Journal of Soil Science and Plant Nutrition
https://doi.org/10.1007/s42729-026-03345-y

ORIGINAL PAPER

# Biochar in Plant Growing Media: A Scientometric Analysis (2011–2024)

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Received: 5 December 2025 / Accepted: 12 May 2026

## Abstract

This study presents a comprehensive scientometric analysis of the use of biochar in plant growing media between 2011 and 2024. Bibliometric analysis tools (VOSviewer and Bibliometrix) were applied to map patterns of scientific collaboration, authors, institutions, and global thematic trends based on publications retrieved from the Web of Science platform. The analysis comprised 973 publications and revealed exponential growth in scientific output, with a strong positive linear trend from 2020 to 2024 ($R^2 = 0.95$) and a peak of 169 publications in 2024. China led global production and impact with 297 articles and 11,407 citations, followed by the United States with 122 articles and 4,197 citations, while the Chinese Academy of Sciences ranked as the most relevant institution with 28 publications and 1,097 citations. The most frequent terms were “biochar” (537 occurrences), “soil” (200), “compost” (163), and “growth” (162), reinforcing the role of biochar in improving substrate properties, promoting plant development, and supporting sustainable alternatives to peat. Biochar represents a promising solution for formulating sustainable growing substrates, although the standardization of production methods and the understanding of its interactions with plants and microorganisms remain challenges for future research.

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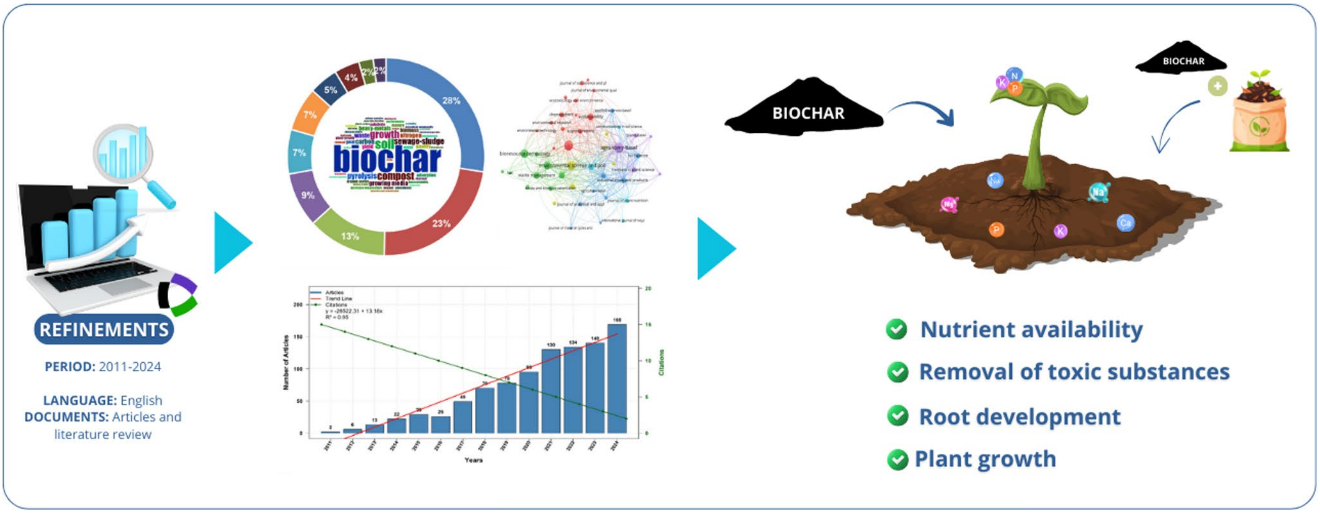
## Graphical Abstract



## Highlights

- Scientometric analysis (2011–2024) of biochar use in growing media.
- Scientific production on biochar in substrates has grown exponentially.
- China, USA and Australia lead research efforts, with strong international collaboration.
- Biochar and organic blends improve substrates and enhance plant growth.
- Biochar emerges as a sustainable alternative to peat, requiring standardization and further testing.

**Keywords** Substrates · Peat · Sustainability · Plant growth · Horticulture

## 1 Introduction

Biochar, a carbon-rich solid material produced through the thermochemical decomposition of biomass under limited oxygen conditions, is notable for its carbon sequestration potential and for improving soil quality (Lehmann and Joseph 2009; Agegnehu et al. 2017; Chrysargyris et al. 2024a). Its production occurs primarily via slow pyrolysis, although processes such as gasification, torrefaction, and hydrothermal carbonization (HTC) are also employed (Masebinu et al. 2019). The physicochemical properties of biochar depend on the biomass feedstock and pyrolysis conditions, particularly temperature, which influences pH, electrical conductivity, surface area, ash content, and aromaticity (Enders et al. 2012; Song and Guo 2012; Gascó et al. 2018b; Cárdenas-Aguiar et al. 2024). Lower H/C and O/C atomic ratios indicate greater carbon stability (Gascó et al. 2018b), and the IBI recommends an H/C ratio below 0.7 to classify the material as biochar.

