions and countries, map the temporal evolution of research topics, recognize influential authors and papers, and detect emerging topics that have not yet been consolidated in the literature; this approach has been widely used in environmental and agricultural sciences to provide structured overviews of rapidly expanding fields of knowledge [8, 45].

Thus, this study aimed to evaluate, through bibliometric analysis, publication trends, key actors (authors, institutions, and countries), collaboration networks, and emerging topics related to the use of biochar for improving soil quality in tropical and semi-arid regions. In doing so, it seeks not only to synthesize the state of the art of this research field but also to identify gaps and opportunities that can guide future investigations and strengthen scientific production aimed at the sustainability of agricultural systems in these regions.

2 Materials and methods

2.1 Database and collection procedure

Data were obtained from the Web of Science (WoS) database, recognized for its comprehensiveness, standardization, and rigor in indexing international scientific publications [25]. We opted to use WoS exclusively due to its consistency in curating records and the high quality of the indexed journals, especially within the scope of the Science Citation Index Expanded (SCI-Expanded), which brings together relevant studies in the environmental and agricultural fields [49]. Although other databases, such as Scopus, also offer broad coverage, the choice of WoS is justified by its established use in bibliometric studies and the reliability of its metadata, which contributes to greater robustness and reproducibility of the analyses conducted.

The search was conducted on October 21, 2025, using the “Topic” (TS) field, which covers the title, abstract, and keywords of the documents, allowing for a more comprehensive retrieval of relevant studies. As a refinement criterion, a language restriction was applied, considering only documents published in English, with the aim of ensuring greater standardization and reliability in the bibliometric analysis.

The strategy was developed using Boolean operators, considering terms representing both biochar and aspects of soil quality in tropical and semi-arid climates with TS=((biochar* OR bio-char* OR "bio carbon" OR "biomass charcoal") AND ("soil fertility" OR "soil productivity" OR "soil quality" OR "soil nutrients" OR "soil amendment" OR "soil health" OR "soil remediation") AND (tropical OR "tropical soils" OR subtropical OR

arid OR semi-arid OR semiarid OR "dryland soils")) [75]. The inclusion of studies was based on the occurrence of terms related to tropical, arid, semi-arid, or dryland environments in the title, abstract, or keywords indexed in the Web of Science database. Therefore, the bibliometric analysis considered the environmental focus and thematic scope of the studies rather than the overall climatic classification of the countries associated with the authors' affiliations.

Based on the search strategy, 666 records were initially identified, which were subsequently refined based on criteria for publication year, document type, and language. It should be noted that data pertaining to the year 2025 were considered incomplete, as the data collection was conducted prior to the end of that period. After applying the eligibility criteria and completing the screening stage, 505 records were consolidated (Fig. 1), constituting the final basis for the analysis [48].

Another metric used was Total Link Strength (TLS), which is employed in the VOSviewer software and utilized in this study to interpret the relationships presented in the analyzed networks. It is a bibliometric indicator that quantifies the intensity of connections between network nodes, such as countries, authors, or institutions. In the context of co-authorship networks between countries, TLS corresponds to the sum of the strengths of all links that a given country maintains with the others, with calculated based on the frequency of joint collaborations in scientific publications. Thus, the higher the TLS value, the greater the level of scientific integration and collaboration of that country within the analyzed network, indicating a more central and influential position in global research interactions.

2.2 Statistical analyses and bibliometric mapping

Descriptive analyses and scientific mapping were conducted using the following tools:

- RStudio (Bibliometrix): used for statistical data processing and descriptive bibliometric analyses, including the creation of graphs showing the temporal distribution of publications, citation impact assessment, and identification of the most representative countries and journals [9]. Additionally, minimum filtering criteria were applied for inclusion in the analyses, considering, for example, the minimum number of documents per author, country, or journal, as required by each analysis. For the networks generated in the bibliometrix environment, the association strength normalization method was adopted to ensure greater consistency in the analysis of relationships between elements.
- VOSviewer: used to construct and visualize bibliometric network maps, including co-authorship, institutional collaboration, and keyword co-occurrence, allowing for the exploration of the intellectual structure and main topics in the field [64]. To generate the networks, minimum occurrence thresholds were defined (e.g., minimum number of documents per author or minimum frequency of keywords) to ensure that only the most relevant items were included in the analysis. The networks were normalized using the association strength method, a standard feature of the software, and visualization was configured based on the clustering technique, enabling the identification of thematic communities and patterns of scientific collaboration.

Based on these analyses, it was possible to:

- Identify the researchers and institutions with the greatest influence on the topic;
- Map international collaboration relationships;
- Identify thematic clusters representing the main research focuses;

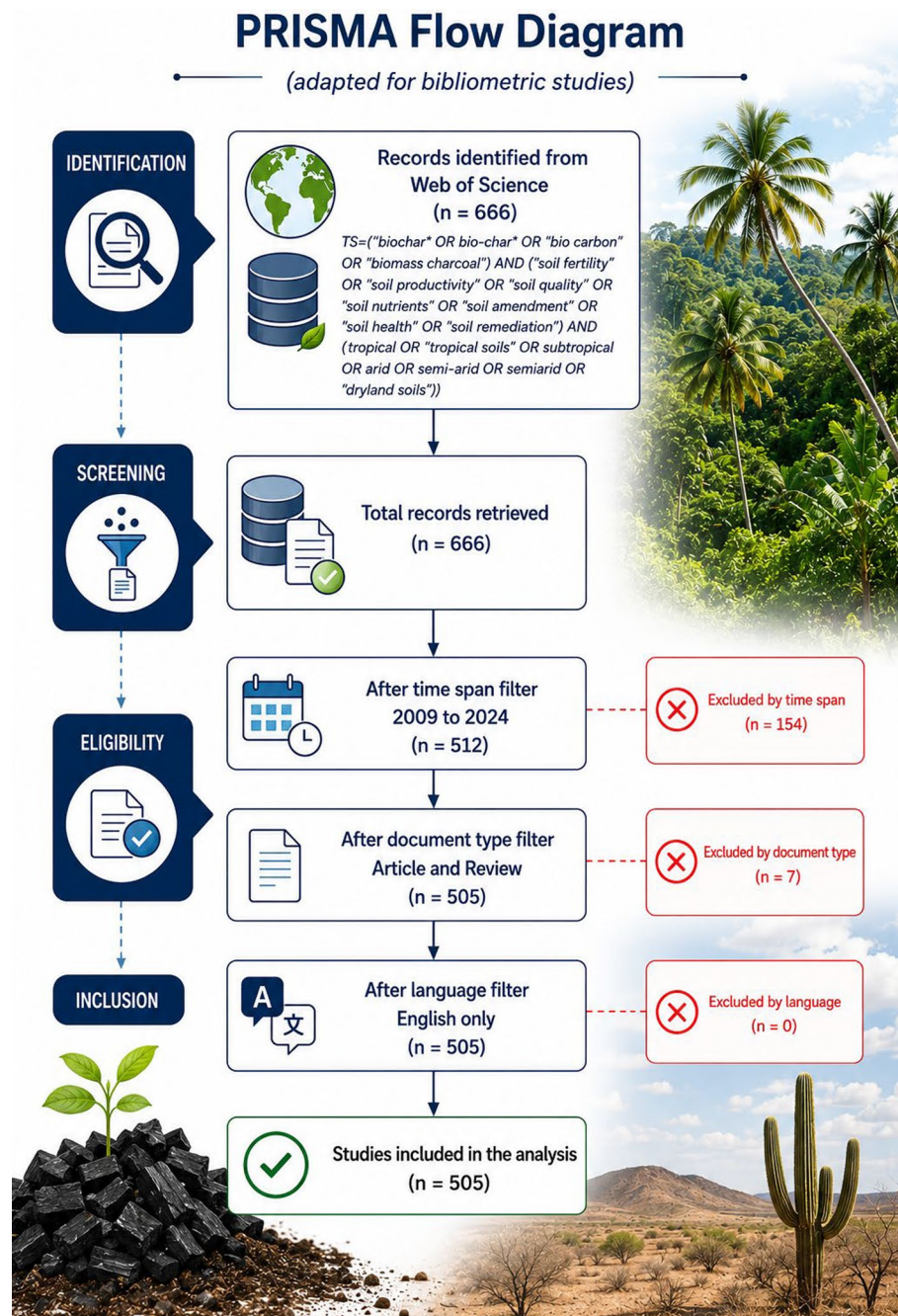


Fig. 1 PRISMA flow diagram of the bibliometric analysis [52]

• Distinguish emerging trends associated with the use of biochar in tropical and semi-arid soils, especially regarding soil fertility, nutrient cycling, and water retention [64].

