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A Bibliometric-Based Review of Biochar for Salt-Affected Soil Restoration: Mapping Research Trends and Future Directions

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ABSTRACT

In recent years, biochar has been studied for its range of applications. Recognized by the IPCC as a key Carbon Dioxide Removal (CDR) strategy, it also stands out as an important tool for reclaiming degraded lands, including vast global areas affected by salinity, such as those in China, India, and Australia. This study explores the application of biochar in these salt-affected soils through a bibliometric analysis and literature review. The research used the Web of Science database, from which 42,928 articles were initially identified. After careful keyword selection, the number was refined to 326 relevant publications. The analysis mapped the contributions of countries, institutions, and authors. Keyword analysis identified five thematic clusters, confirming that research is predominantly focused on soil application. The results show that China leads scientific production on this topic. However, a significant knowledge gap persists regarding the main research fronts in this field. The most relevant journals, such as *Science of the Total Environment* and *Agronomy-Basel*, are the primary platforms for these studies. The overview highlights biochar's main applications in remediating saline soils, while addressing advances and challenges. The study also suggests future research directions, such as improving production technologies, adapting biochar to different soil types, and assessing long-term environmental impacts.

1 | Introduction

Soil salinization is one of the main causes of soil degradation worldwide, affecting more than 1 billion hectares of land. The expansion of this phenomenon poses a significant threat to global food security, as approximately 50% of cultivated land may be impacted by salinization by 2050 (Kumar et al. 2024; Zhou et al. 2024). Salinization occurs due to natural factors, such as excessive evaporation in arid and semi-arid regions, as well as anthropogenic activities, including inadequate irrigation and excessive use of nitrogen (Jalali et al. 2024; Ratandeep et al. 2024). In saline soils, the high salt concentration reduces the ability of plant roots to extract water, thereby compromising plant metabolism and agricultural productivity (Muhammad et al. 2024; Yan et al. 2024).

Developing effective strategies to improve soil quality and promote agricultural sustainability is essential. In this context, the Intergovernmental Panel on Climate Change (IPCC) highlights biochar as one of the main Carbon Dioxide Removal (CDR) strategies for both the recovery of degraded soils—including saline soils—and the reduction of greenhouse gases. Furthermore, biochar has proven to be an important tool for the recovery of degraded areas, including those affected by salts, which are widespread globally, with significant occurrences in countries such as China, India, and Australia (Liu et al. 2023; Shoudho et al. 2024).

Building on this, researchers have extensively investigated biochar as a promising approach for the remediation of saline soils (Kapoor and Zdarta 2024; Waheed et al. 2025; Satya et al. 2025). However, despite its importance, there is a significant gap in information regarding the main areas of study involving biochar and salt-affected soils.

Due to its highly porous structure and large surface area, biochar can modify the physical and chemical properties of soil, such as pH, cation exchange capacity, and moisture retention, thereby supporting plant growth. Studies indicate that the addition of biochar to soil can enhance hydraulic conductivity and reduce soil bulk density, improving porosity and water retention (Gao et al. 2024; Nazim et al. 2025). In saline soils, where salt accumulation interferes with nutrient uptake and plant morphology, biochar can act as a soil conditioner, regulating the distribution of water and salts within the soil profile (Sultan et al. 2024; Singh et al. 2024). Cui et al. (2022) evaluated the effects of wheat-straw-derived biochar on saline soil recovery by applying doses of 0, 20, 40, and 60 $t\,ha^{-1}$ over 3 years (Cui et al. 2022). The results showed that biochar significantly increased soil water content, enhanced cation exchange capacity, and reduced soluble salt concentration, leading to greater crop growth.

Bibliometric analysis has proven to be an essential tool for systematizing scientific knowledge on biochar application in saline soils (Chen et al. 2023). This study employs this approach to analyze 326 articles listed in the Web of Science (2013–2024), using the VOSviewer and Bibliometrix tools. The methodology allows mapping global research trends, such as collaboration networks between countries, institutions, and authors, and identifying thematic clusters on biochar application in saline soils. Thus, the empirical contribution of this work lies in the organization and systematic analysis of the publication landscape, offering advanced strategies for remediating salinized soils.

This study also provides a significant theoretical contribution, framing biochar as a dual-purpose solution: a corrective for saline soils and a strategy for climate mitigation through carbon sequestration. Unlike previous reviews, this work combines quantitative bibliometric evidence with qualitative insights, offering a comprehensive framework for understanding the practical applications and knowledge gaps surrounding the use of biochar as a remediator for saline soils.

Therefore, this study aims to conduct a bibliometric analysis of the application of biochar for saline soil restoration. Using data obtained from Web of Science and the VOSviewer and Bibliometrics software, we aimed to identify research trends, impacts, and knowledge gaps. Furthermore, a systematic review of the effects of biochar on improving physicochemical properties was conducted to understand its potential for saline soil restoration. It is hoped that these findings will contribute to the advancement of sustainable agricultural management practices, increasing agricultural productivity and ensuring food security in regions affected by salinization.

2 | Methodology

The bibliometric analysis was conducted based on previous studies (Phiri et al. 2024; Esener 2025; Melo et al. 2024, 2023). Figure 1 presents the steps for developing the bibliographic and bibliometric research. The searches were carried out in the Web of Science (WoS) database, chosen for its broad coverage, consolidated use in bibliometric analyses, and availability of suitable metadata for network mapping.

The keywords were refined to focus on the topic, resulting in 42,928 articles for "biochar," 10,787 articles for "biochar" and "agricultural use," and finally, 326 articles for "biochar," "agricultural use," and "saline soil." Other terms were tested (such as "biocarbon," "charcoal," "black carbon," and "salinized soils"), but they produced irrelevant results, with publications outside the scope of this research. The search was limited to the document types "article" and "review," following a systematic approach that covers the period from 2013 to 2024.

The following questions guided the extraction of relevant information in this study: "How has research on the topic evolved over the past 12 years?"; "Which were the main journals, countries, institutions, and authors?"; "Which articles were the most cited?"; "Which were the most frequently mentioned keywords?"; and "In which research areas were the articles published?"

The selected articles were exported and analyzed using two software tools designed for bibliometric analysis. VOSviewer (version 1.6.18) (https://www.vosviewer.com/) was employed to construct network maps, identifying the most frequent and cited journals, countries, institutions, authors, and keywords in the field. For the construction of these networks, thresholds were set at MND = 5 (minimum number of documents) and MNC = 5 (minimum number of citations). These criteria were consistently applied to journals, countries, institutions, and authors, ensuring the formation of representative clusters while preserving visual clarity.

The Bibliometrix extension (version 3.0) (https://www.bibliometrix.org/), available in the R language through R Studio, was used to generate the three-field plot, bibliometric rankings (presented in the tables of this study), and to analyze thematic clusters. In addition, the analyses conducted with Bibliometrix were performed using the following parameters: for the thematic map, number of words = 250, minimum cluster frequency = 5, label size = 0.3, and the Walktrap clustering algorithm; for the factorial analysis, multiple correspondence analysis was applied

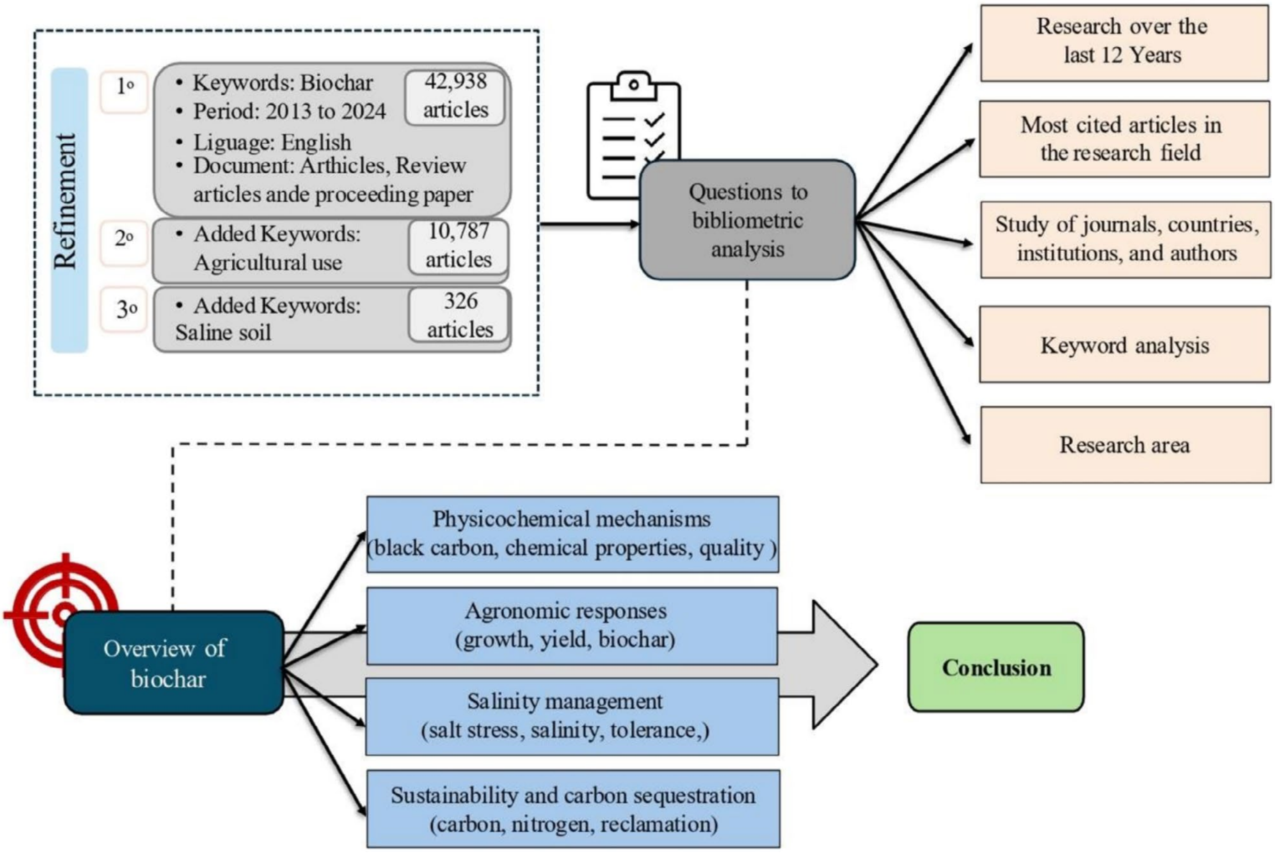

FIGURE 1 | Methodological steps of bibliometric analysis. [Colour figure can be viewed at wileyonlinelibrary.com]

with 30 terms and 4 clusters; and for the coupling clustering, 170 units were considered, with minimum cluster frequency = 5, label size = 0.3, and local citation score as the impact measure. These parameters were selected after sensitivity tests, which showed that lower thresholds produced networks that were too dense to interpret, whereas higher thresholds substantially reduced thematic diversity.

This combined approach has been widely employed in recent bibliometric studies, supporting the robustness of the methodology (Al-Shattarat et al. 2025; Benameur et al. 2025, 2023; Hassanein et al. 2025; Tahat et al. 2025; Hassanein and Mostafa 2023). Finally, a general summary was prepared, highlighting the main applications, registered patents, research trends, and future perspectives on the use of biochar in saline soils.

3 | Results and Discussion

3.1 | Bibliometric Analysis on Biochar in the Last 12 Years

Figure 2 presents the evolution of publications on using biochar in salt-affected soils over the past 12 years. In 2024 alone, 81 articles had already been published, representing a significant increase compared to previous years.