HTC has emerged as an alternative for materials with high moisture content, producing hydrochars with more aliphatic structural characteristics than those obtained through conventional pyrolysis, as observed in studies using pig manure (Gascó et al. 2018b). In agriculture, biochar has been widely applied due to its capacity to enhance soil fertility, improve water retention, and stimulate plant productivity (Lehmann 2007; Agegnehu et al. 2017). In the context of growing media, it stands out as a promising alternative to peat, whose extraction entails environmental impacts and high costs (Hirschler and Thrän 2023). European countries have already set targets to eliminate peat use by 2030, reinforcing the search for substitute materials (Vandecasteele et al. 2023). Owing to its high porosity and low bulk density, biochar is among the most prominent candidates for this substitution (Steiner and Harttung 2014).

When combined with organic amendments, biochar enhances physical and chemical improvements in soil, increasing organic carbon and reducing nutrient leaching (Schulz et al. 2013; Agegnehu et al. 2017). From a hydrophysical perspective, its application decreases bulk density and increases water retention due to its porous structure (Agegnehu et al. 2017; Suliman et al. 2017). Studies show that hydrochars produced via HTC may exhibit greater available water capacity than pyrolytic biochars, making them suitable for growing media formulations (Gascó et al. 2018b).

In nutritional terms, biochar increases cation exchange capacity, raises pH, reduces Al toxicity, and retains essential nutrients, in addition to decreasing losses of N and $NH_3$ (Laird et al. 2010; Agegnehu et al. 2017; Masebinu et al. 2019). In substrates containing food-waste digestate, biochar also mitigates negative effects associated with excess nitrogen, enhancing plant growth and water retention (Paetsch et al. 2018; Mickan et al. 2022). At the biological level, its porous structure supports microbial and mycorrhizal activity, although some studies report a reduction in Actinobacteria abundance in specific substrate formulations (Lehmann and Joseph 2009; Agegnehu et al. 2017; Mickan et al. 2022). In anaerobic digestion, high-temperature biochars may stimulate methanogenesis through direct electron transfer mechanisms (Zhang et al. 2022).

Despite the growing scientific interest and increasing number of publications in the field (Agegnehu et al. 2017; Chrysargyris et al. 2024a), significant gaps remain. Long-term field studies, analytical standardization, and assessments exploring interactions among biochar, mineral nutrition, and plant physiology are still lacking. In horticulture, studies addressing detailed morphophysiological effects remain scarce, and reports of seedling toxicity have been documented, attributed to the presence of organic compounds, salinity, or heavy metals (Ruzickova et al. 2021; Chrysargyris et al. 2024a). Moreover, high proportions of biochar in substrates may reduce N and P availability due to microbial immobilization (Lehmann and Joseph 2009; Chrysargyris et al. 2024a).

Considering these gaps, it is essential to develop research that optimizes the formulation of substrates containing biochar, particularly under nursery conditions, involving physiological performance, nutrient assimilation, and tolerance to water and salt stress. Such studies will strengthen the production of sustainable substrates and the efficient management of resources, in addition to supporting the commercial-scale adoption of biochar. Consolidating this field requires integration among researchers, the productive sector, and public policies, underscoring the importance of combined advances in the characterization, management, and application of this technology (Lehmann 2007; Agegnehu et al. 2017; Chrysargyris et al. 2024a).

Therefore, this study was conducted through a systematic bibliometric review with the primary objective of mapping scientific advances related to the application of biochar in plant growing substrates. The investigation covered publications from 2011 to 2024.