3 Results and discussions

3.1 Publication trends and geographic distribution

Figure 2A illustrates the annual publication of articles between 2009 and 2024. There has been steady and significant growth since 2014, with the highest number of articles published in 2024 (73). The trend line confirms this increase and indicates the expansion of the topic. In contrast, the average number of citations per article has steadily declined

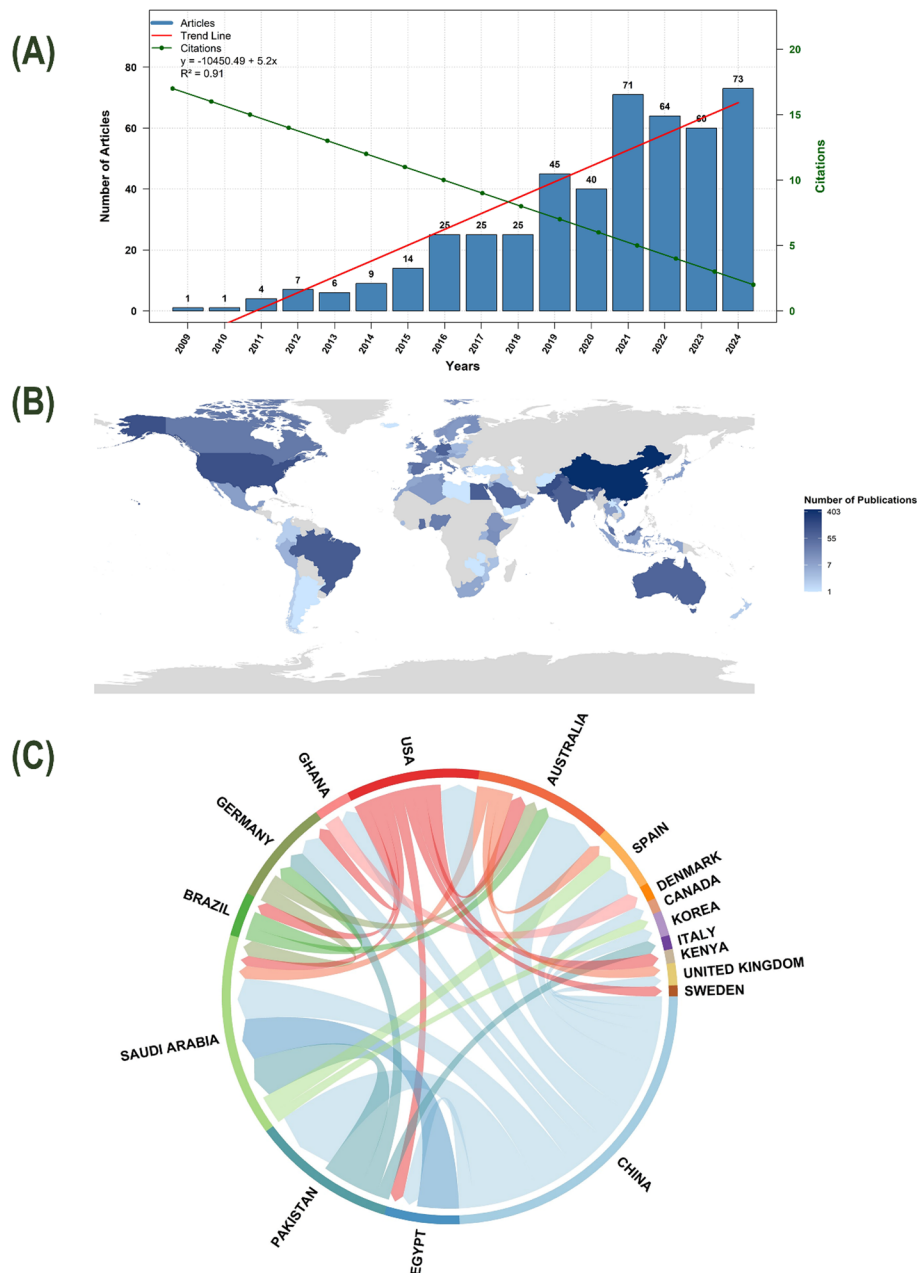


Fig. 2 **A** The annual evolution of the number of articles and citations between 2009 and 2024 **B** The spatial distribution of publications by country, highlighting the regions with the highest academic production; and **C** The international collaboration network between the main knowledge-producing countries, illustrating the connections and cooperative flows in global biochar research

since 2009. This decline is evident since 2009. This decline can be attributed to the fact that more recent works have not yet had time to accumulate a significant number of citations. Alternatively, this decline could be due to the greater decentralization of scientific production and the greater dispersion of topics covered, resulting in a low relative impact on the topic of biochar [2].

The geographical distribution of publications on biochar, as shown in Fig. 2B, can be explained by the combination of the global push for biochar research and the critical need for soil improvement solutions in vulnerable regions (tropical and semi-arid

climates). The countries with the highest number of articles were China, Pakistan, and the United States. Several bibliometric studies confirm that China leads by a wide margin in the number of publications on biochar, followed by the United States and, to a lesser extent, countries such as Brazil, Pakistan, Ghana, Saudi Arabia, and Egypt.

The highest concentration of studies in China can be attributed to investments in research, policies, and specific challenges of soil degradation in the country's arid regions [28, 40, 68]. It is worth noting the presence of countries with tropical and semi-arid climates, such as Brazil, Pakistan, Ghana, Saudi Arabia, and Egypt, which, although with a lower incidence of articles, appear with significant work in the area, highlighting a possible interest in studies of biochar and its effects on climatic realities, accompanying recent growth in studies focused on specific applications for degraded soils in arid and semi-arid regions [19, 41].

Figure 2C presents an international collaboration network in the form of a string diagram, illustrating partnerships between countries in the study of this topic. China emerges as the main global hub for collaboration, as evidenced by the thicker strings in the figure. Among its main partnerships are Pakistan (25), Australia (20), Saudi Arabia (16), and the United States (14), positioning it as a scientific epicenter in the area. Pakistan and Saudi Arabia also stand out, not only for their mutual collaboration with China, but also for their strong regional research integration with countries in the Middle East, South Asia, and Oceania.

3.2 International collaboration networks

Figure 3A illustrates the scientific collaboration network between countries investigating the application of biochar in soil quality improvement. In the co-authorship analysis, China consolidates itself as the central core of scientific production, registering the highest total link strength in the network (Total Link Strength = 700). It is followed by the United States (TLS = 404), Australia (TLS = 290), Pakistan (TLS = 256), Saudi Arabia (TLS = 212), and Germany (TLS = 184), all exhibiting robust and consistent connections with other nations. The thicker lines denote frequent collaborations, particularly between China-Pakistan, China-Saudi Arabia, China-Australia, and the United States-Australia, revealing a network focused on countries with significant research investment capacity and/or a need for technologies to restore degraded soils.

Figure 3B represents the same network but incorporates a temporal dimension. China, Pakistan, and Saudi Arabia have established recent and growing links, which underlines the growing interest in the topic in arid and semi-arid regions. Countries such as Germany, Spain, France, and Canada exhibit more evenly distributed collaborations over time, while Brazil (35 documents; TLS = 105) emerges as a relevant actor, albeit with a less pronounced influence on the network than the central countries. These results reflect an internationalized area of research with a network-based structure centered around China. China has expanded its partnerships with countries facing soil degradation challenges [15, 36]. Additionally, they highlight China's emergence as a global hub for scientific research and the significant regional roles played by Pakistan and Saudi Arabia among Middle Eastern, South Asian, and Oceanian countries [55].