Research in this field began in 2013, with the publication of a single article in the journal *Science of the Total Environment*, which has since accumulated 44 citations. That study evaluated the potential for carbon sequestration in semiarid soils through the incorporation of plant residues, analyzing CO_2 emissions and carbon storage across different soil types, including saline soils (Badía et al. 2013).

Since then, the number of publications has increased substantially. A comprehensive review published in *Science of the Total Environment* in 2018, which accumulated 352 citations, stands out among the 14 articles published that year. This review examined the effects of biochar on improving soil properties and plant growth in saline soils. While highlighting biochar's potential as a soil amendment, the study highlighted key challenges, such as high production costs and limited large-scale feasibility (Saifullah et al. 2018).

From 2019 onward, the growth has been steady: 22 publications in 2019, 28 in 2020, 45 in 2021, 44 in 2022, 63 in 2023, and 81 in 2024. In 2024, the most cited article (with 20 citations) was published in the *Journal of Environmental Management* and reviewed the application of biochar in saline soil remediation. The study highlighted the potential of biochar to lower soil salinity, foster the development of beneficial microbiomes, and strengthen microbial interactions, thereby supporting plant growth in degraded environments (Wang et al. 2024).

This temporal trend can be divided into three main stages of research development. The emerging phase (2013–2015) corresponds to the initial studies that explored the potential of biochar

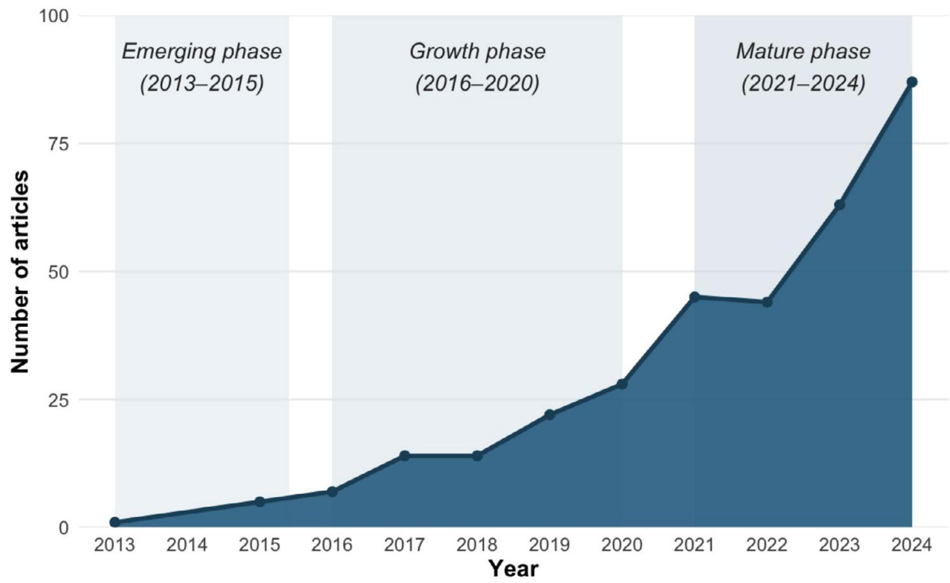

FIGURE 2 | Evolution of the number of publications between 2013 and 2024. [Colour figure can be viewed at wileyonlinelibrary.com]

for carbon sequestration and the improvement of degraded soils, including saline environments. The growth phase (2016–2020) is characterized by a steady increase in publications, with studies evaluating the physicochemical and agronomic effects of biochar in salt-affected soils. Finally, the mature phase (2021–2024) demonstrates a rapid expansion of scientific output and the strengthening of collaboration networks, reflecting the consolidation of biochar as an important strategy for soil restoration and the mitigation of climate change impacts.

3.1.1 | Study of Journals, Countries, Institutions, and Authors

The advancement of research on biochar and its application in salt-affected soils has been driven by a growing number of scientific publications distributed across various journals, countries, institutions, and authors, as shown in Table 1.

The journal that stood out the most in terms of publication volume was Science of the Total Environment, which not only led in quantity but also impact, with a total of 1216 citations and an AC factor (average citations per article) of 71.53. The most cited article from this journal, with 352 citations, was published in 2018 by Saifullah et al., presenting a comprehensive review of the use of biochar for the remediation of degraded soils, including those affected by salinity Saifullah et al. (2018).

Regarding country-level distribution, leads in the number of publications, followed by Australia and Pakistan. However, when considering the AC factor, Australia (66.50) and Denmark (67.17) surpass China, indicating a higher average impact per publication.

The most prolific institutions are predominantly Chinese. The Chinese Academy of Sciences ranks first with 44 publications, followed by the *Chinese Academy of Agricultural Sciences* (17) and the University of the Chinese Academy of Sciences (16). Despite having only six publications, the University of Copenhagen, in Denmark, recorded the highest institutional AC factor (67.17), highlighting the relevance of its studies in this field.

Among the most productive authors, Jin R. and Yao R. lead with 11 and 10 publications, respectively, followed by Wang X. and Xie W., both with nine articles. However, the author with the highest number of total citations (434) and the highest AC factor (72.33) is Wu L., standing out for the impact of his contributions. His most cited article, with 181 citations, was published in 2019 in the *Journal of Cleaner Production*. It discusses using MgO-modified biochar, demonstrating its effectiveness in enhancing phosphate retention and increasing rice yields in saline-alkaline soils (Wu et al. 2019).

Figure 3 presents the results of the bibliometric analysis of the journals that have published the most studies on biochar applied to the remediation of salt-affected soils.

Figure 3a shows the journals with the highest number of publications, with Agronomy-Basel standing out as the most prolific, with 19 publications. However, the journal *Science of the Total Environment*, ranking second in several publications (17), stands out as the most impactful, having accumulated 1216 citations and an AC factor of 71.53. The most cited article in this journal, with 352 citations, was the review by Saifullah et al. (2018), which analyzed the application of biochar in saline soils. The second most cited article in the same journal, with 240 citations, was the study by Sun et al. (2017), which investigated the use of biochar in saline soils to reduce nitrogen leaching. The results showed that biochar applications contributed to soil nitrogen retention, reducing leaching losses (Saifullah et al. 2018; Sun et al. 2017).

Figure 3b presents the network analysis generated by VOSviewer, highlighting the connections between the leading journals in this field. The science of the Total Environment has a strong centrality in the network, demonstrating its influence in disseminating knowledge on biochar and its application in rehabilitating degraded soils.

TABLE 1 | Ranking of the top 10 journals, countries, institutions, and authors with the highest number of publications on the use of biochar in saline soils in the last 12 years.

Ranking		NP	NC	AC
	Journal			
1	*Science of the Total Environment*	17	1216	71.53
2	*Agricultural Water Management*	8	521	65.13
3	*Environmental Science and Pollution Research*	12	471	39.25
4	*Agronomy-Basel*	19	370	19.47
5	*Journal of Environmental Management*	5	335	67.00
6	*Journal of Soils and Sediments*	6	326	54.33
7	*Applied Soil Ecology*	7	266	38.00
8	*Soil and Tillage Research*	6	257	42.83
9	*Scientific Reports*	6	215	35.83
10	*Plants-Basel*	14	180	12.86
Country				
1	China	211	4867	23.07
2	Australia	18	1197	66.50
3	Pakistan	35	1184	33.83
4	Arabia	35	967	27.63
5	USA	17	807	47.47
6	Egypt	32	765	23.91
7	Iran	21	407	19.38
8	Denmark	6	403	67.17
9	India	10	376	37.60
10	Germany	12	299	24.92
Institutions				
1	*Chinese Academy of Sciences*	44	1211	27.52
2	*Qingdao Agricultural University*	12	486	40.50
3	*University of Agriculture Faisalabad*	12	482	40.17
4	*Hohai University*	14	421	30.07
5	*University of the Chinese Academy of Sciences*	16	415	25.94
6	*University of Copenhagen*	6	403	67.17

(Continues)

TABLE 1 | (Continued)

Ranking		NP	NC	AC
7	*Assiut University*	10	354	35.40
8	*Bahauddin Zakariya University*	8	336	42.00
9	*Chinese Academy of Agricultural Sciences*	17	321	18.88
10	*Jiangsu Academy of Agricultural Sciences*	9	319	35.44
Authors				
1	Wu, Lipeng	6	434	72.33
2	Ding, Xiaodong	6	432	72.00
3	Zhang, Shirong	6	432	72.00
4	Eissa, Mamdouh A.	7	201	28.71
5	She, Dongli	6	187	31.17
6	Yao, Rongjiang	10	184	18.40
7	Yang, Jingsong	8	183	22.88
8	Wang, Xiangping	9	183	20.33
9	Xie, Wenping	9	183	20.33
10	Jin, Feng	11	178	16.18

Abbreviations: AC, average citations (NC/NP); NC, number of citations; NP, number of publications.

Unlike some previous studies on biochar in saline soils, which generally listed the main journals but did not quantify citation impact or visualize network centrality, this study provides a bibliometric mapping highlighting the volume of publications and the interconnections between journals, identifying *Science of the Total Environment* as a central hub for dissemination on the topic.

Figure 4 presents a bibliometric analysis of the scientific production of biochar and its use in salt-affected soils, highlighting the most productive countries in this field.

Figure 4a displays countries with the most publications geocoding. China stands out as the leading country, with a significantly higher number of published articles (211), surpassing other countries by a considerable margin. The most cited article from China, with 282 citations, was published in 2015 by Akhtar et al. (2015). Other countries with relevant contributions include Australia (18), Pakistan (35), Saudi Arabia (35), United States (17), Egypt (32), Iran (21), Denmark (6), India (10), and Germany (12). These data reveal a concentration of publications in Asian, European, and North American nations.