## 2 Materials and Methods

Data collection was performed in the Web of Science Core Collection using the Advanced Search function on October 28, 2025. The search was conducted in the Topic field (TS), which includes title, abstract, author keywords, and Keywords Plus, using the following query: TS=(“biochar” OR “bio-char” OR pyrochar OR hidrochar) AND (compost* OR “organic compost” OR vermicompost* OR vermicomposto OR “co-compost*” OR “composted manure” OR biosolid* OR “sewage sludge” OR “green waste” OR digestate* OR coir OR “coconut coir” OR peat OR “peat moss” OR “pine bark” OR “wood fiber” OR “rice husk” OR perlite OR vermiculite OR sawdust OR “sugarcane bagasse” OR vinasse) AND (“growing media” OR “growth media” OR substrat* OR “potting mix*” OR “potting soil” OR soilless OR “container media” OR “container substrate” OR “nursery media” OR “nursery substrate” OR “seedling substrate” OR “germination substrate” OR seedling* OR nursery OR “plug tray*” OR “seedling tray*” OR tray* OR vase* OR container* OR recipien* OR viveir* OR seedlings OR horticultur* OR floricultur*) AND PY=(2011–2024)**. The inclusion criteria comprised documents indexed in the Web of Science Core Collection, retrieved through the predefined search strategy, published between 2011 and 2024, and directly related to the use of biochar in plant growing media, substrates, or soilless cultivation systems. The search string was iteratively refined through preliminary retrieval tests to improve thematic adherence and to ensure broad coverage of publications related to biochar, substrate materials, and plant growing media. The exclusion criteria comprised the following document types: Proceeding Paper, Meeting Abstract, Book Chapters, Early Access, Correction, Editorial Material, and Retracted Publication. Records published in Spanish, Portuguese, and Polish were also excluded, as well as entries classified as Associated Data. The remaining records were screened based on title and abstract, and studies not directly related to the application of biochar in plant growing media were excluded. This procedure resulted in a final dataset of 973 records, which were exported for subsequent bibliometric analyses. (Aria and Cuccurullo 2017a; Donthu et al. 2021; Valderrama et al. 2023).

For bibliometric processing and analysis, the retrieved articles were subjected to an integrated approach using two specialized tools. VOSviewer© software (version 1.6.18) (Van Eck and Waltman 2010) was employed to generate visualizations of scientific networks, enabling the mapping of connections among journals, countries, institutions, authors, and the most influential keywords in the field (Wodnicka 2024). Complementarily, the Bibliometrix platform (version 3.0) (Aria and Cuccurullo 2017b), integrated into the R Studio environment, was used to create thematic graphs (such as the three-field plot), classify impact indicators, and identify thematic clusters (Atienza-Barba et al. 2024; Arthur et al. 2024). Additionally, Microsoft Excel was used to organize the data, facilitating the visualization and tabulation of results (Donthu et al. 2021; Valderrama et al. 2023).

The combined use of VOSviewer and Bibliometrix was essential for creating interactive maps that facilitated the interpretation of collaboration patterns, co-citation, and term co-occurrence, as well as enabling the identification of emerging research trends (Suliman et al. 2017). This methodological integration allowed not only the quantification of academic output but also the exploration of practical applications, knowledge gaps, and promising directions for the future development of biochar as an agricultural substrate (Valderrama et al. 2023; Melo et al. 2024).

## 3 Results and Discussion

### 3.1 *Scientometric Analysis of the use of Biochar in Plant Growing Media (2011–2024)*

#### 3.1.1 Temporal Trends, Geographical Distribution, and Thematic Structure of Scientific Production

An exponential increase in the number of publications on biochar in plant growing media is evident (Fig. 1-A). This pattern highlights the progressive consolidation and inherent relevance of this topic within the scientific literature. Between 2011 and 2015, an initial phase emerged in which the potential of biochar as a growing-media conditioner and soil fertility enhancer was explored (Dumroese et al. 2011; Doan et al. 2015). Subsequently, from 2018 onward, growth became more consistent, reflecting the expansion of biochar applications across diverse agricultural and environmental contexts, with emphasis on emission control, improvement of growing-media structure, and interactions with microbial communities (Chen et al. 2018; Gao et al. 2018).