Figure 3C shows the countries with the highest scientific output on the application of biochar in improving soil quality. China leads with a significant advantage, having accumulated 183 articles and 7257 citations, which reflects not only high productivity but

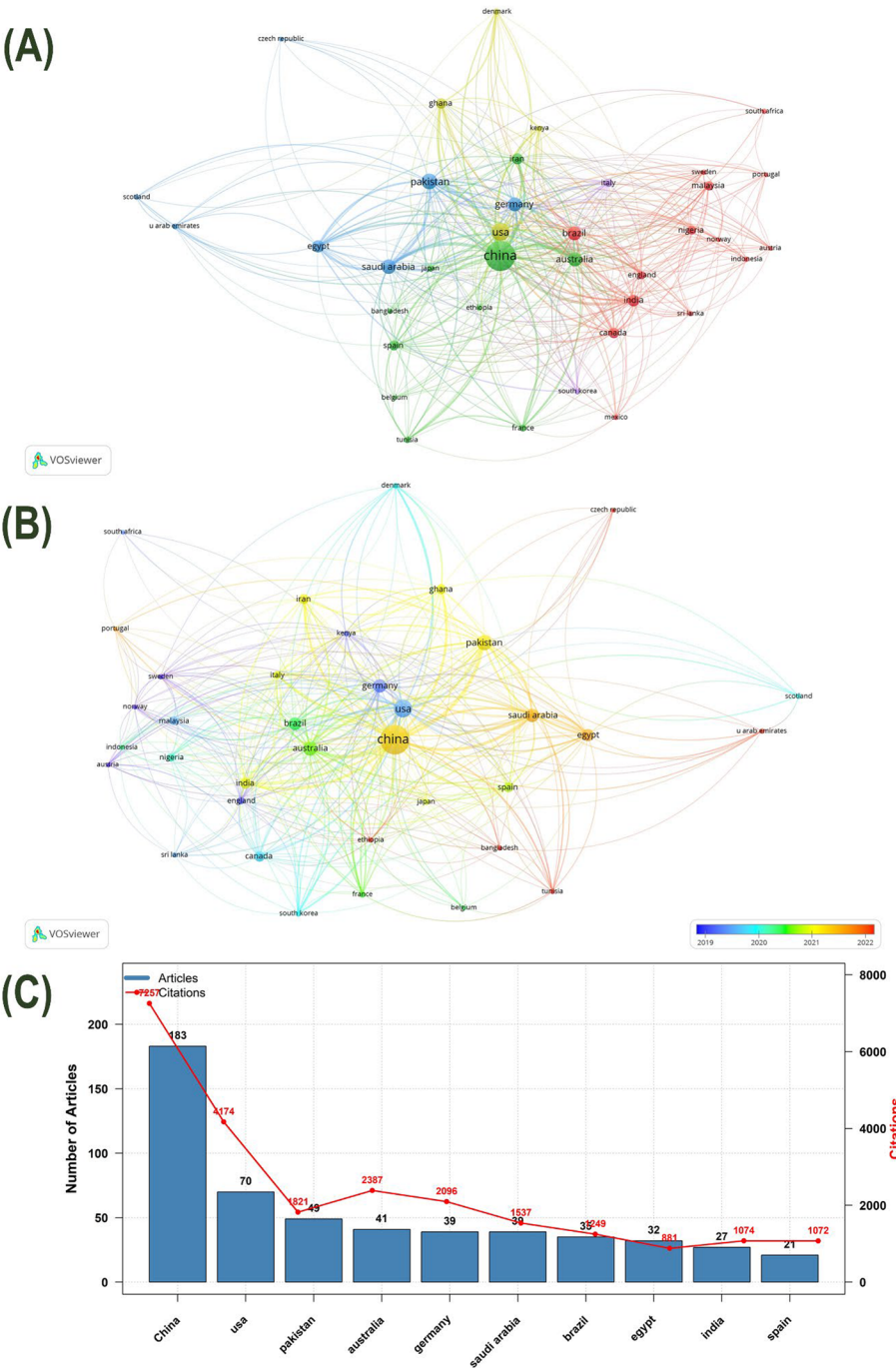


Fig. 3 **A** Map of co-authorship between countries, highlighting the intensity of collaborative connections; **B** Temporal evolution of collaborations, highlighting the dynamics and strengthening of international partnerships over the years; and **C** Ranking of the main knowledge-producing countries, represented by the number of articles published and the total number of citations, indicating scientific leadership and the global impact of biochar research

also a notable influence in the field. The United States ranks second, with 70 publications and 4174 citations, followed by emerging nations in this field, such as Pakistan (49 articles; 1821 citations), Australia (41 articles; 2387 citations), and Germany (39 articles; 2096 citations). Brazil occupies an intermediate position, with 32 publications and 1249 citations.

The concentration of publications and citations in the leading countries indicates not only quantity but also scientific relevance and influence. Countries such as China, the US, Australia, and Germany have a high h-index and citations per article, demonstrating that their research is widely recognized and used as an international reference [5, 36]. Brazil's relatively lower impact, despite growth in publications, suggests the need to strengthen international collaborations and increase the visibility of national studies. The growth of countries such as Pakistan and Brazil in scientific production highlights the internationalization of the topic and the interest of tropical and semi-arid regions in solutions for degraded soils [10, 36].

3.3 Collaboration among authors and scientific impact

Figure 4A shows a collaboration network among authors, illustrating how researchers from different countries interact and share knowledge regarding the influence of biochar

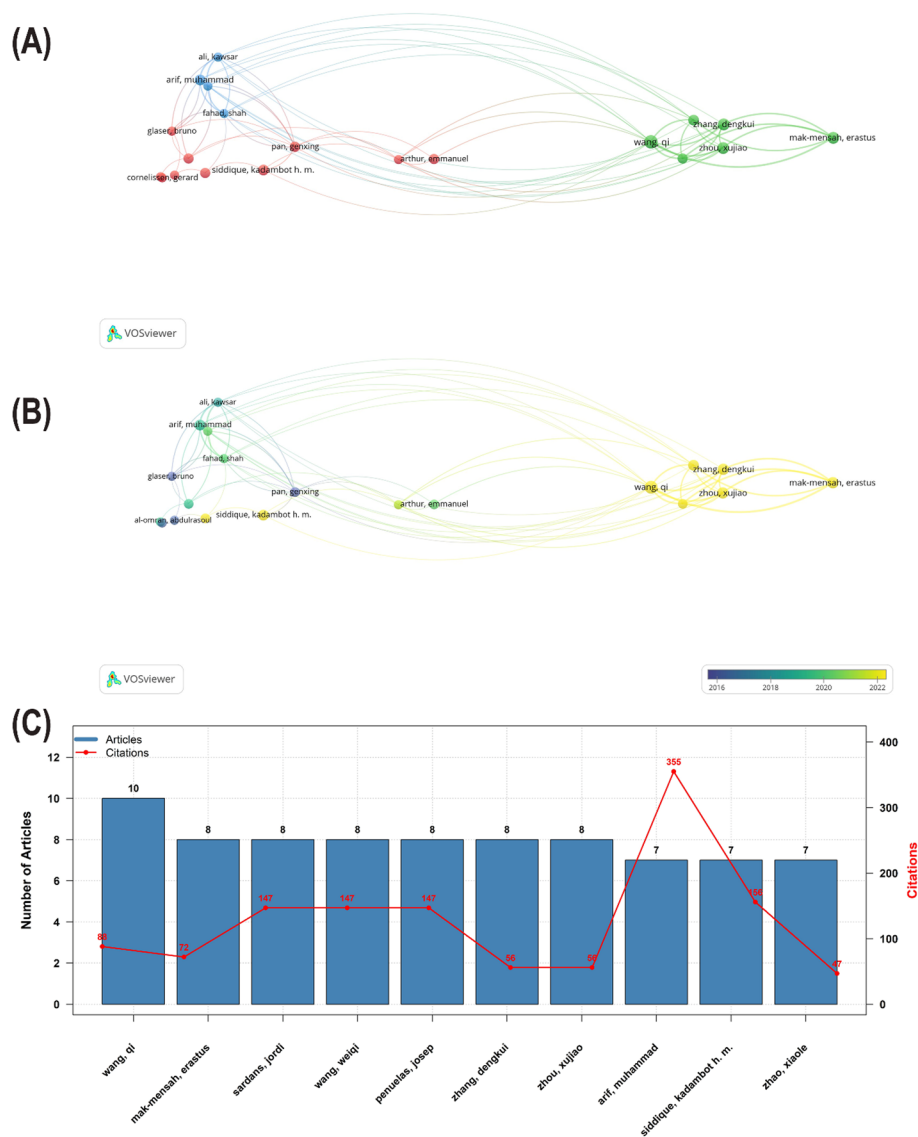


Fig. 4 **A** Network analysis of authorship patterns; **B** collaboration networks; **C** scientific impact on research on the use of biochar in soil quality

on improving soil quality in tropical and semi-arid regions. Mapping these connections reveals collaborative patterns and highlights the formation of international communities that drive progress in the field, indicating the consolidation of a global scientific network and the strengthening of international cooperation as a key factor in advancing knowledge.

The three main groups of authors indicate a community of researchers with intense internal collaborations. Among them, the following stand out: Ali, Kawsar; Arif, Muhammad; Fahad, Shah; Cornelisen, Gerard; Glaser, Bruno; Siddique, Kadambot H. M.; Wang, Qi; Zhang, Dengkui; Zhou, Xujiao; and Mak-Mensah, Erastus. The greatest contributions were made by Wang, Qi, who stands out as a central author with 10 publications, acting as a bridge between the groups and reinforcing his influence and active role in the circulation of knowledge, which suggests a strategic role in coordinating collaborations and disseminating information within the field.