Figure 4b shows the network analysis of the most active countries in the field using the VOSviewer software. Five main collaboration networks can be identified. The largest, shown in red, is centered around China, which connects with several countries such as Australia, Saudi Arabia, and Canada. The United States dominates the green cluster, with strong links to Germany, Iran, and

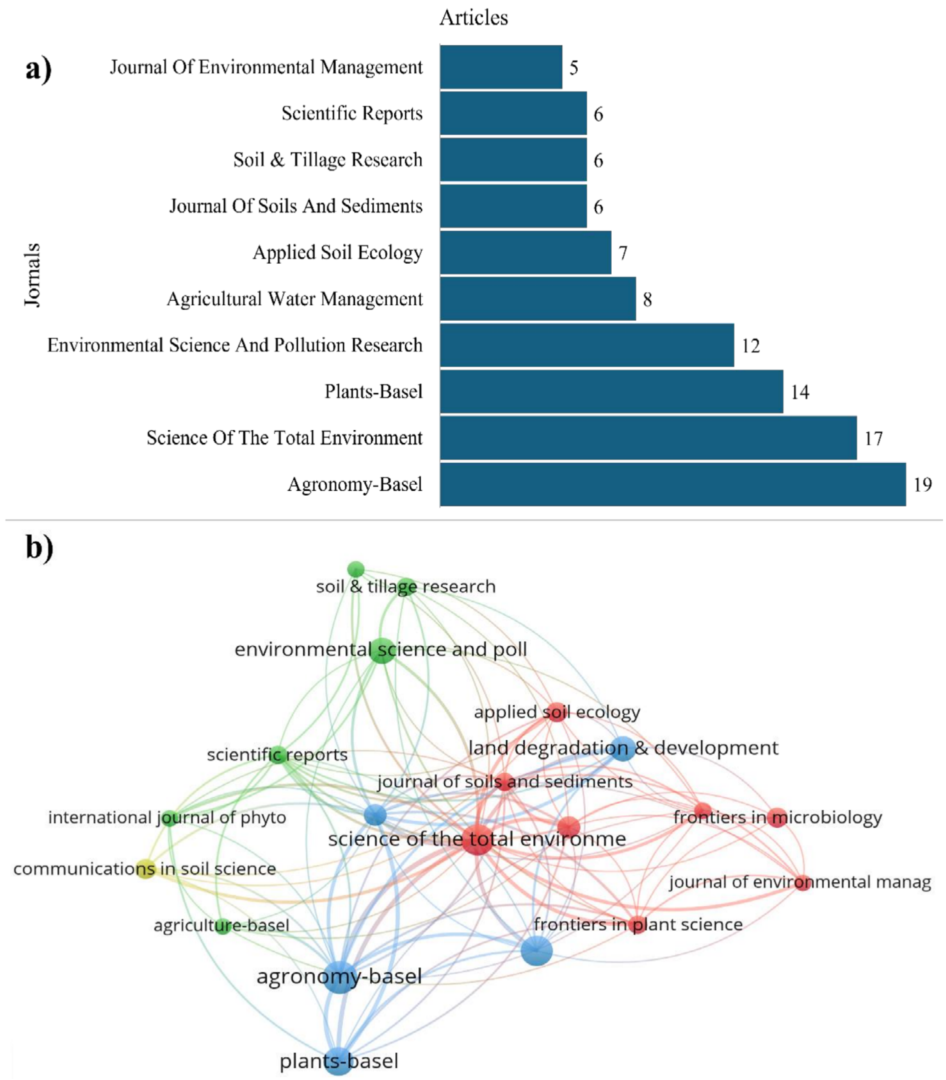

FIGURE 3 | Bibliometric analysis of journals publishing research on biochar and saline soils. (a) Ranking of the 10 journals with the highest number of publications; larger bars indicate higher output. (b) Network map generated with VOSviewer (thresholds: MND = 5; MNC = 5), where circle size represents the number of articles, and colors group journals into clusters of similar citation patterns. [Colour figure can be viewed at wileyonlinelibrary.com]

Denmark. Egypt leads the blue cluster, while the purple and yellow clusters represent other collaborations among European and Asian countries. The strong interconnectivity between China and the United States suggests that both play a central role in the dissemination of knowledge on biochar in salt-affected soils.

From this analysis, it is evident that China leads research on salt-affected soils, as the country has one of the largest extents of salinized land in the world, estimated at approximately 36.9 million hectares (Lei et al. 2025; Ma and Tashpolat 2023). This agricultural challenge has driven substantial investments in research on remediation strategies, among which the application of biochar stands out, with the aim of ensuring food security and promoting sustainable land management.

Countries such as Australia and Denmark show a smaller number of publications; however, they present higher AC factors. This occurs because their research is more focused, with greater presence in high–impact journals and strong participation in international collaborations. In contrast, despite Pakistan, Saudi Arabia, and Egypt reporting a relatively high number of publications, their average citation rates are lower. This may be related to the predominance of publications in regional journals, limited integration into global research networks, and a strong emphasis on locally focused case studies. These patterns highlight the importance of considering both productivity and scientific visibility when interpreting international trends in biochar research.

Figure 5 presents a bibliometric analysis of the most productive institutions in research on biochar and its application in salt-affected soils.

Figure 5a displays a bar chart representing the institutions with the most publications in this area. The Chinese Academy of Sciences leads by a wide margin, with the most significant volume of research output. Its most cited article, published in 2017, received 240 citations and investigated using biochar to reduce nitrogen leaching in salt-affected soils (Sun et al. 2017). Other Chinese universities, such as Qingdao Agricultural University, Hohai University, and Nanjing Agricultural University, also

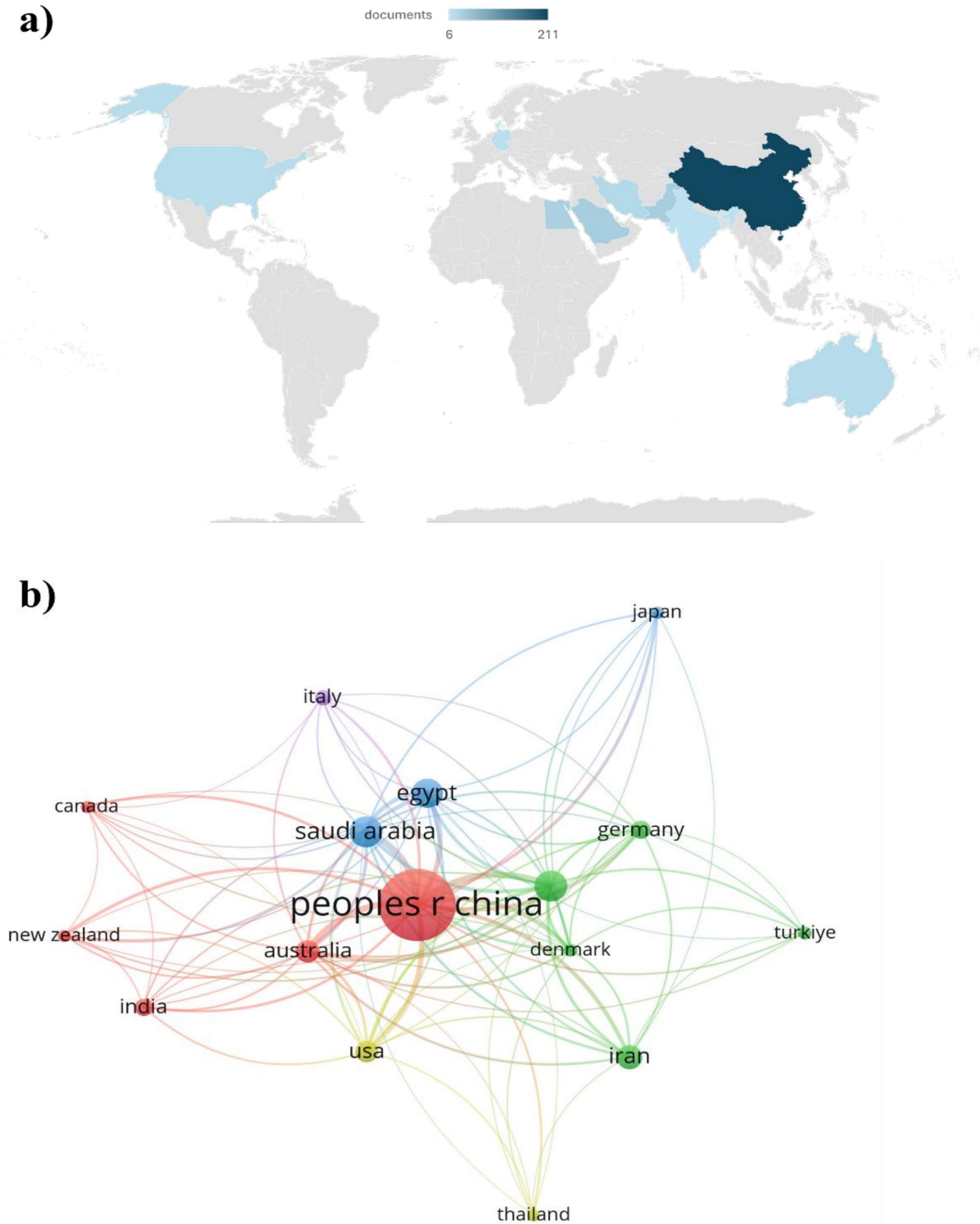

FIGURE 4 | Bibliometric analysis of countries publishing on biochar in salt-affected soils. (a) Top contributing countries ranked by publication output. (b) Network map generated with VOSviewer (thresholds: MND = 5; MNC = 5), where circle size indicates publication frequency, and colors represent collaboration clusters between countries. [Colour figure can be viewed at wileyonlinelibrary.com]

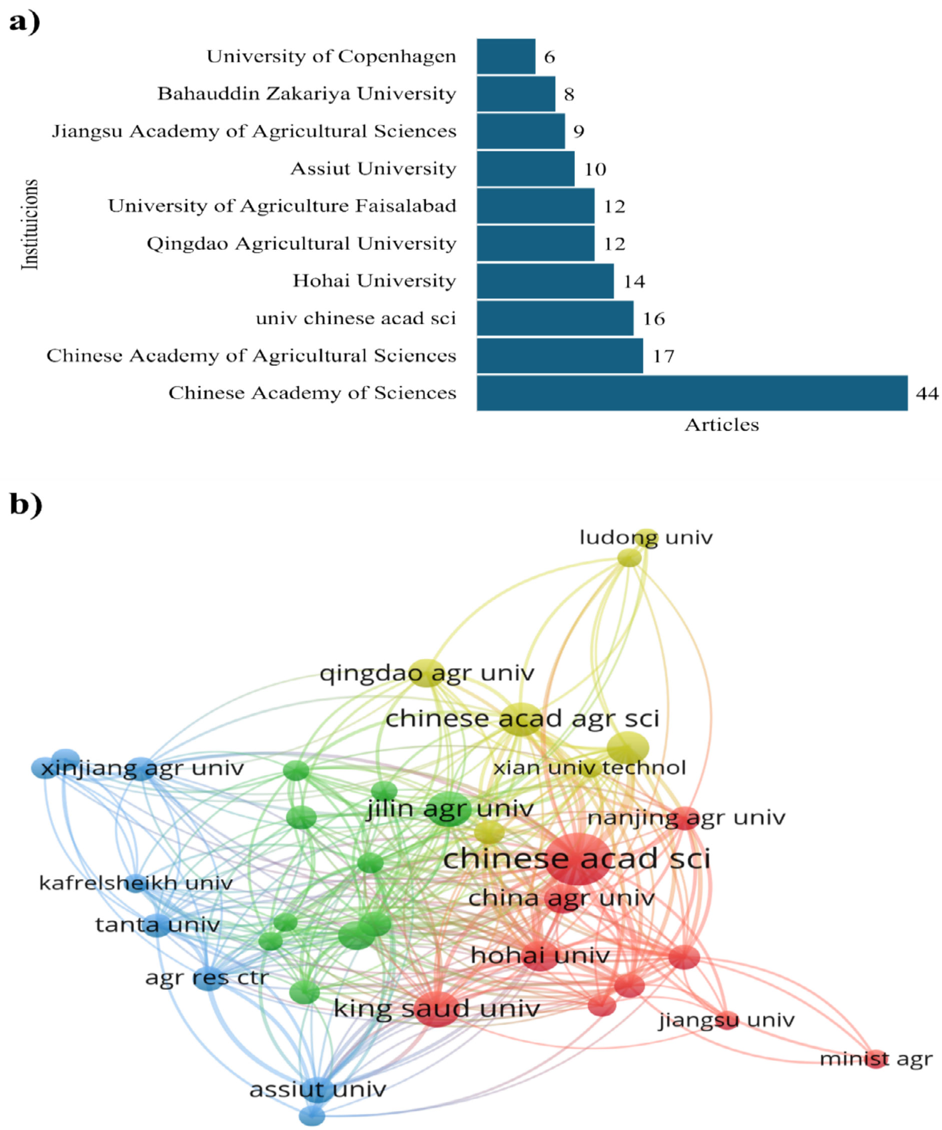

FIGURE 5 | Bibliometric analysis of institutional contributions to biochar research in salt-affected soils. (a) Ranking of the most productive institutions by publication output. (b) Network map generated with VOSviewer (thresholds: MND = 5; MNC = 5), where circle size reflects number of articles, and colors indicate clusters of institutional collaboration. [Colour figure can be viewed at wileyonlinelibrary.com]

stand out. Beyond China, institutions from different countries have contributed significantly, including King Saud University (Saudi Arabia) and Egyptian universities such as Assiut University and Kafrelsheikh University.