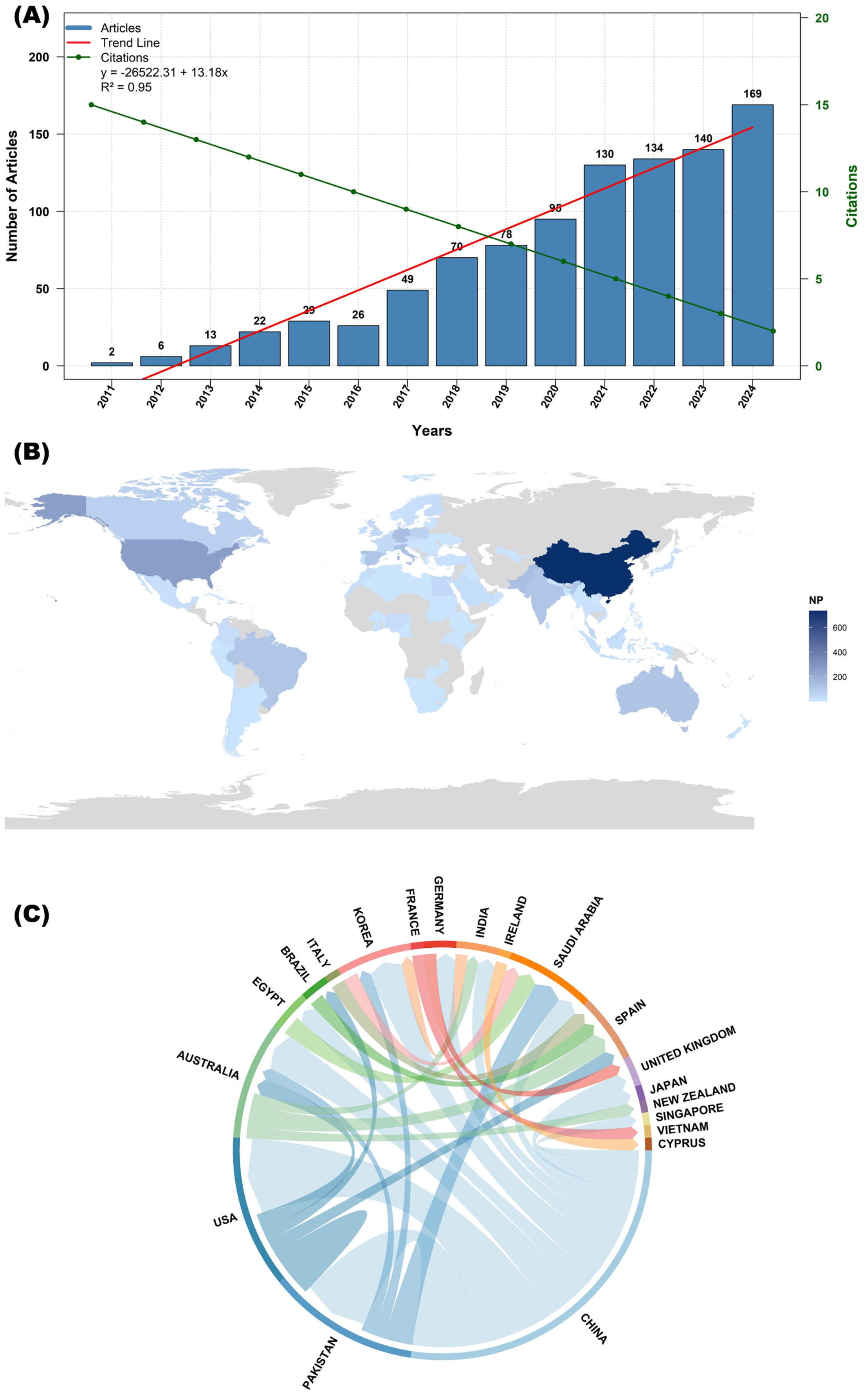
Following an initial exploratory phase (2011–2015) and a more consistent expansion from 2018 onward, the period between 2020 and 2024 was highlighted because it represents the most recent stage of sustained and approximately linear growth in the literature ($R^2 = 0.95$). This phase was marked by an intensification of research on functionalized biochar, integration with biotechnological processes, and incorporation into circular economy models (Hu et al. 2021; Kumar and Bhattacharya 2021; Li et al. 2021). The peak in 2024, with 169 publications, confirms the growing interest in modified biochars and their use in agricultural crops under stress, such as tomatoes and beans (Aljarani et al. 2025; Fornes et al. 2025). The recent decrease in citations per year does not indicate reduced relevance; rather, it reflects the natural lag in the accumulation of impact for newly published studies, indicating that the topic continues to expand and consolidate rapidly.

**Fig. 1** Global trends and patterns in research on biochar in plant growing media. (**A**) Annual evolution of publications and citations per year (2011–2024). (**B**) Geographical distribution of scientific output, expressed as number of publications (NP) by country. (**C**) International cooperation network among countries, in which links represent co-authorship relationships and link thickness reflects total link strength

In terms of distribution, Fig. 1-B presents the geographical map of publications on biochar in growing media, showing the highest absolute concentration of studies in China, followed by the United States and Australia. Notable contributions are also observed from European countries such as Germany and the United Kingdom, along with a growing participation from South American countries, particularly Brazil. As this representation is based on absolute publication counts, it should be interpreted as a descriptive spatial overview rather than as a normalized comparison of scientific performance among countries. Nevertheless, the observed pattern highlights the broad global dispersion of research efforts, demonstrating that interest in the topic extends across diverse production systems and environmental conditions.