Within the clusters, the connections point to frequent collaborations, while the links between them reflect international exchange, indicating that biochar research is characterized by cooperation among different scientific communities. This type of collaboration is of great importance for the advancement of research, as it broadens the scope of studies, encourages multidisciplinary approaches, and fosters the development of new methodologies, in addition to enabling the application of results under different soil and climate conditions, thereby increasing the relevance and applicability of the research [61, 72].

The productivity and impact of the leading authors are demonstrated by the number of published articles and the total number of citations received, highlighting the researchers with the greatest scientific influence in the field of biochar, which allows us to understand not only who produces the most but also who exerts the greatest influence on the direction of research.

In Fig. 4B, the clusters reflect the temporal evolution of scientific partnerships between 2016 and 2022. It is observed that researchers such as Wang Qi, Zhang Dengkui, Zhou Xujiao, and Mak-Mensah Erastus are part of a rising group, indicating the strengthening of a new leadership and the emergence of new research fronts [70, 72], which points to the expansion of the field and the renewal of the scientific community.

Figure 4C shows the relationship between productivity, represented by the number of published articles, and impact, measured by the number of citations received for each author. Although Wang Qi leads in the number of publications, with 10 articles, he has a relatively low citation index, with 88 citations, unlike Arif Muhammad, who has greater academic influence, with 355 citations and 7 publications during the analyzed period. This result demonstrates that scientific impact depends not only on quantity but primarily on the relevance of the studies conducted [70, 72], indicating that research with greater depth and scientific contribution tends to generate greater recognition in the field.

3.4 Influence of journals and co-citation analysis

Figure 5A, B illustrates the structure of co-citation networks among scientific journals, indicating the frequency with which two journals are cited together. Three main clusters can be observed, representing distinct thematic communities, notably Science of the Total Environment and Agronomy-Basel, reflecting the centrality of these journals in the

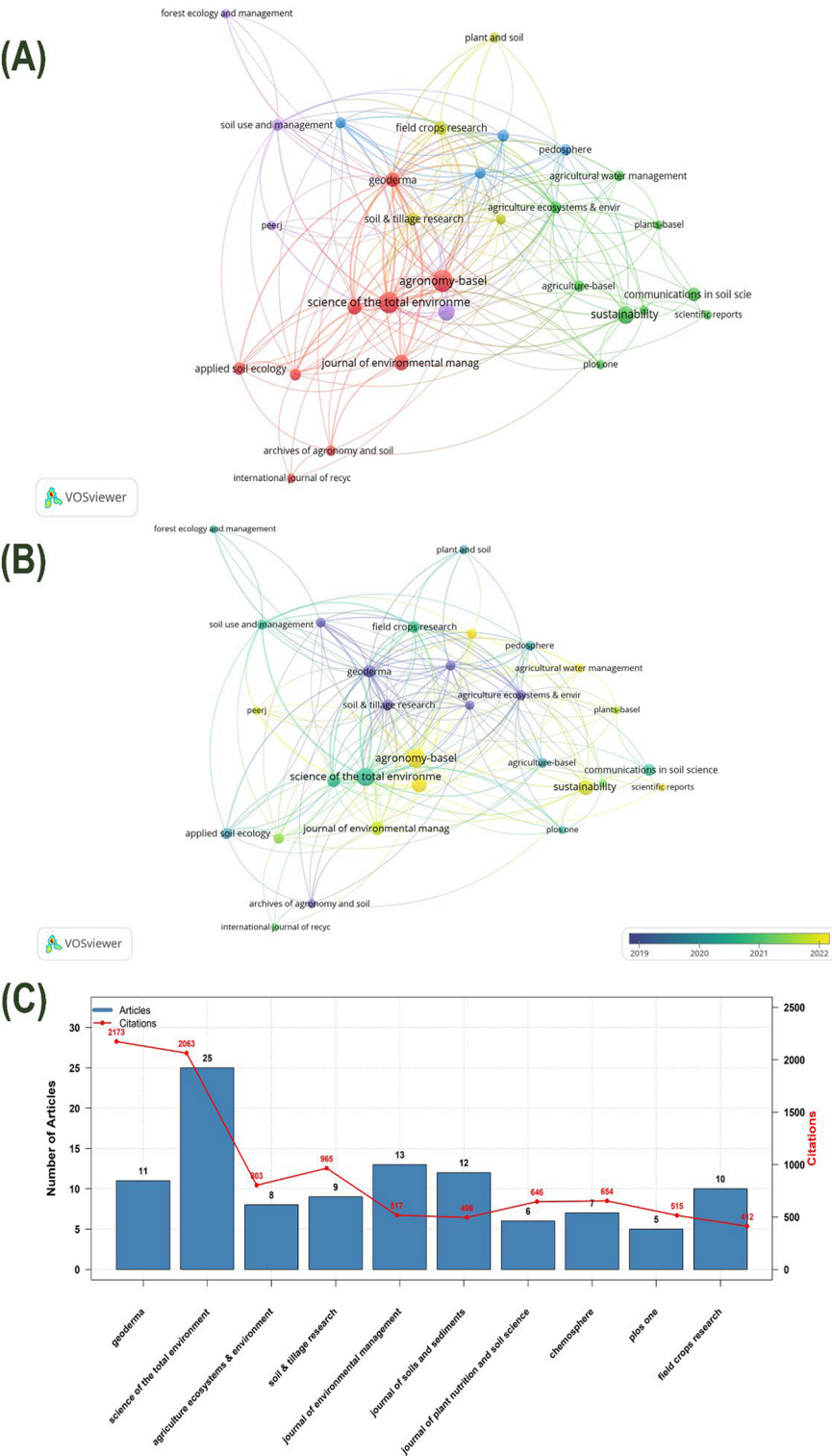


Fig. 5 **A** Co-citation network among the most referenced journals, showing thematic clusters and interactions between the main scientific sources; **B** presents the temporal co-citation network, indicating the evolution of citations over the years; finally, **C** shows the journals with the greatest impact, represented by the number of articles published and their respective citations

literature and their role as key connectors and sources for researchers in the field, which highlights their importance in the structuring and dissemination of scientific knowledge.

Figure 5B presents temporal information through a color gradient, illustrating the evolution and dynamics of these relationships between 2019 and 2022. This pattern indicates that certain journals have been gaining relevance over time, in line with the growing interest in innovative approaches to biochar use, the evolution of the scientific field, and the emergence of new research trends [61].

Figure 5C quantitatively presents the ten journals with the highest number of publications in the field and their respective citations. The journal *Science of the Total Environment* leads in the number of articles published on biochar and soil quality, with 25 publications and 2173 citations, standing out as the primary vehicle for disseminating knowledge in the field, which reinforces its scientific relevance and influence.

The *Journal of Environmental Management* ranks second, with 13 publications and 517 citations. Next, the journal *Geoderma* shows an inverse relationship, with a smaller number of articles (11) but a high number of citations (2063), indicating strong recognition and scientific relevance, which reflects the publication of studies with greater impact and contribution to the field. Other notable journals include *Soil & Tillage Research*, which, although it has only 9 published articles, has accumulated 965 citations, indicating the significant relevance of the published works, possibly associated with more in-depth research or research with greater published applicability [72].

In general, the volume of publications and citation impact vary considerably among journals, reinforcing that scientific influence is not limited to the quantity of publications but also to the quality and impact of the published research, indicating that journals with a lower volume of articles can play a relevant role in the consolidation of scientific knowledge [72].

3.5 Research networks

Figure 6A shows the grouping of institutions, indicating the existence of well-structured production and dissemination of knowledge in studies on biochar. The Chinese Academy of Sciences stands out, located at the epicenter of connections, suggesting high scientific productivity. The network layout suggests intense flows of knowledge between regional clusters, but there are still points of intermediation that unite nationally distinct groupings, pointing to broader scientific interactions.

In Fig. 6B, it is possible to identify the temporal distribution of publications on the use of biochar, represented by the color scale. This gradation allows us to observe the evolution of research over the years, showing a recent increase in collaborations and scientific production, especially since 2020. The lighter colors indicate more recent publications, demonstrating the continuity and strengthening of academic interest in the topic. This trend shows that biochar has established itself as a strategic line of research within the context of environmental mitigation and sustainable soil management.