Figure 5b presents the network analysis of the most influential institutions in the field, using VOSviewer software. The collaboration map shows the interconnectivity between universities and research centers, highlighting five main clusters. The Chinese Academy of Sciences dominates the red cluster, which is linked to other Chinese institutions such as Hohai University and China Agricultural University. The green cluster reflects the strong presence of Chinese agricultural universities, including Jilin Agricultural University. The yellow cluster includes the Chinese Academy of Agricultural Sciences and Qingdao Agricultural University. In contrast, the blue cluster highlights contributions from Egyptian and Saudi institutions, such as King Saud University, Assiut University, and Kafrelsheikh University.

Figure 6 presents a bibliometric analysis of the principal authors who have contributed to research on biochar and its use in salt-affected soils.

Figure 6a shows a bar chart representing the researchers with the most publications in the field. Among the most productive authors are Yao R. (10 publications), Wang X. (9), and Yang J. (8). However, Zhang S., Wu L., and Ding X. (each with six publications) stand out for having the highest number of citations. Together, their articles total 327 citations, with the most cited study published in 2019 in the *Journal of Cleaner Production*, which received 181 citations. This article investigated the modification of biochar with MgO to enhance soil phosphate (P) retention and improve agricultural productivity (Wu et al. 2019).

Figure 6b presents the author collaboration network, generated using VOSviewer software. The map highlights three main clusters. The red cluster is centered around authors Che W. and Jin

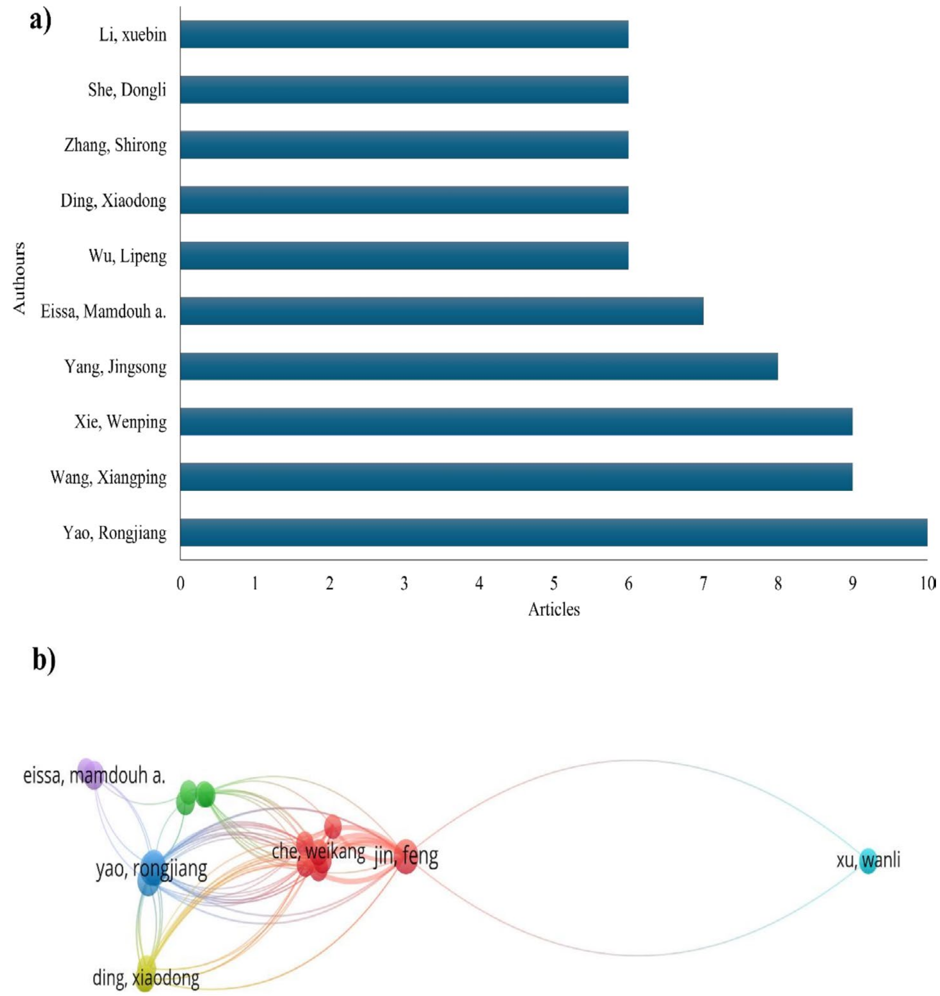

FIGURE 6 | Bibliometric analysis of authors publishing on biochar in salt-affected soils. (a) Ranking of the most productive authors by number of publications. (b) Network map generated with VOSviewer (thresholds: MND = 5; MNC = 5), where node size indicates publication count, and colors represent clusters of co-authorship networks. [Colour figure can be viewed at wileyonlinelibrary.com]

F., who maintain connections with several other researchers in the field. The blue cluster is represented by Xu W., who appears more isolated, suggesting limited direct collaboration. The green cluster includes Yao R. and Ding X., connected to authors such as Eissa M. A., indicating active collaboration across different institutions.

Figure 7 presents conclusive bibliometric analyses of the countries, authors, and institutions involved in research on biochar in salt-affected soils.

Figure 7a displays the geocoding and international collaborations between countries. China is the primary contributor, with significant scientific information exchange with countries such as Germany, the United States, New Zealand, Australia, Egypt, and Saudi Arabia. These connections highlight China's leading role in knowledge dissemination and its strategic collaborations with research institutions across different regions of the world.

Figure 7b illustrates a three-field plot generated through bibliometric analysis, linking countries, authors, and institutions. China demonstrates its dominance in the field, being directly connected to top authors such as Jin F., Yao R.J., Wang X.P., and Yang J.S., who are in turn affiliated with prominent institutions like the Chinese Academy of Sciences, the Nanjing Institute of Soil Science, and Jilin Agricultural University. Additionally, institutions from other countries—such as King Saud University, Assiut University, and the Agricultural Research Center of Egypt—play a relevant role in the collaboration network. The visualization confirms China's strong influence in global research on biochar in saline soils, while other countries maintain significant, albeit smaller-scale, contributions. Thus, while Figure 4 highlights China's centrality at the national level, Figure 7 reveals how this leadership is consolidated through networks of authors and institutions that function as hubs of national and international collaboration.

3.1.2 | Most Cited Articles in the Research Field

Table 2 presents the 10 most cited articles on biochar and its use in salt-affected soils. The analysis of these publications reveals the central topics related to this theme.

The most cited article was published in *Science of the Total Environment* in 2018, with 352 citations. The study explores the challenges and opportunities associated with using biochar to remediate saline and sodic soils, emphasizing its

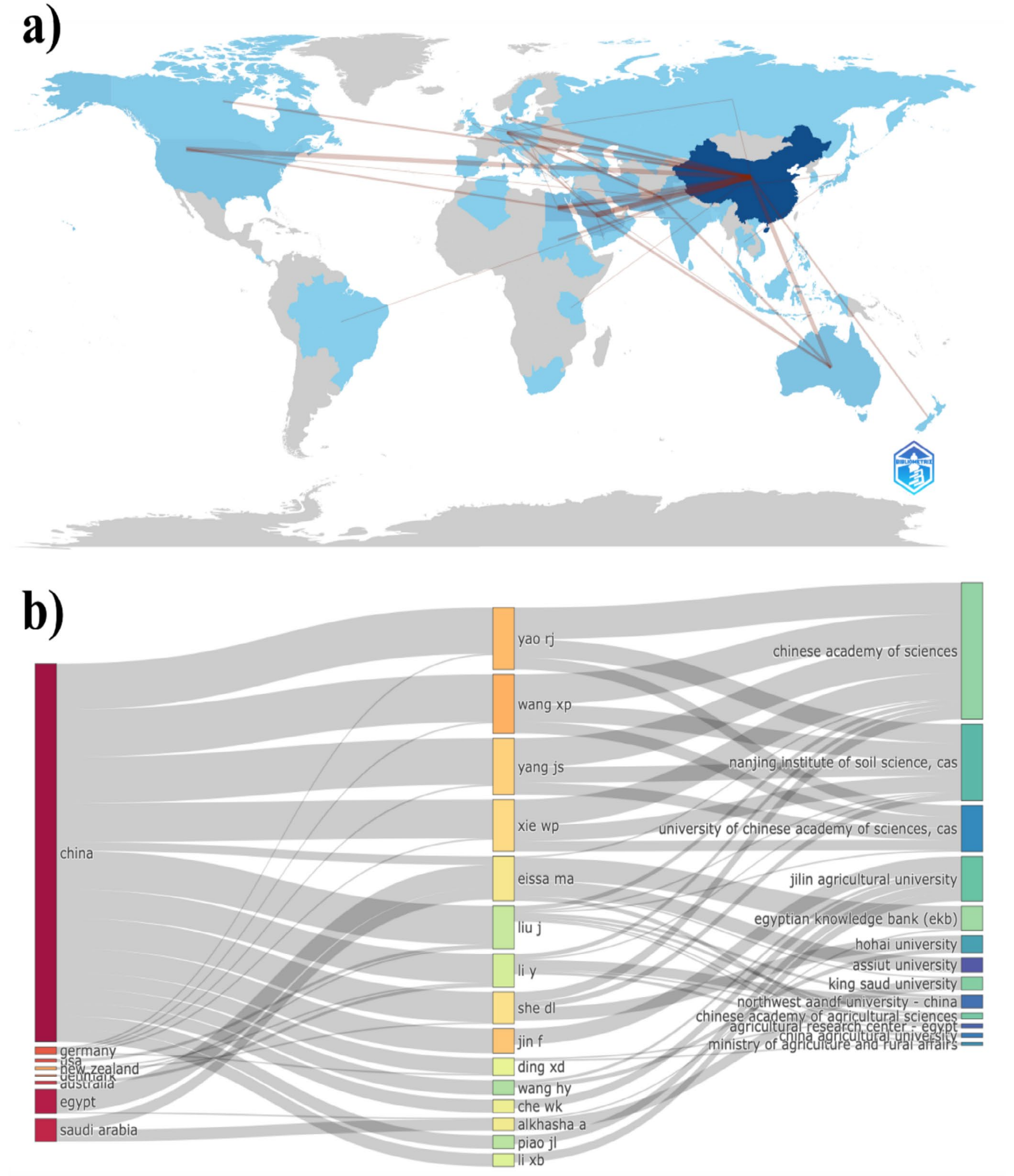

FIGURE 7 | Bibliometric analysis of research on biochar and its use in saline soils. (a) Cooperation map showing international collaborations among countries publishing in this field. Darker shades of blue represent higher publication output, and connecting lines indicate co-authorship links between countries. (b) Sankey diagram illustrating the relationship between countries (left), authors (middle), and institutions (right). The thickness of the flows indicates the intensity of collaboration or number of publications connecting each element. [Colour figure can be viewed at wileyonlinelibrary.com]

potential to modify their physical, chemical, and biological properties by promoting moisture retention and nutrient availability. However, the effects vary depending on the biochar and soil characteristics, and high application rates can sometimes increase salinity and sodicity. The article also points out challenges such as the high cost of production and the lack of long-term field studies, emphasizing the need for more affordable production methods and further research into the sustainable use of biochar for crop productivity in degraded soils Saifullah et al. (2018).