The international cooperation network among countries publishing on this topic is shown in Fig. 1-C. In this map, each link represents a co-authorship relationship between countries, while the link thickness indicates the intensity of collaboration (total link strength). In this context, China, the United States, and Australia occupy central positions in the network, establishing the strongest collaborative links. Additionally, countries such as the United Kingdom, Germany, Spain, India, Brazil, and Pakistan also form meaningful partnerships, indicating the presence of scientific collaborations among regions with different levels of research output. This cooperative structure reinforces the global nature of the field and the collective interest in advancing the development and application of biochar in plant growing media.

The thematic analysis complements the previous patterns by showing how research on biochar in plant growing media is distributed across different scientific fields (Supplementary Fig. 1). The predominance of the Environmental Sciences and Ecology and Agriculture categories reflects the central focus on sustainability, soil quality improvement, and enhanced plant productivity. The involvement of Engineering, Plant Sciences, and Science and Technology highlights the interdisciplinary nature of the topic, which integrates chemical, biological, and technological approaches to develop and apply biochars with specific properties. This thematic diversity reinforces the role of biochar as a versatile technology situated at the interface between environmental mitigation and agricultural innovation, consolidating its relevance in both fundamental research and practical applications.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INDIA
IRELAND
SAUDI ARABIA
SPAIN
UNITED KINGDOM
JAPAN
NEW ZEALAND
SINGAPORE
VIETNAM
CYPRUS

### 3.1.2 Main Scientific Agents, Collaboration Networks, and Productivity

The journal network, as outlined in Fig. 2-A, exhibits a modular and distinctly interdisciplinary topology, organized into five main clusters that represent different editorial lines and knowledge domains within the study of biochar in plant growing media. Journals such as Bioresource Technology, Environmental Science and Pollution Research, and Scientific Reports function as central nodes, demonstrating their editorial importance and thematic convergence. The organization of the clusters reflects the diversity of the field: the green cluster groups engineering and waste valorization journals (Bioresource Technology); the red cluster concentrates environmental and multidisciplinary journals (Scientific Reports and Chemosphere); and the blue/purple cluster includes publications in agronomic and crop sciences (Agronomy-Basel and Industrial Crops and Products). This mapped configuration reveals a consolidated field, in which environmental engineering and biomass-resource journals operate as structural axes, while multidisciplinary and agronomic journals play an essential role in disseminating and translating knowledge into practical applications.

The analysis shown in Fig. 2-B corroborates the editorial diversity by presenting key information on journal productivity and impact (number of articles and citations, respectively). Agronomy-Basel leads in publication volume (45 articles), reflecting its central role in disseminating applied agronomic studies. In terms of impact, the highest citation counts are observed for Science of the Total Environment (2,262 citations) and Bioresource Technology (2,177 citations), which, despite publishing fewer articles, achieve significantly greater visibility, demonstrating their strong international scientific recognition. Other journals, such as the Journal of Cleaner Production and the Journal of Environmental Management, also stand out for publishing research of high technological and environmental relevance. This pattern reveals a diversified editorial structure in which high-impact environmental/technological journals and agronomic journals act as complementary poles in knowledge dissemination, reinforcing the intrinsically interdisciplinary and applied nature of research on biochar in plant growing media.

At the individual level, the study of scientific collaboration reveals the dynamics of a research field. Figure 3-A displays the co-authorship network, which highlights the existence of consolidated collaborative groups in the study of biochar in plant growing media. Authors such as Gu, Mengmeng; Peterson, Steven C.; and Zhang, Lu appear as visually prominent nodes within the collaborative structure, indicating their relevance in the co-authorship network. Although the network configuration demonstrates robust collaborations, the presence of peripheral clusters (blue and red) suggests less interconnected collaborative subgroups, indicating opportunities for greater interinstitutional and interdisciplinary integration within this research domain.

Complementing this collaborative structure, Fig. 3-B quantifies the productivity and scientific impact of the leading authors between 2011 and 2024, showing a concentrated distribution of publications and citations among a limited number of researchers. Gu, Mengmeng stands out as the most productive author (17 publications), with the highest publication output among the leading researchers. In contrast, Zhang, Lu (8 articles and 679 citations) exhibits the highest relative impact, reflecting strong influence and academic recognition, followed by Li, Guoxue (483 citations). Meanwhile, authors such as Yu, Ping and Peterson, Steven maintain consistent publication activity with moderate impact.

Advancing to the analysis of collaboration among countries, Fig. 4-A presents the co-authorship network by country, illustrating a highly dense and interconnected global structure that reveals transnational scientific alliances in research on biochar in plant growing media. China occupies a central position, evidenced by the largest node and the intensity of its connections, indicating its prominence in the co-authorship network in terms of collaboration strength and network centrality. Western countries such as the United States, Germany, Italy, Australia, and Spain function as strategic cooperation hubs, serving as intermediaries among multiple geographical clusters. The strong interaction observed between Asian and European nations, along with the participation—albeit on a smaller scale—of South American countries such as Brazil, reinforces the multidisciplinary nature and growing internationalization of this research field.