Figure 6C shows the relationship between the number of articles published and the total number of citations received by the main institutions involved. The Chinese Academy of Sciences stands out with the highest volume of publications (29 articles), indicating strong leadership in the field. In contrast, Nanjing Agricultural University, although it has a small number of publications (11 articles and 1249 citations), has a high citation count relative to its published output, demonstrating the high impact and scientific

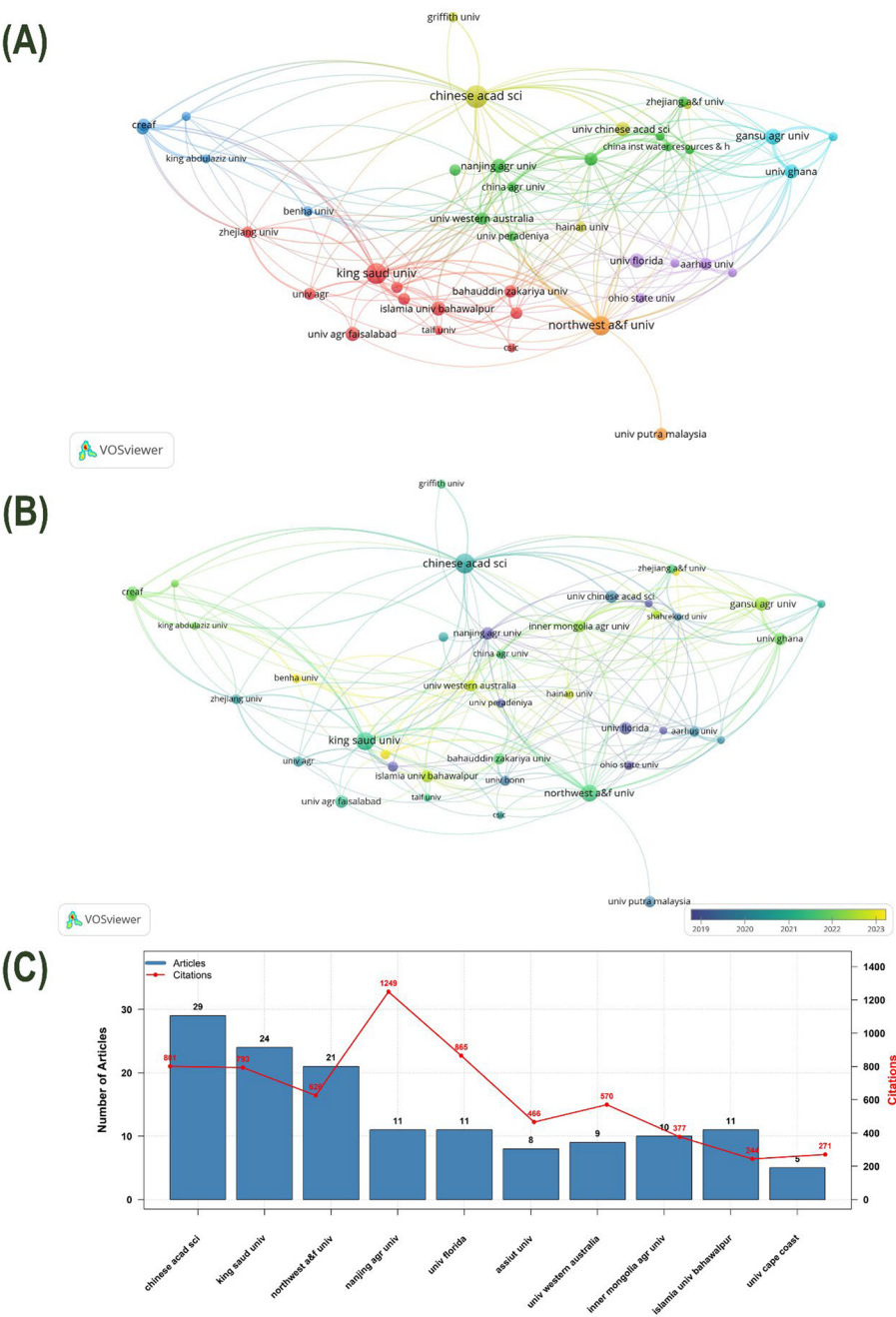


Fig. 6 The institutional co-authorship network is shown in image **A**, highlighting the main groupings and interactions between the institutions that collaborate most in the area. **B** shows the temporal collaboration network, indicating the evolution of institutional partnerships over the years. And **C** shows the institutions with the greatest scientific impact, presented by the number of publications and total citations, highlighting the most relevant research centers for the advancement of knowledge about biochar and soil quality

relevance of its research. This discrepancy suggests that the quality and influence of the studies produced by some institutions may exceed the simple volume of publications, contributing significantly to the advancement of knowledge about the use of biochar in environmental contexts.

Finally, the integrated comparison between the three scenarios reveals that the evolution of the structure and networks reflects not only the maturation of the field but also

the emergence of new research trajectories. The identification of clusters, the quantitative increase in production and impact, as well as the dilution or strengthening of thematic boundaries, indicate that the field of biochar is undergoing a dynamic process of expansion. Such analysis broadens scientific repercussions, promoting an increasingly integrated and innovative thematic trajectory.

3.6 Intellectual structure and influential references

Figure 7 presents a detailed bibliometric analysis of the intellectual structure of research on biochar and soil quality, highlighting the most influential references. This approach helps to identify the main authors, articles, and scientific collaboration networks. Figure 7A, B shows reference clusters, indicating areas of conceptual correlations. Authors such as Laird (2010), Lal (2009), and Agegnehu (2016) occupy central positions, being frequently co-cited and acting as a link between different research centers. However, this allows us to visualize the development of trends, showing that recent references are already gaining space and relevance, although classic works are still widely used to support new research.

Figure 7A illustrates citation networks among the main authors, highlighting highly influential centers such as Laird (2010), Lal (2009), and Agegnehu (2016), which have the highest number of connections and citations. These groupings reflect the formation of consolidated scientific communities, in which certain authors and works serve as central theoretical and methodological references for the field. Figure 7B shows the densification of clusters linked to the number of citations and the recency of publications. The time dynamics indicate not only the constant updating of the topic but also the incorporation of innovative discussions, reflecting the maturation and diversification of scientific research on biochar and soil.

Figure 7C complements the analysis by quantifying the number of links and citations of the main studies. Laird (2010) stands out as the most influential article, with 47 connections and 1116 citations, followed by Agegnehu (2016) and Lal (2009), both with high impact. These metrics confirm the centrality of these works, highlighting their wide acceptance and application in different contexts of biochar study. The presence of various authors in the list of most cited demonstrates the interdisciplinary nature of the topic, integrating aspects such as soil physicochemical properties, agricultural management, and environmental impacts. In addition, the diversity of links between works reveals an international collaborative network, favoring the integrated advancement of knowledge.

These networks, while enabling the consolidation of central paradigms, also pave the way for identifying gaps and research opportunities. Thus, the analysis of the data confirms the dynamism of the theme, demonstrating that conceptual evolution occurs amid a continuous process of innovation. Therefore, the co-participation of different links should be promoted so that these collaborations allow learning between different groups, contributing to diversity and innovation [69, 70]. In short, the intellectual structure revealed by maps and bibliometric metrics reinforces the role of leading authors and works as guides for researchers and highlights the dynamism of the field, with the renewal and expansion of scientific networks over the years.