The second article, published in *Environmental Science and Technology* in 2021 and cited 335 times, addresses the global challenges of soil salinization and its impact on environmental sustainability. It underscores the need for integrated strategies, including biochar and sustainable agricultural practices, to mitigate salinity and enhance productivity. The article also highlights the importance of future research focusing on the interactions between biochar and soil conservation practices under climate change scenarios, aiming to strengthen agricultural sustainability in affected regions (Mukhopadhyay et al. 2021).

The third article, published in the *Journal of Arid Environments* in 2017, has 279 citations. It examined the effect of biochar on reducing cadmium (Cd) toxicity and salt stress in wheat. The results showed that biochar promoted plant growth, reduced oxidative stress, and lowered Cd and Na uptake. However, high biochar application rates in saline soils may have adverse effects, highlighting the need for appropriate management to avoid unfavorable outcomes (Abbas et al. 2018).

The fourth article, published in *Agricultural Water Management* in 2016, has 278 citations. It reviews the challenges of soil salinity and its consequences for soil moisture retention and water use efficiency in agriculture. The study identifies biochar as a sustainable strategy for improving water retention in saline soils by reducing evaporation and enhancing plant water availability. Nonetheless, it underscores the need for further research into the long-term impacts of biochar, particularly concerning the trade-off between improved moisture retention and potential residual salinity (Amini et al. 2015).

The fifth article, published in *Science of the Total Environment* in 2015, with 271 citations, investigated the effects of biochar on wheat production under salt stress. The study demonstrated that biochar reduced Na^+ uptake, alleviated osmotic stress by improving soil moisture, and enhanced the availability of K^+, Ca^{2+}, and Mg^{2+}. The results indicated improved wheat growth, physiological performance, and yield, particularly in highly saline conditions. The authors concluded that biochar holds significant potential for mitigating salt stress but emphasized the need for further field studies to evaluate its long-term effects (Akhtar et al. 2015).

The sixth article, published in *Plant and Cell Physiology* in 2017, with 234 citations, evaluated the effects of biochar on nitrogen retention and the reduction of ammonia (NH_3) leaching and volatilization in coastal saline soils. The study showed that moderate application rates (0.5%–1%) reduced nitrogen losses via leaching and maintained nitrogen in the soil without increasing NH_3 emissions. However, higher doses (2%–4%) increased NH_3 volatilization due to elevated soil pH (Sun et al. 2017).

The seventh article, published in *Plant, Cell and Environment* in 2017, with 221 citations, investigated the effects of biochar on the restoration of coastal saline-sodic soils and the growth of halophytic plants. The results showed that biochar applied alone or combined with fertilizer supported germination, root development, and biomass accumulation. These effects were attributed to enhanced soil health, greater nutrient availability, and stimulated rhizosphere microbial activity, particularly the proliferation of beneficial bacteria such as *Pseudomonas* and *Bacillus* (Zheng et al. 2018).

The eighth article, published in the *Journal of Cleaner Production* in 2019, with 176 citations, explored using MgO-modified biochar to improve phosphorus (P) retention and increase rice yields in saline-alkaline soils. The study found that MgO-biochar had up to 1.46 times higher P adsorption capacity than conventional biochar, maintaining effectiveness even in the presence of competing anions like SO_4^{2-} and CO_3^{2-}. Field trials confirmed higher soil P availability and significant yield increases, supporting the material's potential for efficient and sustainable soil restoration (Wu et al. 2019).

In the ninth position, with 173 citations, is an article published in *Science of the Total Environment* in 2020, which evaluated the use of corn straw biochar for the remediation of sodic-saline-alkaline soils in the Songnen Plain, China. The results showed that biochar strengthened cation exchange capacity (CEC), increased organic matter, and reduced pH, salinity, and sodium (Na^+) levels. It also boosted nutrient availability and elevated corn yield, with the 20 t/ha application rate proving the most effective. These findings reinforce biochar's potential as a sustainable strategy for restoring degraded soils in saline regions (Zhao et al. 2020).

Finally, in the tenth position, with 163 citations, is an article published in *Applied Soil Ecology* in 2017, which analyzed the effects of rice husk biochar on phosphorus availability and the bacterial community in three soil types: acidic red, organic brown, and saline. Results showed that biochar increased phosphorus retention, phosphatase activity, and microbial biomass while stimulating phosphate-solubilizing bacteria such as *Pseudomonas, Thiobacillus, and Flavobacterium* (Liu et al. 2017).

Overall, the 10 most cited articles in this analysis are mainly experimental studies, with three being literature reviews. This combination reflects that research on biochar in salt-affected soils has advanced through theoretical syntheses of current knowledge and empirical evidence generated via field, greenhouse, and laboratory experiments. The main topics addressed include nutrient retention, improvements in soil structure and moisture, mitigation of salinity and heavy metal contamination, carbon sequestration, improved fertilizer efficiency, and stimulation of beneficial soil microbiota. These themes highlight the growing scientific interest in biochar as a sustainable strategy for restoring degraded soils and boosting agricultural productivity in challenging environments.

3.1.3 | Research Areas

Figure 8 illustrates the distribution of the top 10 research areas related to the use of biochar in salt-affected soils. The percentages were normalized based on data obtained from the Web of

TABLE 2 | Top 10 most cited articles of the past 12 years.

Ranking	Article title	Authors	Journal	Year published	Total citations	References
1	Biochar Application for the Remediation of Salt-Affected Soils: Challenges and Opportunities	Saifullah et al.	*Science of the Total Environment*	2018	352	(Saifullah et al. 2018)
2	Soil Salinity Under Climate Change: Challenges for Sustainable Agriculture and Food Security	Raj Mukhopadhyay et al.	*Journal of Environmental Management*	2021	335	(Mukhopadhyay et al. 2021)
3	Effect of Biochar on Alleviation of Cadmium Toxicity in Wheat (*Triticum aestivum* L.) Grown on Cd-Contaminated Saline Soil	Tahir Abbas et al.	*Environmental Science and Pollution Research*	2017	279	(Abbas et al. 2018)
4	Salt-Affected Soils, Reclamation, Carbon Dynamics, and Biochar: A Review	Sevda Amini et al.	*Journal of Soils and Sediments*	2016	278	(Amini et al. 2015)
5	Residual Effects of Biochar on Improving Growth, Physiology, and Yield of Wheat Under Salt Stress	Saqib Saleem Akhtar et al.	*Agricultural Water Management*	2015	271	(Akhtar et al. 2015)
6	Biochar Applied With Appropriate Rates Can Reduce N Leaching, Keep N Retention, and Not Increase NH_3 Volatilization in a Coastal Saline Soil	Haijun Sun et al.	*Science of the Total Environment*	2017	234	(Sun et al. 2017)
7	Enhanced Growth of Halophyte Plants in Biochar-Amended Coastal Soil: Roles of Nutrient Availability and Rhizosphere Microbial Modulation	Hao Zheng et al.	*Plant, Cell and Environment*	2017	221	(Zheng et al. 2018)
8	MgO-Modified Biochar Increases Phosphate Retention and Rice Yields in Saline-Alkaline Soil	Lipeng Wu et al.	*Journal of Cleaner Production*	2019	176	(Wu et al. 2019)
9	Apply Biochar to Ameliorate Soda Saline-Alkali Land, Improve Soil Function, and Increase Corn Nutrient Availability in the Songnen Plain	Wei Zhao et al.	*Science of the Total Environment*	2020	173	(Zhao et al. 2020)
10	Rice Husk Biochar Impacts Soil Phosphorous Availability, Phosphatase Activities, and Bacterial Community Characteristics in Three Different Soil Types	Saimon Liu et al.	*Applied Soil Ecology*	2017	163	(Liu et al. 2017)

Science (WoS), reflecting the diversity of approaches and applications of biochar in agriculture and soil science.

The most prominent topic was plant growth and agricultural yield, representing 29% of the publications. This section examines the effects of biochar on agrarian productivity, highlighting how its application can promote plant development, improve nutrient uptake, and mitigate the adverse impacts of salinity. Next, soil quality and nutrient retention appear as the second most studied area, accounting for 21% of the publications. This field investigates how biochar enhances the physical and chemical properties of the soil, influencing its structure, water-holding capacity, and the availability of essential nutrients for plants.

The soil's interaction between biochar and nitrogen accounts for 20% of the analyzed publications. This topic examines how biochar can regulate nitrogen dynamics by influencing mineralization, uptake by plants, and the reduction of leaching losses.

Another relevant aspect is salinity management and salt stress, comprising 14% of the studies. The remaining areas include biochemical and microbiological mechanisms of biochar in the soil (5%), biochar use in biomass and composting (3%), and other minor topics such as soil carbon and environmental impacts (2% each).

The field of Environmental Sciences includes 131 out of the 326 analyzed articles. The most cited article in this area is a review, listed as the first entry in Table 2, with 352 citations (Saifullah et al. 2018). The study reviews the application of biochar in salt-affected soil remediation, highlighting its positive effects on improving the physical, chemical, and biological properties of soil and plant growth. However, it also points out key challenges, such as the high production cost and the risk of increased salinity and sodicity when applied at high rates.

The field of Soil Science comprises 98 publications. The most cited article in this area, with 278 citations, is a review that discusses the chemical, physical, and biological challenges of salt-affected soils and different rehabilitation strategies. The study highlights biochar as a promising alternative for increasing carbon stocks and improving soil quality. It also emphasizes the lack of specific research on its application in saline soils, underscoring the need for long-term studies under field conditions (Amini et al. 2015).

The field of Plant Sciences includes 92 publications. The most cited article, with 266 citations, analyzed the effects of biochar on the restoration of coastal saline-sodic soils and the growth of halophytic plants. The study demonstrated that biochar application, either alone or combined with fertilizer, enhanced nutrient availability, stimulated beneficial microbial activity in the rhizosphere, and supported plant growth, highlighting its potential for rehabilitating degraded soils (Zheng et al. 2018).

3.1.4 | Keyword Analysis

The bibliometric analysis also examined the most relevant keywords in the field, allowing the identification of research clusters. Figure 9 presents the network analysis generated using VOSviewer, in which four main groups can be observed.

Figure 9a shows a red cluster centered around the keyword "salinity," which is strongly connected to terms such as "salt stress," "tolerance," "physiology," and "osmotic adjustment." This group reflects the growing concern about the impact of salinity on agricultural productivity and the search for strategies to mitigate its effects. Biochar emerges as a potential soil amendment, improving soil properties and increasing water and nutrient retention capacity.

In the green cluster, the dominant keyword is "biochar," interconnected with terms like "carbon," "nitrogen," "soil reclamation," and "carbon sequestration." This group reinforces the role of biochar in restoring degraded soils and enhancing soil's chemical and biological properties. Studies indicate that biochar application can increase soil organic carbon content, stimulate microbial activity, and improve soil fertility, thereby contributing to more sustainable agricultural practices (Waheed et al. 2025; Narayanan et al. 2024).

The blue and yellow clusters include terms associated with agricultural productivity and water retention, such as "plant growth," "production," "irrigation," and "adsorption." These topics indicate a growing interest in improving water use efficiency and crop yield through biochar in salt-affected soils.