The asymmetry in the global distribution of knowledge is confirmed by the productivity and impact data by country, expressed as publication output (number of articles) and citation impact (number of citations), respectively, as detailed in Fig. 4-B. China consolidates its position as the primary global center, leading markedly both in production (297 articles) and impact (11,407 citations). The United States ranks second in both indicators (122 articles; 4,197 citations), followed by Germany (72 articles) and Spain (65 articles), which, despite having a lower publication volume, maintain considerable impact levels. Countries such as Italy, Australia, and Brazil also show relevant contributions in terms of scientific output and visibility, suggesting growing engagement and potential for further expansion.

The analysis in Fig. 5-A complements the country-level collaboration by depicting the institutional co-occurrence network, which reveals a structure composed of multiple clusters that indicate regional and thematic research hubs.

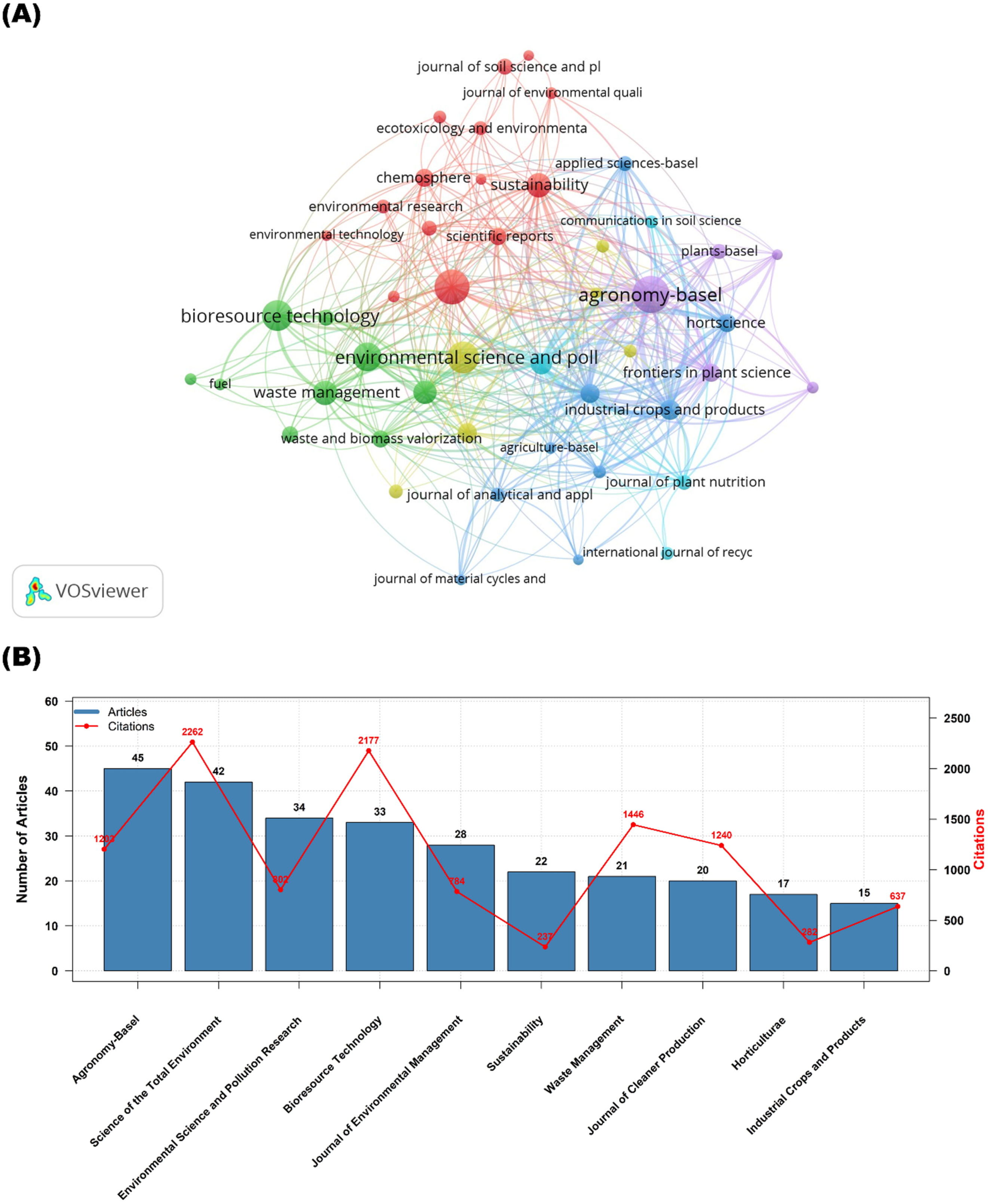

**Fig. 2** Mapping of the main scientific journals on biochar in plant growing media. (**A**) Journal co-occurrence network, in which each node represents a journal, node size reflects its relative prominence within the network, links represent relationships of co-occurrence, and colors indicate the main thematic clusters identified by the software. (**B**) Productivity and impact of the ten most relevant journals, expressed as number of publications and number of citations, respectively

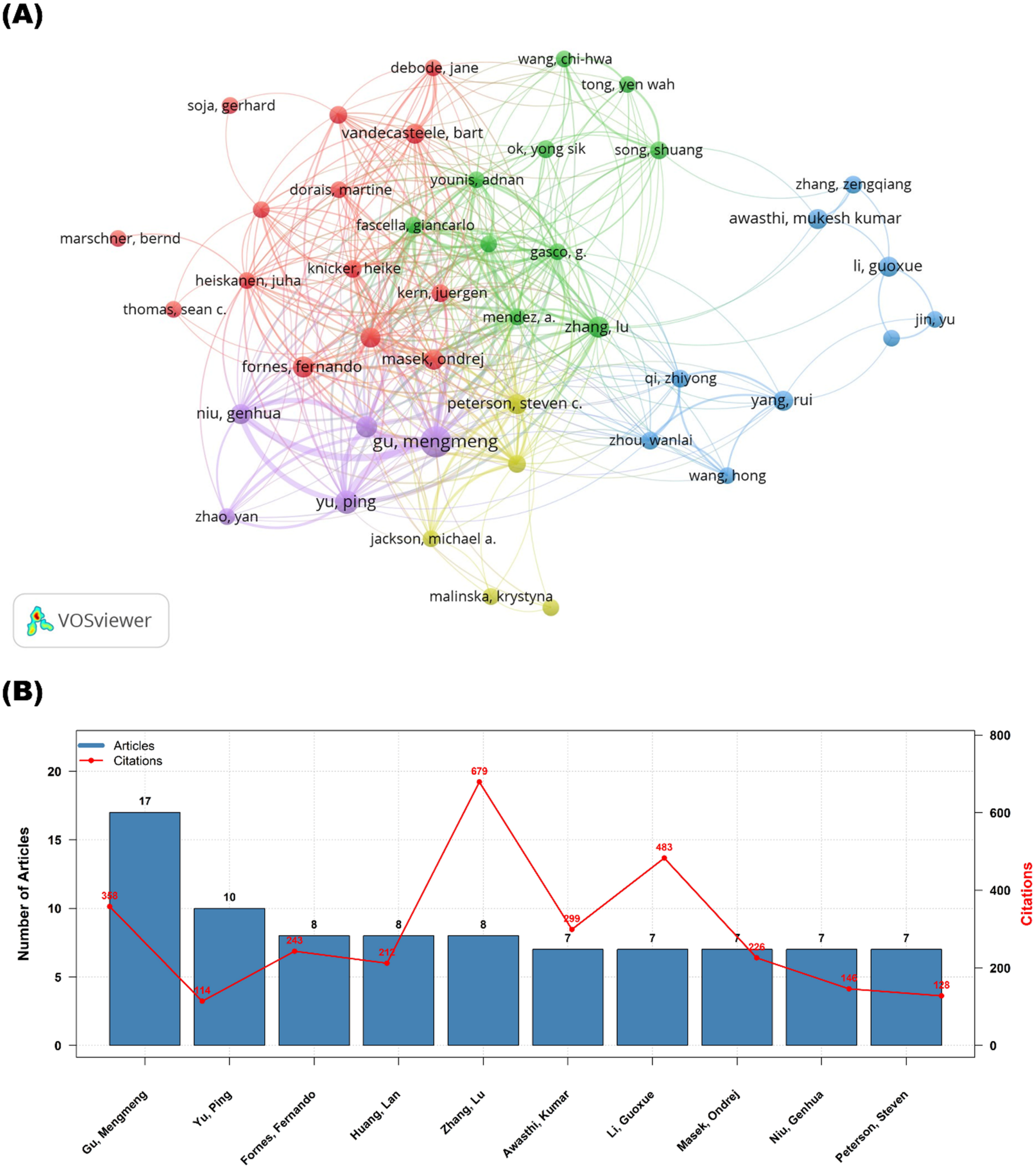

**Fig. 3** Mapping of the main contributing authors in studies on biochar in plant growing media. (**A**) Co-authorship network, in which each node represents an author, node size reflects the author's relative prominence in the network, links represent co-authorship relationships, and colors indicate collaborative clusters. (**B**) Productivity and impact of the ten most relevant authors, expressed as number of publications and number of citations, respectively