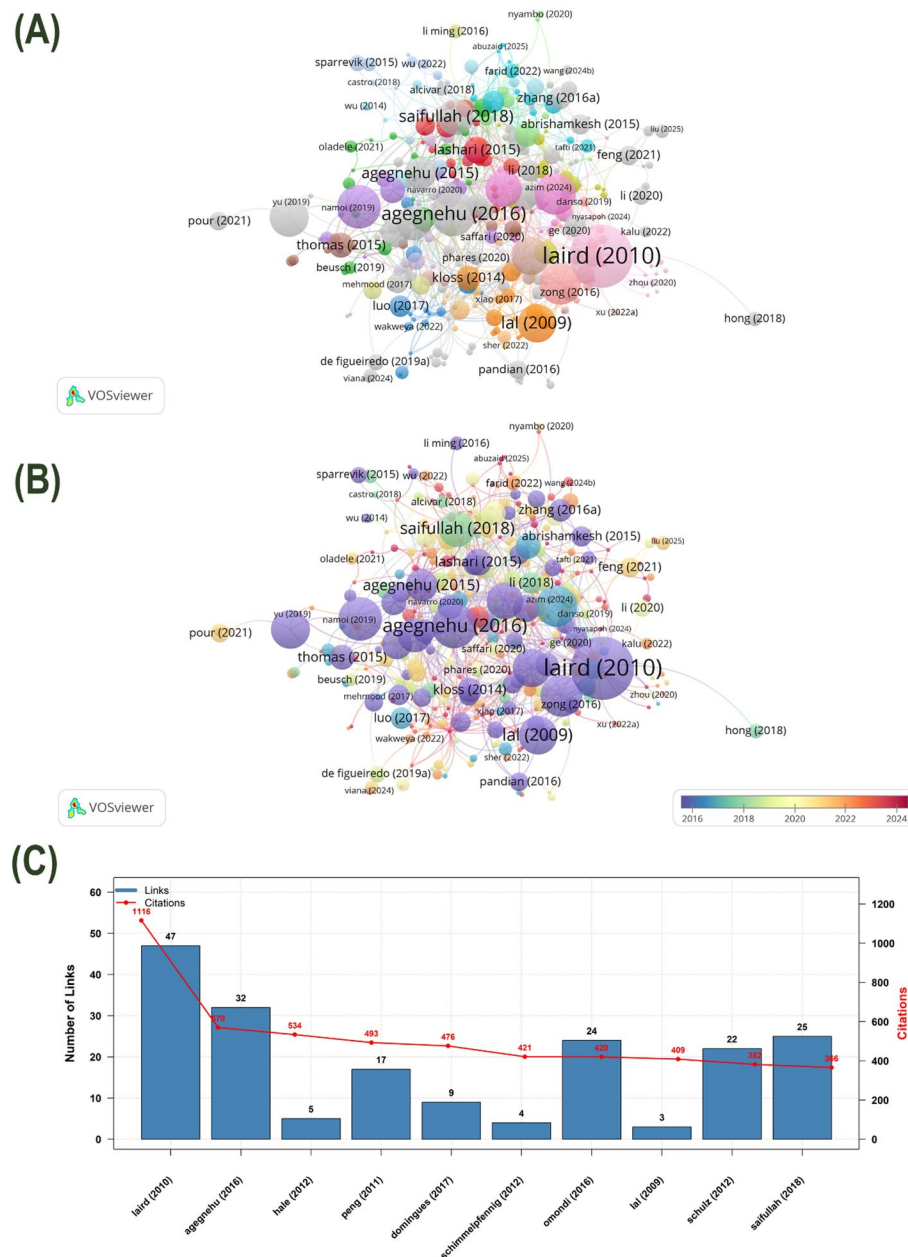


Fig. 7 The co-citation network between authors is shown in figure **A**, highlighting the main researchers who form the intellectual basis of research on biochar and soil quality. **B** The temporal co-citation network is evidenced by the evolution of the authors' contributions over the years. Finally, image **C** shows the most influential authors based on the number of connections established in the network and the total number of citations received, demonstrating those who have the greatest impact on the construction of scientific knowledge about biochar

3.7 Keyword co-occurrence and thematic evolution

The bibliometric analysis illustrated in Fig. 8 reveals the evolution of research trends on biochar, especially those focused on carbon sequestration and climate change mitigation. The keyword co-occurrence network in Fig. 8A displays the conceptual structure of the field, identifying four main thematic clusters (Table 1) that are interconnected and express the most active areas of research.

The central cluster is dominated by the terms “biochar,” “soil,” and “carbon,” representing the core of the investigations and reflecting the focus on the application of biochar

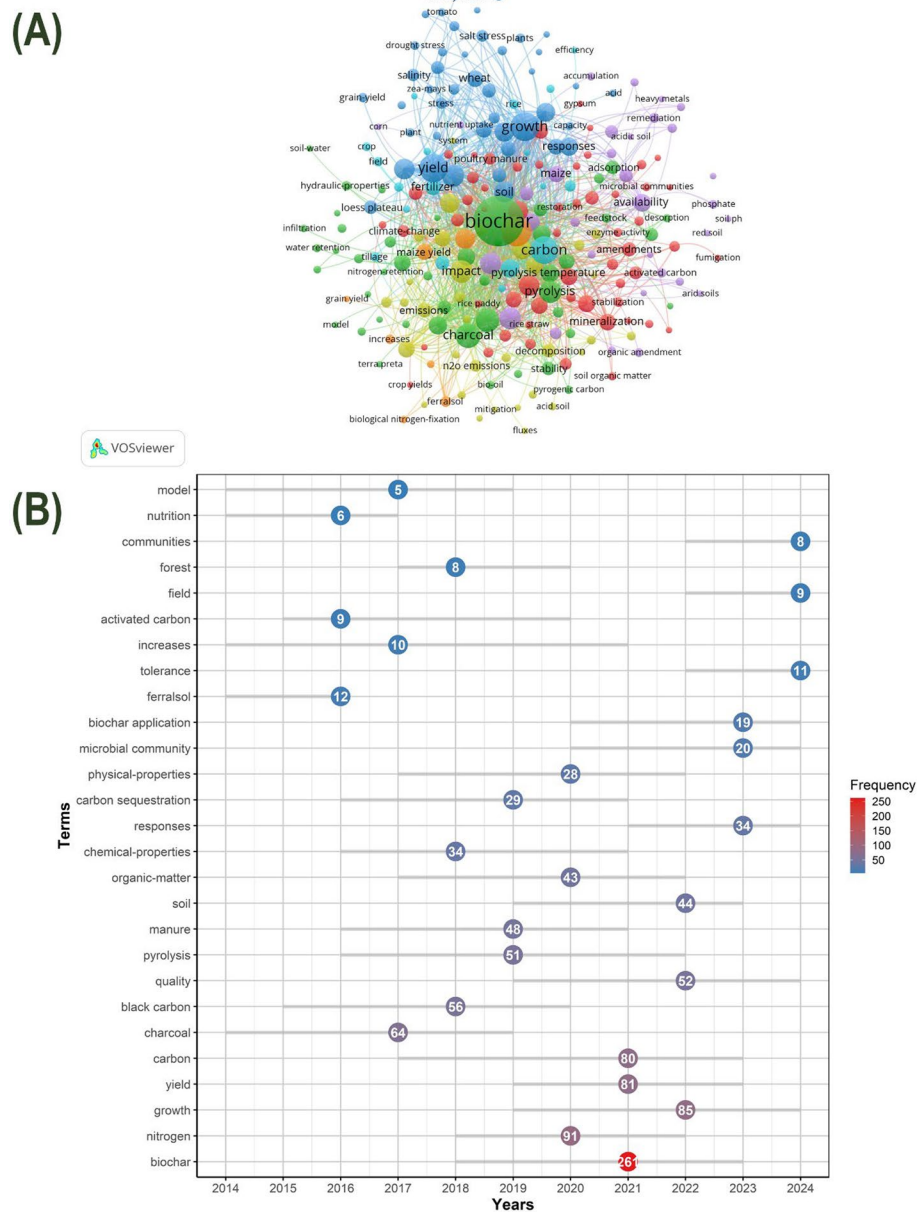


Fig. 8 **A** shows the co-occurrence network of terms, highlighting the main themes, conceptual interrelationships, and research foci associated with the use of biochar in improving soil quality. In **B**, the temporal evolution of the most frequent terms is shown, highlighting the emergence, intensity, and changes in thematic focus over the years, with an emphasis on recent trends in biochar research in tropical and semi-arid environments

as a soil conditioner and carbon sequestration agent. An adjacent cluster, associated with agricultural production, is demonstrated by terms such as “yield,” “growth,” “fertilizer,” and “crop,” indicating an increase in attention to the agronomic applications of biochar and its effects on productivity. Between 2001 and 2020, five main focuses emerged, including crop yield, greenhouse gases, and soil carbon fractions.

A third cluster involves terms related to pyrolysis and the physicochemical properties of biochar, such as “pyrolysis,” “temperature,” “charcoal,” and “emissions,” showing the decisive role of production conditions in the final properties of the material [31]

Table 1 Summary of the four main thematic clusters in the keyword co-occurrence network (Fig. 8A)

Cluster	Main topic	Main keywords	Dimension (number of prominent terms)	No-table publications
1 (Central, red)	Biochar as a soil conditioner and for carbon sequestration	biochar, soil, carbon	20–30 key terms	[42, 66]
1 (Central, red)	Biochar as a soil conditioner and for carbon sequestration	biochar, soil, carbon	20–30 key terms	[42, 66]
2 (Agricultural, green)	Agronomic applications and productivity	yield, growth, fertilizer, crop	15–25 terms	[30, 71]
3 (Production, blue)	Physicochemical properties and pyrolysis	pyrolysis, temperature, charcoal, emissions	10–20 terms	[31]
4 (Remediation, yellow)	Environmental remediation	heavy metals, adsorption, remediation, phosphate	10–15 emerging terms	[53, 69]

demonstrated that pyrolysis temperature and biomass type directly affect the stability and chemical composition of biochar, modulating its resistance to degradation.

Finally, an emerging cluster focuses on environmental remediation, with an emphasis on "heavy metals," "adsorption," "remediation," and "phosphate," involving the use of biochar as an agent for contaminant immobilization and degraded soil recovery [69] identified hotspots in biochar for bioremediation and metal immobilization.

The temporal analysis in Fig. 8B reveals three distinct evolutionary phases:

1. Initial Phase (2014–2017): Focus on fundamental aspects of characterization ("model," "nutrition," "activated carbon," "ferralsol").
2. Diversification Phase (2018–2020): Thematic expansion to agricultural systems ("field," "manure," "microbial community").
3. Consolidation Phase (After 2021): Consolidation of approaches applied to climate mitigation and soil sustainability.