Figure 9b presents the keyword density map, highlighting "biochar" and "salinity" as the primary research focuses. This suggests that the scientific community has increasingly directed efforts toward understanding the interaction between biochar and salt-affected soils, exploring its potential as a solution to the challenges of soil salinization and low productivity in arid and semiarid environments.

Table 3 presents the ranking of the 20 most frequently occurring keywords in the analyzed articles, along with their Total Link Strength (TLS). The most recurrent keyword is "biochar," with a frequency of 198 and a highly relevant TLS of 1356, highlighting its central role in current research.

In addition, terms such as "growth," "yield," and "salinity" are also among the most cited, emphasizing the focus of studies on the interaction between biochar, increased agricultural productivity, and mitigation of salt stress. The presence of keywords like "carbon," "quality," and "saline soil" further reinforces the importance of biochar in improving soil quality and contributing to carbon sequestration.

Terms such as "mechanisms," "availability," and "reclamation" reflect the growing interest in understanding the biogeochemical processes associated with biochar application. These findings suggest that current research prioritizes biochar as a sustainable tool for rehabilitating degraded soils, contributing to greater productivity and improved agricultural stability in salinity-affected environments.

Figure 10 was generated using data obtained from Bibliometrix. It shows the correlation between impact and centrality of keywords in research on biochar and salt-affected soils, organized

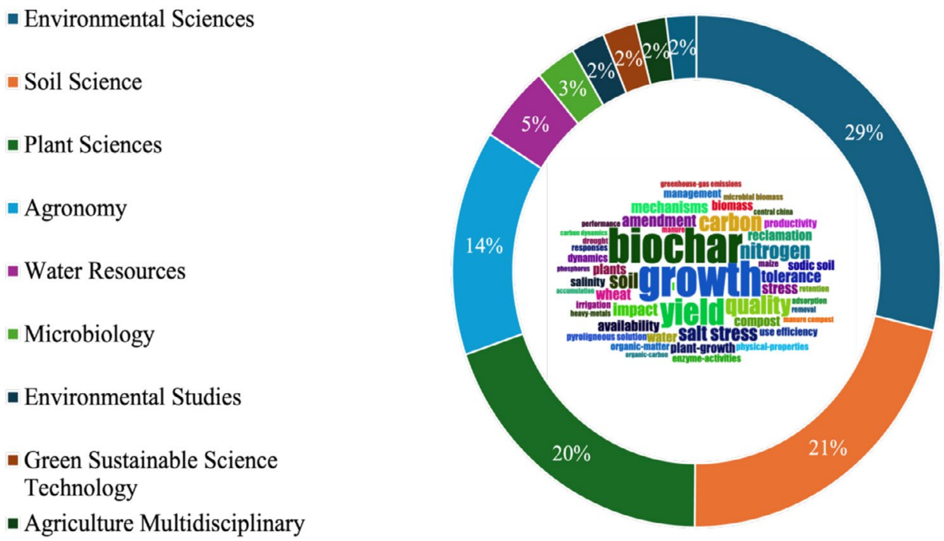

FIGURE 8 | Distribution of research areas for articles on biochar in saline soil. [Colour figure can be viewed at wileyonlinelibrary.com]

into a four-quadrant diagram. This mapping allows the identification of the most influential terms in the field and their connections to key themes in the scientific literature.

In the upper right quadrant, keywords such as "growth," "yield," and "pyroligneous solution" are found. These terms exhibit high centrality and impact, indicating their strong relevance in research focused on the influence of biochar on agricultural productivity and soil quality.

The upper left quadrant includes terms like "black carbon," "chemical properties," and "quality." This cluster is associated with the physicochemical characteristics of biochar, highlighting its role in carbon retention, soil structure improvement, and environmental impact.

In the lower right quadrant, keywords such as "salt stress," "growth," and "yield" appear. Although these terms have lower centrality, they still maintain considerable impact, suggesting ongoing interest in mitigating the effects of salinity on crop productivity through biochar application.

Lastly, the lower left quadrant contains terms like "biochar," "growth," and "yield," indicating their presence in the literature but with lower impact and centrality compared to other clusters.

Figure 10 highlights biochar as a central topic in research, especially about plant growth, soil quality, and salt stress mitigation. These findings underscore biochar's value as a sustainable tool for rehabilitating degraded soils and enhancing agricultural productivity Table 4.

Figure 11 was generated using data obtained from Bibliometrix. Figure 11a presents the distribution of clusters based on the centrality and density of keywords, organized into four categories: emerging or declining themes, basic themes, niche themes, and motor themes. The chart highlights a high-density group (in pink) located in the niche theme quadrant, where the terms "growth," "biochar," and "yield" are found. This cluster indicates that the study of biochar's effects on plant development and crop productivity is a specialized and still evolving field.

Another group, shown in blue, appears in the basic theme region, with higher centrality. This cluster includes keywords such as "salinity," "salt-affected soil," and "bioenergy," demonstrating the relevance of biochar in the remediation of degraded soils and its potential as a sustainable strategy for agricultural management.

Figure 11b presents a factorial cluster analysis, identifying four distinct conceptual groups. The blue cluster is associated with mechanisms of biochar in the soil, including its interaction with water and productivity. The green cluster relates to plant nutrition and development, with terms like "nitrogen," "composting," and "growth." The pink cluster focuses on biochar application management and its impacts, including keywords such as "management," "impact," and "soil quality." Lastly, the purple cluster centers on environmental challenges and salinity, featuring terms like "salt-affected soils," "tolerance," and "salinity."

This conceptual analysis confirms that biochar is pivotal in restoring degraded soils and promoting agricultural productivity, highlighting its connection to multiple sustainable strategies within agriculture.

3.2 | Overview of Biochar

This section provides an overview of biochar, based on the bibliometric analysis presented in previous sections. It begins with the definition of biochar and its production processes, highlighting the main techniques and types of biomass used. Next, it explores the physicochemical effects of biochar in saline soils, emphasizing its interactions with chemical, physical, and structural soil properties. Agronomic and microbial responses are also discussed, focusing on the impacts of biochar on crop productivity and the dynamics of microbial communities. Finally, a bibliometric and bibliographic synthesis of research on biochar is presented, integrating quantitative and qualitative findings

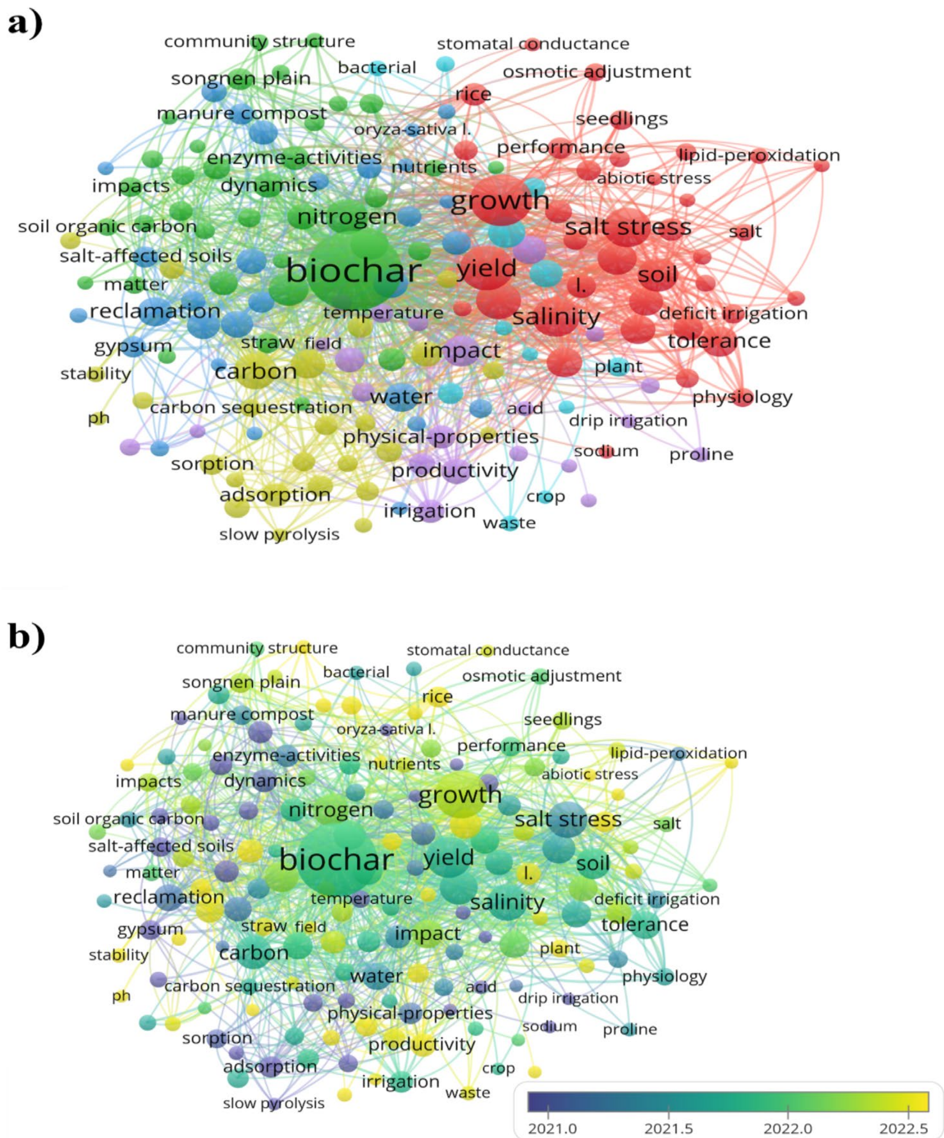

FIGURE 9 | Grouping of the authors' most frequent keywords. (a) Map of terms based on different clusters. (b) Density map of the main keywords. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 | Classification of the 20 most recurrent keywords identified in the analyzed articles.

Ranking	Keyword	Frequency	TLS	Ranking	Keyword	Frequency	TLS
1	Biochar	198	1356	1	Wheat	31	235
2	Growth	81	620	2	Amendment	30	212
3	Yield	60	462	3	Compost	28	220
4	Salinity	46	319	4	Impact	28	198
5	Salt stress	46	355	5	Tolerance	27	201
6	Quality	42	307	6	Mechanisms	26	218
7	Carbon	39	235	7	Stress	25	194
8	Nitrogen	36	283	8	Availability	24	201
9	Soil	34	244	9	Biomass	24	192
10	Saline soil	32	221	10	Reclamation	24	181

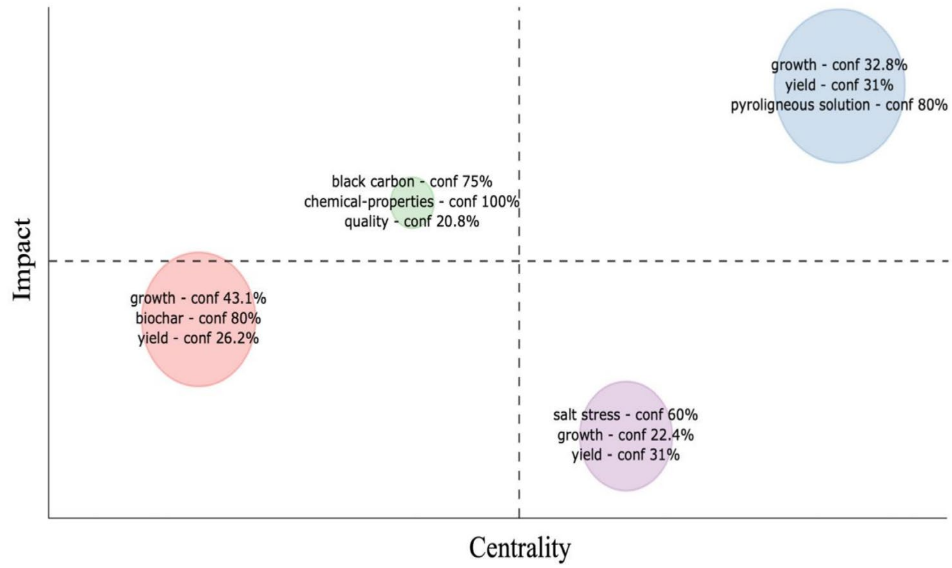

FIGURE 10 | Map of the main keywords correlating the impact and centrality of the theme. [Colour figure can be viewed at wileyonlinelibrary.com]

and highlighting trends, knowledge gaps, and future perspectives for advancing this field of study.