Global balance studies, such as those by Lehmann et al. [42] and Tisserant and Cherubini [62], provide mechanistic support for this trend, estimating that large-scale use of biochar could reduce between 2.6 and 10.3 PgCO₂, which is equivalent to up to 6% of global emissions, positioning biochar as an important climate mitigation technology. At the mechanistic level, Wang et al. [66] found an average increase of 61% in soil carbon after biochar application, favoring aggregation and the formation of organo-mineral complexes, especially in medium to fine-textured soils.

The centrality of productivity (Cluster 2) is validated by Han et al. [30], who reported average increases of more than 14% in water and nitrogen use efficiency. In addition, Yang et al. [71] demonstrated synergistic effects between biochar and nitrogen fertilizers, resulting in cumulative productivity gains and reduced emissions of methane (CH₄) and nitrous oxide (N₂O) over 5 years.

In terms of global tactics, the data converge in pointing to China and the United States as the most productive countries [73] however, although China leads in volume, the average impact of US research remains higher, reflecting a priority on mechanistic and predictive approaches. This trend is aligned with emerging applications, such as machine learning models for predicting heavy metal immobilization efficiency [53] and

the integration of biochar in anaerobic digestion to increase methane production, reducing latency time by up to 64% [30].

3.8 Thematic analysis and conceptual structure of keywords related to the use of biochar for soil quality improvement

Figure 9A shows high impact with moderate centrality, highlighting essential themes such as biochar, soil fertility, soil health (30.5–39.1%), soil properties (63.6%), and soil changes (33.3–44.4%). These themes reveal the consolidated recognition that biochar acts as a transforming agent of the physical, chemical, and biological properties of the soil–plant system, transcending its initial function as a simple conditioner. The second Fig. 9B, positioned at high centrality and with a moderate degree of development, groups emerging themes of growing relevance such as salt stress, heavy metal adsorption, and environmental remediation. Nitrogen, phosphorus, and carbon act as driving

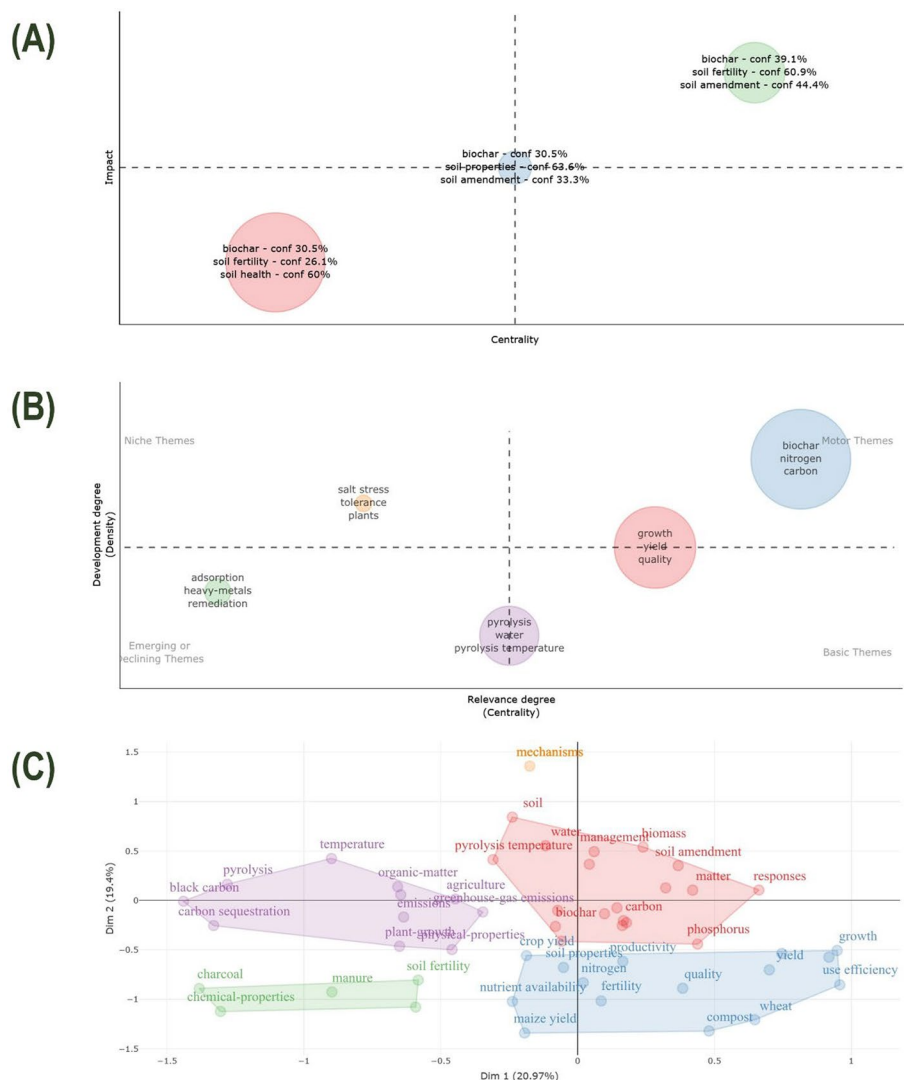


Fig. 9 **A** Strategic map of themes, classifying keyword clusters according to their centrality and impact, indicating driving, basic, emerging, and niche themes. **B** Refined thematic structure, highlighting the degree of development and relevance of each group of terms throughout biochar research. **C** Conceptual distribution of keywords in correspondence analysis, showing the organization of the main thematic axes that structure the field of research on biochar applied to soil quality

themes (greater relevance). This pattern suggests that biochar applications are strategically expanding into contexts of environmental remediation and mitigation of biotic and abiotic stresses, while maintaining deep roots in fundamental agricultural applications.

The analysis of the 9C thematic coordinate space demonstrates the organization of knowledge into semantically coherent clusters:

- The orange-red cluster (mechanisms, pyrolysis temperature, management, and biomass) represents studies focused on transformation and application processes.
- The pink cluster (carbon, biomass, productivity, and quality) brings together research on agronomic efficiency and carbon sequestration.
- The light blue cluster (nitrogen, phosphorus, fertility, growth, and use efficiency) focuses on studies of biogeochemical cycles, corroborating the critical importance of nutrient cycling as a key mechanism.

The peripheral positioning of terms such as “pyrolysis” and “temperature” in relation to the central core indicates that, although important for production, these technical processes do not constitute the thematic focus of agricultural research, which remains centered on edaphic and agronomic consequences. The bibliometric findings corroborate the scientific evidence of Kabir et al. [35], which reinforces that biochar improves soil structure and water retention through its high porosity.

The mechanism of nutrient retention and cycling is validated by Gao et al. [27], who demonstrated that biochar reduces leaching and improves cycling through its porous structure, providing sites for adsorption. The increase in the soil's cation exchange capacity (CEC) intensifies cation retention, ensuring prolonged availability to plants, which validates the thematic emphasis given to “phosphorus”, “nitrogen” and “fertility”.

The research community has progressively recognized that biochar fundamentally alters the structures and functions of microbial communities. Thematic analysis reveals “responses,” “biomass,” and “microbial community” as connecting elements. Kerner et al. [38] demonstrated, via meta-analysis, positive effect sizes for multiple microbial responses, and Wang et al. [66] highlighted that the structure of biochar creates ideal habitats for beneficial microorganisms.

Overall, Ding [20] found that biochar application increased total nitrogen and promoted the transformation of ammonium nitrogen (N-NH_4^+) into nitrate (N-NO_3^+), showing that changes in the microbial community structure correlate with changes in the expression of critical metabolic genes.

Finally, the field of abiotic stress is supported by Abbey et al. [1], who concluded that biochar application increases plant growth, biomass, and productivity under water or salt stress, mediating increased tolerance primarily through improved soil properties, increased water status, and reduced Na^+ absorption.

4 Overview

4.1 The importance of biochar for soil quality in tropical and semi-arid environments

Biochar consists of stable organic carbon obtained by the pyrolysis of biomass with limited oxygen. Its application to the soil mitigates problems of water availability, low fertility, and erosion, which are common in tropical and semi-arid regions [37, 51].