The four research directions addressed in this section—physicochemical mechanisms, agronomic responses, salinity management, and sustainability and carbon sequestration—were derived from the keyword clustering and thematic mapping analyses (Figures 9 and 11; Table 3).

3.2.1 | Definition and Production of Biochar

Biochar is a carbon-rich solid material produced through the thermal decomposition of biomass under limited or no oxygen conditions. This transformation occurs via several thermochemical pathways, including pyrolysis, gasification, hydrothermal carbonization, and torrefaction (Figure 12). Among these methods, pyrolysis is the most widely adopted due to its efficiency in converting biomass into three primary fractions: biochar (solid), bio-oil (liquid), and syngas (gas) (Sun et al. 2017; Foong et al. 2020).

Pyrolysis is a thermochemical process involving the decomposition of biomass at high temperatures under an absence or limited supply of oxygen. It can be classified as slow, conventional, or fast, primarily based on process conditions such as heating rate, temperature, and residence time. The key variables that differentiate the various pyrolysis technologies are the heating profile, pyrolysis temperature, and residence time. The literature outlines the specific parameters that define whether a pyrolysis process is slow, conventional, or fast, and each modality is optimized to favor the production of a particular end product, such as biochar, syngas, or bio-oil. Table 5 summarizes the operational parameters used for biochar production (Singh et al. 2024; Sun et al. 2017; Foong et al. 2020; Bahiri et al. 2025).

The selection of biomass is a determining factor in the quality and properties of the resulting biochar, directly influencing the products generated during the pyrolysis process. Different types of biomasses have optimal temperature ranges depending on their composition, which affects thermal conversion efficiency. These variations significantly impact the morphological and chemical characteristics of the final biochar, making its detailed characterization essential for environmental applications (Foong et al. 2020; Bahiri et al. 2025).

TABLE 4 | Clusters based on bibliometric analysis.

Cluster	Main keywords	Frequency
1	growth—conf 43.1% biochar—conf 80% yield—conf 26.2%	51
2	growth—conf 32.8% yield—conf 31% pyroligneous solution—conf 80%	67
3	black carbon—conf 75% chemical properties—conf 100% quality—conf 20.8%	16
4	salt stress—conf 60% growth—conf 22.4% yield—conf 31%	36

Physical analyses, such as assessments of surface area and porosity, help predict the performance of biochar in applications like strengthening soil and promoting carbon sequestration. In contrast, chemical characterization, including elemental and spectroscopic analyses, provides information on the composition, functional groups, and potential contaminants necessary for defining the material's functionality (Saifullah et al. 2018; Sun et al. 2017).

Understanding these properties is fundamental for optimizing production parameters and tailoring biochar to specific applications. Furthermore, targeted analytical methods are used to evaluate the environmental stability of biochar, supporting its safe and efficient application across diverse agronomic and ecological contexts.

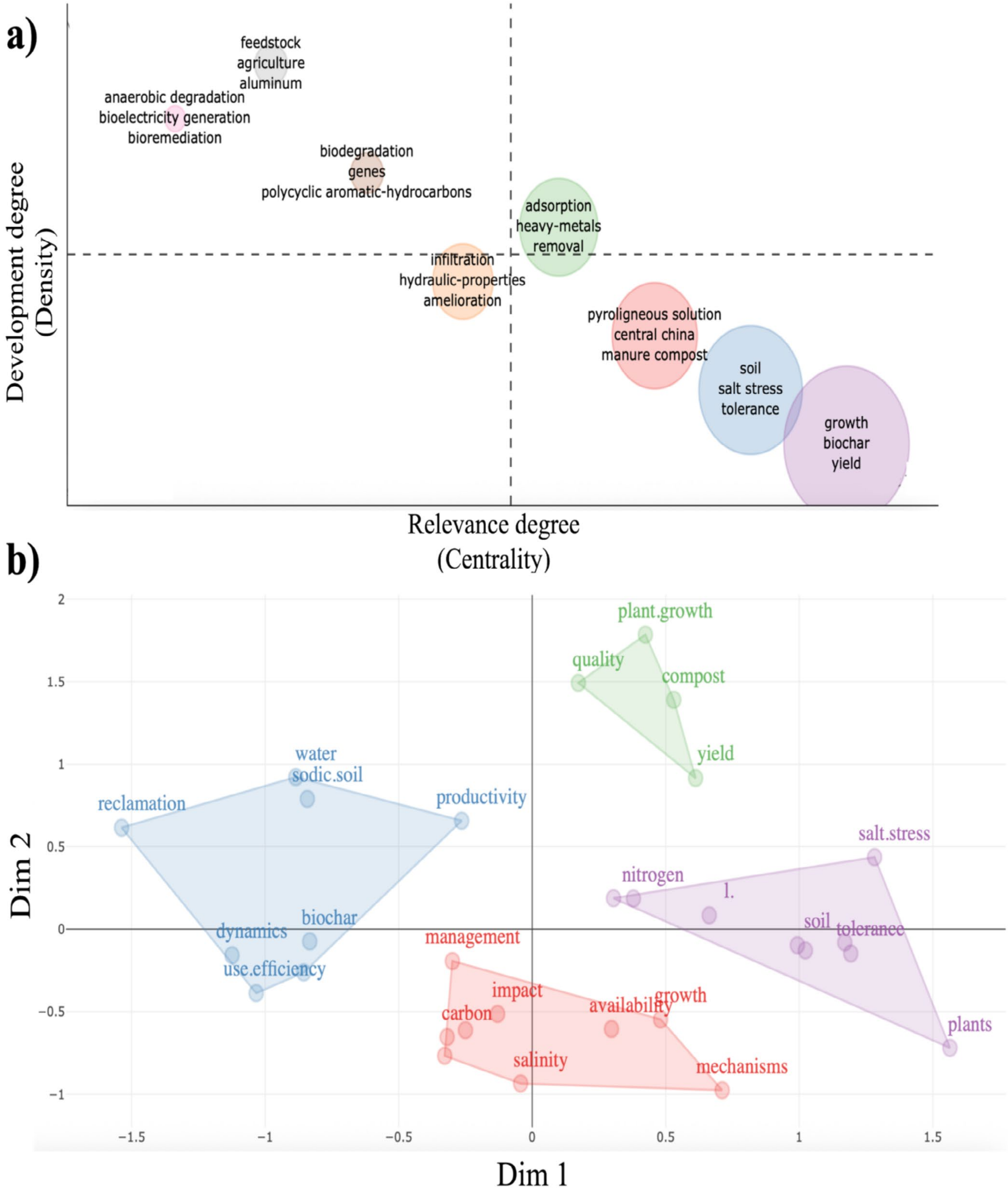

FIGURE 11 | Bibliometric analysis of research on biochar in saline soil. (a) Thematic map from keyword co-occurrence. The x-axis (centrality) indicates theme relevance and the y-axis (density) indicates degree of development. Larger bubbles represent more frequent themes. Quadrants: Upper-right: Motor themes; upper-left: Niche themes; lower-right: Basic themes; lower-left: Emerging/declining themes. (b) Factorial analysis: Colors denote clusters and polygons enclose each cluster; coordinates reflect thematic proximity. [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.2 | Biochar's Physicochemical Effects in Saline Soils

In recent years, biochar has gained prominence as a promising strategy in agriculture, particularly due to its potential in the restoration of salt-affected soils. In addition to improving soil quality, its application contributes significantly to carbon sequestration, reducing greenhouse gas emissions such as carbon dioxide (CO_2) and methane (CH_4) (Nazim et al. 2025; Khaliq et al. 2024). This characteristic makes biochar an effective agricultural tool and a strategic resource for carbon credit generation and climate change mitigation.

As highlighted in previous sections, biochar has been widely used to remediate salt-affected soils due to its ability to modify various physicochemical properties. Its effects include increased porosity, which promotes better aeration and water retention, as well as pH adjustment, creating a more favorable environment for plant growth and beneficial microbial activity (Yuan et al. 2023; Abbas et al. 2024). Beyond its structural role, biochar plays an essential role in soil fertility and health. It functions both as a source and a reservoir of nutrients, gradually releasing essential elements and reducing losses through leaching (Figure 13).

These effects have been confirmed in field experiments. For example, Cui et al. (2022) evaluated the effects of wheat straw-derived biochar on the restoration of coastal saline-alkaline soils in Yancheng, China. Biochar was applied at 0, 20, 40, and 60 t ha^{-1} in a field experiment conducted over three consecutive years (2014–2016). The results showed that biochar significantly increased soil water content, ranging from 12.4% to 63.4%, depending on the year and application rate. Additionally, chemical properties such as pH, cation exchange capacity (CEC), and soil organic matter (SOM) improved significantly, with increases between 0.2% and 139.6%. Biochar application also reduced total soluble salts (TSS) in the soil by 15.9%–54.6%. It decreased concentrations of exchangeable and soluble cations, such as calcium (Ca), magnesium (Mg), chloride (Cl), and sodium (Na), following the same trend as TSS. On the other hand, soil soluble potassium (K) concentration increased by 19.2% to 233.8% due to the contribution of biochar (Fedeli et al. 2024). Overall, these physicochemical changes establish the basis for agronomic and microbial responses, which will be discussed in the following section (Cui et al. 2022).

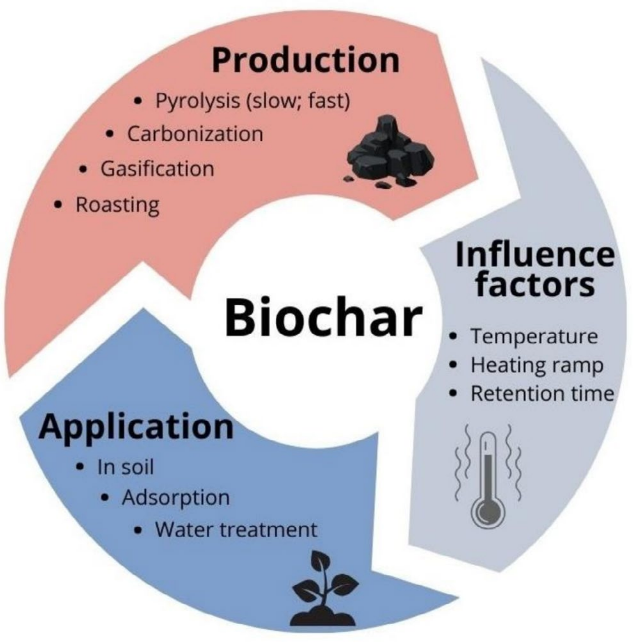

FIGURE 12 | Biochar production processes, influencing factors, and applications. [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.3 | Agronomic and Microbial Responses

In addition to affecting the physicochemical properties of the soil, biochar also directly influences plant agronomic responses and microbial dynamics. Improvements in soil structure, porosity, and nutrient availability create a more favorable environment for plant growth and for the activity of beneficial microorganisms, resulting in greater resilience under saline stress conditions.