Local interest in biochar research stems from the urgent need to restore degraded soils, increase agricultural resilience to climate variability, and promote sustainable

Table 2 Effects of biochar on soil quality in tropical and semi-arid environments

Soil quality parameter	Main effects/improvements	Environments (tropical/semi-arid)	Sources
Physical and hydric properties	Increased available water retention and porosity	Increases total porosity, including microporosity, which is crucial for increasing water retention capacity in tropical sandy soils and mitigating water stress	[7, 45, 46]
Chemical properties	pH modulation and acidity correction	Induces moderate soil alkalization. In acidic tropical soils, increased pH reduces aluminum toxicity and improves micronutrient availability, supporting root growth	[32, 33, 43]
	Increased Nutrient Availability and Efficiency	Optimizes nutrient availability (N and P) when combined with fertilizers. Helps compensate for fertility deficiencies in calcareous soils and increases the sorption of essential cations	[4, 32, 43]
Biological properties	Stimulation of biomass and enzymatic activity	Increases microbial biomass, enzymatic activity, and functional diversity in the soil, which is essential for nutrient cycling and carbon mineralization in low-fertility tropical soils	[22, 32, 43]
	Increased microbial resilience	The porosity and pH adjusted by biochar create niches that support microbial communities involved in nitrification and mineralization, providing greater resilience to water stress and moderate salinity	[29, 32, 63]
Agronomic responses	Increased crop yields	Promotes yield increases in low-fertility tropical soils and semi-arid environments, especially when combined with liming, fertilizers, and proper irrigation management	[33, 45, 60]

practices that use abundant agricultural residues as feedstock for biochar production [12, 13, 75].

Tropical and semi-arid countries seek economically viable solutions adapted to their specific edaphoclimatic conditions; therefore, they invest in research evaluating different biomass sources, application rates, and combinations with other organic or mineral inputs to maximize the agronomic and environmental benefits of biochar. In this context, biochar represents a strategic tool for addressing local challenges of soil degradation, food insecurity, and adaptation to climate change in these regions [3, 11, 57]. Table 2 presents a survey of biochar parameters and effects on soil in tropical and semi-arid environments.

In summary, evidence suggests that biochar plays a functional and promising role in improving soil quality in tropical and semi-arid environments, especially by increasing water retention in sandy soils and correcting acidity in tropical soils [32, 46].

Nevertheless, responsible adoption requires assessment of biochar composition to mitigate environmental risks, such as the introduction of contaminants [24]. Future research should focus on long-term studies to understand the aging dynamics of biochar and the stability of its benefits, as well as comparative analyses between different biomasses and pyrolysis conditions to consolidate practical and scalable management guidelines [17, 65]. Integration with other soil and water conservation management practices is key to maximizing the effects of biochar and ensuring the resilience of agricultural systems in these vulnerable regions [23, 60].

4.2 Current challenges and future directions for the use of biochar in improving soil quality in tropical and semi-arid regions

Bibliometric analysis is a tool that reveals biochar as an important pyrolysis product for improving soil quality, especially in regions where degradation is a critical concern, such as arid and semi-arid areas. Major scientific advances indicate that biochar, when incorporated into the soil, can improve the physical and chemical properties of the soil, as it is a carbon-rich material, which has made it a hot research topic in the agricultural and environmental context as a soil improver, and its application is seen as fundamental to long-term soil health. The expansion of biochar use worldwide depends on international collaboration, especially in countries with degraded soils [39].

The use of biochar has high potential, but challenges remain and hinder its expansion, as the production and characterization of the material depend on the type of biomass to be used and the pyrolysis conditions, which can result in a material with varying physicochemical properties, ultimately affecting its effectiveness and permanence in the soil [44]. The lack of methodological standardization, limited long-term data on field effects, and difficulties in modeling the carbon dynamics of biochar in different environments are other important barriers [61]. Another important point is the risk of contamination when the raw material contains toxic residues. These factors limit the use of biochar, especially in tropical and semi-arid countries, where soil degradation problems and resource constraints are more pronounced [70, 72].

Future research directions point to interdisciplinary actions focused on three fronts: developing more robust models to predict the permanence and behavior of biochar in the soil; increasing international collaborations involving developing countries to adapt solutions to local realities; and integrating biochar with other management strategies, such as organic/chemical fertilizers and bioremediation practices. Of particular note is the need for long-term experiments, standardization of evaluation methods, and public incentive policies to maximize the benefits of biochar and expand its contribution to the sustainability of tropical and semi-arid soils [61, 70].

4.3 Emerging trends and research gaps

Biochar research has evolved significantly, transcending its initial application as a soil conditioner and carbon sequestration agent. Technological innovations in production processes, such as microwave-assisted pyrolysis, co-pyrolysis with industrial waste, and nanocatalytic functionalization, have enabled the engineering of biochars with superior physicochemical properties [59, 72].

Respectively, the range of applications has expanded to integrated wastewater remediation systems, waste treatment, and even as a component in building materials and energy storage devices. In agriculture, the focus remains on improving soil fertility, water use efficiency, and mitigating biotic and abiotic stresses, particularly in tropical and subtropical regions. Long-term and more complex field trials have provided more robust insights into soil-biochar-microbiota interactions, which are essential for validation under real-world conditions [74].

Despite rapid progress, critical gaps remain and represent the main challenges for large-scale biochar adoption. Understanding the persistence (half-life) of biochar in soil over decades, under various soil and climate conditions, remains insufficient. The mechanisms of aging and the resulting loss of environmental effectiveness are complex and

not yet fully understood [56]. The evident variability in responses, depending on the type of biochar and soil properties, makes it difficult to extrapolate controlled laboratory data to heterogeneous field scenarios.

Other significant gaps include the scarce assessment of the long-term effects of biochar on tropical and arid soils, the lack of standardized ecotoxicological protocols to assess environmental risks, and the uncertainties associated with the use of alternative raw materials and nanotechnological modifications [26]. Furthermore, the viability and traceability of carbon credits attributed to biochar lack consolidated methodologies and recognition in various regulatory frameworks, which limits their economic potential.

Overcoming these gaps will require interdisciplinary and transdisciplinary approaches, integrating soil science, chemistry, engineering, computer science, and socioeconomics. Long-term investigations, conducted across multiple biomes, are imperative. The consolidation of biochar as a key technology for regenerative agriculture, climate change mitigation, and sustainable waste management, especially in developing countries, will depend not only on scientific advances but also on supportive policy frameworks. The research agenda for the next decade should prioritize the customization of biochars for specific applications, effective integration into circular economy principles, and the establishment of robust MRV (Measurement, Reporting, and Verification) systems for carbon sequestration [18, 54].

5 Conclusions

The bibliometric analysis demonstrates the sustained consolidation and rapid expansion of biochar research for soil quality improvement in tropical and semi-arid regions from 2009 to 2024, with China leading both in publication output and citation impact, establishing itself as the primary hub of global scientific collaboration. Although countries such as China and the United States are not entirely located within tropical or semi-arid climatic zones, a substantial proportion of the retrieved studies specifically addressed dryland and vulnerable agroecosystems, reflecting the thematic focus established in the bibliometric search strategy. The prominence of countries with tropical and semi-arid conditions, including Brazil, Pakistan, and Ghana, highlights the strategic relevance of biochar for soil restoration in environmentally vulnerable regions.

The intellectual structure of the field converges on three core and interconnected domains: (i) climate change mitigation via carbon sequestration, positioning biochar as a stable Carbon Dioxide Removal (CDR) strategy; (ii) enhancement of agricultural productivity through thematic emphasis on processes associated with soil water retention, nutrient dynamics, and soil functionality; and (iii) soil remediation, particularly in the immobilization of heavy metals and mitigation of abiotic stresses. These thematic trends were consistently identified through keyword co-occurrence networks, temporal evolution analyses, and the predominance of research clusters associated with soil sustainability and environmental restoration.

From a policy and research funding perspective, these findings provide clear guidance for priority setting in vulnerable regions. First, the concentration of scientific production and collaboration networks indicates the need for targeted funding mechanisms to strengthen research capacity in tropical and semi-arid countries, particularly through international partnerships and technology transfer programs. Second, the identification of dominant and emerging themes suggests that funding agencies should prioritize long

term field experiments, standardization of biochar production and application protocols, and the development of context specific solutions adapted to local edaphoclimatic conditions. Third, the growing relevance of biochar in climate mitigation frameworks supports its inclusion in public policies related to carbon markets, sustainable agriculture, and land restoration initiatives.

Despite the foundational influence of seminal studies such as Laird (2010), further advancement of the field depends on addressing key limitations, notably the scarcity of long-term studies on biochar stability across pedoclimatic conditions and the lack of methodological standardization. Future progress will rely on integrative, interdisciplinary approaches and strengthened international collaboration to ensure the scalability and contextual validation of biochar-based solutions.

Author contributions

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Funding

This study was carried out with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) — Financing Code 001, Brazil.

Availability of data and materials

No datasets were generated or analysed during the current study.

Clinical trial number

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 5 January 2026 / Accepted: 25 June 2026

Published online: 07 July 2026

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