Several studies have demonstrated the effects of biochar use in saline soils and its influence on crop growth and productivity. This can be observed in the study by Fedeli et al. (2024), which evaluated the potential of biochar to mitigate the adverse effects of salt stress in lettuce (*Lactuca sativa* L.). The biochar used in the experiment was produced by pyrolysis at temperatures between 600°C and 650°C from agricultural and forestry residues. Six NaCl concentrations (0, 50, 100, 200, 300, and 400 mM) were tested with and without the addition of 5% (w/w) biochar. The ability of biochar to alleviate salinity-induced damage was assessed through biometric parameters (fresh weight), physiological parameters (chlorophyll content), and biochemical parameters (electrolyte leakage, total antioxidant capacity, total soluble proteins, free amino acids, and mineral content). The results obtained after 4 weeks of experimentation showed that NaCl negatively affected plant physiology at concentrations between 100 and 200 mM. Biochar showed a limited capacity to mitigate the effects of salinity in lettuce. Positive changes were observed in fresh weight, chlorophyll content, total antioxidant capacity, total soluble proteins, and potassium (K) concentration; however, these effects were statistically significant in only a few cases. On the other hand, biochar did not reduce sodium (Na) accumulation in plant tissues nor alter the levels of free amino acids in the leaves (Fedeli et al. 2024).

Another example can be seen in the study by Akhtar et al. (2015), who reported that biochar reduced Na^{+} absorption and improved wheat yield; Abbas et al. (2018) showed that biochar decreased cadmium (Cd) toxicity and salt stress

TABLE 5 | Difference between slow, fast, and instant pyrolysis.

Pyrolysis type	Temperature (°C)	Retention time (min.)	Heating ramp (°C/s)	Final product
Slow	400–900	> 5 (can go up to several hours)		Biochar
Fast	450–850	0.5–25	10–200	Bio-oil
Instantania	600–1200	< 1	0.1–10	Synthesis gas

FIGURE 13 | Application of biochar in salt-affected soils. [Colour figure can be viewed at wileyonlinelibrary.com]

in wheat plants; Wu et al. (2019) reported that MgO-modified biochar increased phosphorus retention and enhanced rice productivity in saline-alkaline soils; and Zhao et al. (2020) demonstrated that maize straw biochar increased nutrient availability and maize yield in sodic-saline soils. These studies highlight that the magnitude of agronomic effects depends on the crop, the type of biochar, and the salinity intensity, but overall, they indicate benefits for plant physiological performance and productivity.

Soil microorganisms play a key role in biochemical processes, promoting microcirculation within the plant ecosystem and significantly enhancing soil fertility. The diversity and structure of the soil microbial community can greatly affect soil quality and are important factors for its assessment. Thus, microbial diversity and community structure play a fundamental role in soil fertility, health, productivity, and ecosystem functioning (Jin et al. 2024; Deshoux et al. 2023; Zhang and Shen 2022).

In addition to its effects on plants, biochar also influences soil microbiota, as its porous structure provides niches for microbial colonization, contributing to increased microbial activity. This activity is extremely important for soils, as it affects fertility, soil health, ecological balance, and crop productivity (Jin et al. 2024; Yan et al. 2022).

This can be observed in the study by Zhang and Shen (2022), in which the authors evaluated the effects of biochar on soil microbial diversity and community structure in clay soil. The results showed that biochar application caused significant changes in the microbial community, with higher alpha diversity observed at the 20 t/m^3 dose. The dominant phyla identified were Proteobacteria, Cyanobacteria, and Actinobacteria, with the latter showing marked differences among treatments. The most representative genera included Skermanella, Nostoc, and Frankia. The authors also highlighted that microbial structure was influenced by factors such as soil porosity and moisture, as well as nutrient availability.

Other studies, such as Zhang et al. (2025), evaluated the use of different types of biochar on microbial activity and the influence of pH on its development. Alkaline biochar, for example, enhanced microbial metabolic efficiency, whereas acid-modified biochar produced distinct responses, showing that the properties of the material directly influence microbial processes.

The research by Gu et al. (2023) also demonstrated the influence of biochar, alone or in combination with bioorganic fertilizers, on the rhizosphere of saline-alkaline soils. The results showed marked changes in the structure of the bacterial community, with Actinobacteriota, Proteobacteria, and Chloroflexi being the predominant groups, indicating that biochar addition favored microorganisms adapted to saline stress and contributed to increased microbial diversity.

Similar results were reported by Cai et al. (2024), who used biochar derived from aquaculture residues. In this case, biochar application stimulated soil enzymatic activities, reorganized microbial networks, and reduced competition among species, promoting greater community stability in saline-alkaline environments.

3.2.4 | Bibliometric/Bibliographic Syntheses of Biochar Research

Section 3.1, the bibliometric analysis, complements the evidence discussed in Section 3.2, Overview. The keywords and the term map based on different clusters help contextualize research on the use of biochar in saline soils, linking experimental findings with broader scientific trends. Several cited studies highlight the growing scientific interest in this topic, reinforcing biochar as a promising strategy for the recovery of salt-affected soils (Jajarmi et al. 2023; Meki et al. 2022; Guan et al. 2024).

In the bibliometric analysis, terms such as “salinity” and “salt stress” reflect the connection with the physicochemical functions of biochar, such as the reduction of soluble salts, pH regulation, and improved water retention. Terms like “growth,” “productivity,” and “nitrogen” are associated with agronomic and microbial responses, emphasizing gains in crop yield and nutrient uptake. Meanwhile, the frequent occurrence of “biochar” and “carbon” underscores its dual role as both a soil conditioner and a climate change mitigation strategy. This integration demonstrates that bibliometric trends are consistent with experimental results, consolidating biochar as a promising alternative for the remediation of saline soils.

In the overview of biochar, recent advances in its production also stand out, with emphasis on the development of technologies focused on its synthesis. Studies involving different types of biomass have proven to be strategic for enhancing the efficiency of biochar application in soils, thus broadening its viability across diverse agricultural contexts (Potnuri et al. 2023; Zhou et al. 2025). These perspectives reflect the dynamism and continuous innovation in the field, contributing to the growing interest in biochar and its increasing relevance in environmental and agronomic applications. Despite this remarkable progress, research on biochar still presents several gaps that need to be addressed to optimize its efficiency and expand its application potential.

The main challenges include improving agronomic efficiency in different soil types, assessing long-term impacts on soil and associated microbiota, and integrating biochar use into sustainable agricultural practices (Hao et al. 2025; Ihsanullah et al. 2025; Amalina et al. 2025). Overcoming these challenges will be essential to consolidate biochar as an effective and sustainable solution for saline soil remediation and agricultural productivity enhancement.

Although it reinforces important trends, the bibliometric analysis also presents limitations that need to be acknowledged. First, this study relied exclusively on the WoS database as the source of data, which may exclude articles indexed in other platforms such as Scopus or Dimensions. Nevertheless, choosing WoS does not compromise the credibility of the analysis, since it is a widely recognized and consolidated database for bibliometric studies. Second, author name ambiguity may cause distortions in collaboration networks, as variations in spelling or affiliation can fragment the records of the same researcher. Finally, citation counts are subject to inflation, meaning that highly cited articles do not always reflect higher scientific quality. Even with these constraints, the methodological strategy adopted remains consistent with recent bibliometric research and provides a robust perspective on the evolution of studies on biochar applied to saline soils.

Overall, the bibliometric evidence and literature synthesis indicate that research on biochar for salt-affected soils is currently in a consolidation stage: there is a steady increase in publication output, supported by a growing body of experimental evidence on its physicochemical and agronomic effects. However, important challenges remain, including long-term validation under field conditions and the definition of optimal application strategies depending on soil type, biochar feedstock, and application rate (Jin et al. 2024; Wu et al. 2024).

4 | Conclusions

Using biochar in soils has emerged as a promising and strategic approach for the remediation of degraded areas, especially salt-affected soils. Applying biochar as a soil conditioner has demonstrated positive results, such as improved physical structure, enhanced moisture retention, pH regulation, and increased availability of essential nutrients for plants, promoting greater plant resilience and agricultural sustainability.

The bibliometric analysis revealed significant and continuous growth in publications on the topic over the past 12 years, reflecting the growing interest of the scientific community. It provides evidence from 326 Web of Science articles published between 2013 and 2024, analyzed using VOSviewer and Bibliometrix, which map research trends, collaboration networks, and thematic clusters.

The results reveal that China has established itself as the main hub of scientific production, leading in the number of publications, citations, and institutions involved, such as the Chinese Academy of Sciences. Furthermore, authors such as Jin F., Wu L., Ding X., and Zhang S. were identified as the most influential, with high-impact publications and vigorous collaborative activity. Their institutions, including the University of the Chinese Academy of Sciences, are interconnected in co-authorship networks, demonstrating a highly integrated research dynamic. Science of the Total Environment was identified as the most cited among the analyzed journals. At the same time, Agronomy-Basel had the highest number of publications, serving as a key platform for disseminating research on biochar applied to agriculture and the remediation of saline soils.

The keyword analysis identified five thematic clusters, with terms such as biochar, growth, yield, and salinity standing out. These clusters reflect the use of biochar in mitigating the effects of secondary salinization, a phenomenon mainly caused by poor irrigation practices and inadequate soil management. These thematic areas reinforce the importance of biochar in rehabilitating saline soils through physical mechanisms such as water retention and chemical and biological processes that enhance nutrient availability and plant development.

Despite the overall benefits of biochar, the findings of this review indicate that its effectiveness in saline soils is not uniform. Moderate application rates are often associated with consistent improvements in soil properties and crop performance, while higher rates may lead to adverse effects or only limited gains. These divergent outcomes highlight that biochar effectiveness is context-dependent, influenced by factors such as soil characteristics, feedstock type, pyrolysis conditions, and crop sensitivity. Nevertheless, the literature consistently reinforces biochar's potential as a sustainable strategy, not only for soil remediation but also for long-term climate benefits through carbon storage and greenhouse gas mitigation.

Based on the evidence obtained in this study, a roadmap for future research on biochar in saline soils can be outlined. In the short term, standardization of biochar production and characterization methodologies is needed to enable consistent comparisons across studies. In the medium term, further investigations into agronomic and microbial mechanisms are essential, particularly osmotic adjustment in plants under salt stress. In the long term, multi-site field trials across different soil types and environmental conditions are recommended to assess sustained impacts over time.

Furthermore, the implications of this study extend beyond academia. For policymakers, the findings reinforce that biochar should be considered a climate-smart agricultural practice, with the potential to contribute to Land Degradation Neutrality (LDN) and to the Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger and sustainable agriculture), SDG 13 (action against global change), and SDG 15 (Life on Land). For farmers and practitioners, the results emphasize the importance of context-specific application: biochar effectiveness depends on soil type, feedstock properties, and application rate. Thus, public policies and agricultural practices can be more effective when global climate mitigation strategies are aligned with technical recommendations tailored to local realities.

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Data Availability Statement

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

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