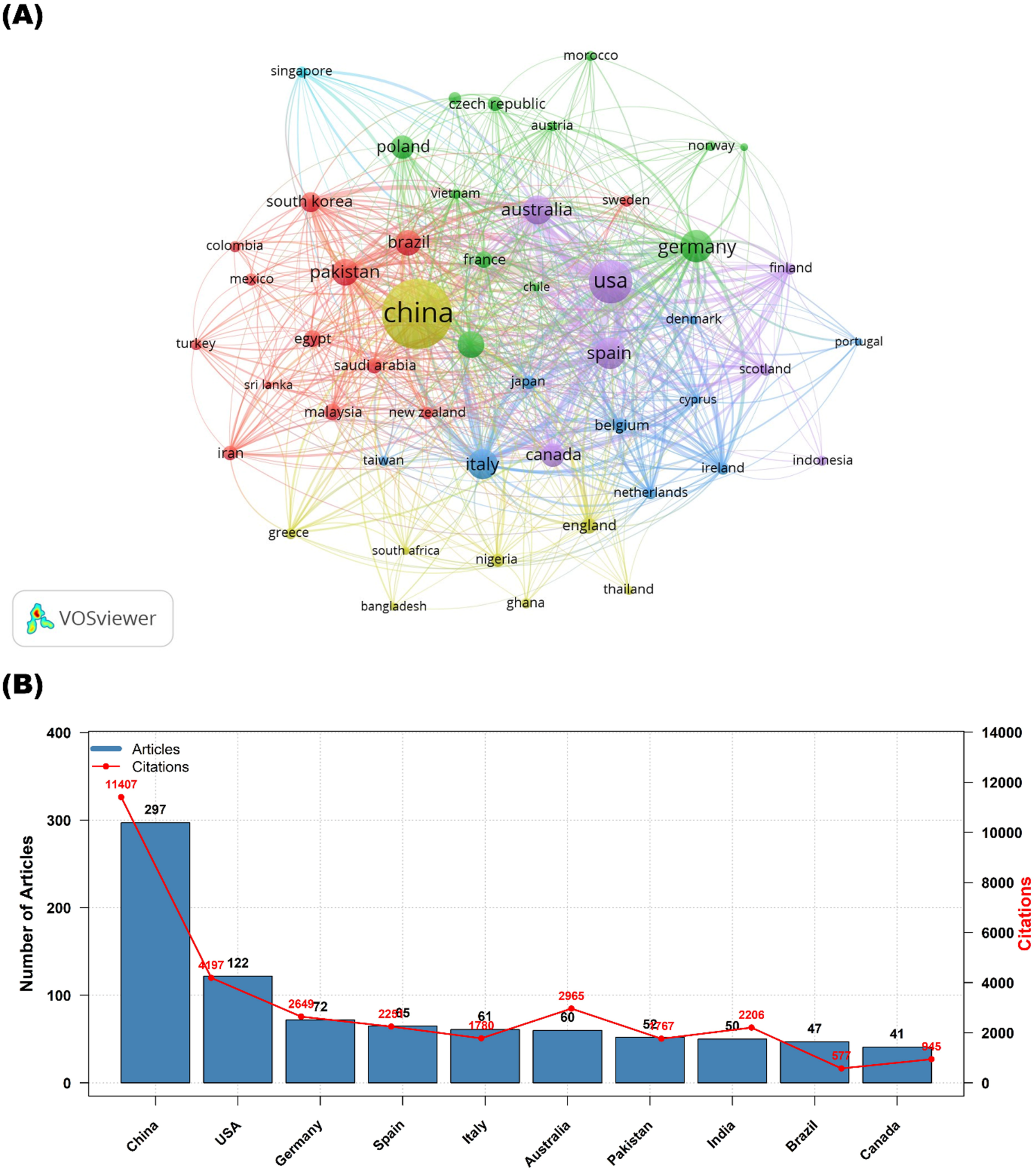

**Fig. 4** Mapping of the main contributing countries in research on biochar in plant growing media. (**A**) Country collaboration network, in which each node represents a country, node size reflects its prominence in the co-authorship network, links represent co-authorship relationships between countries, and link thickness reflects total link strength. (**B**) Productivity and impact of the ten most relevant countries, expressed as number of articles and number of citations, respectively

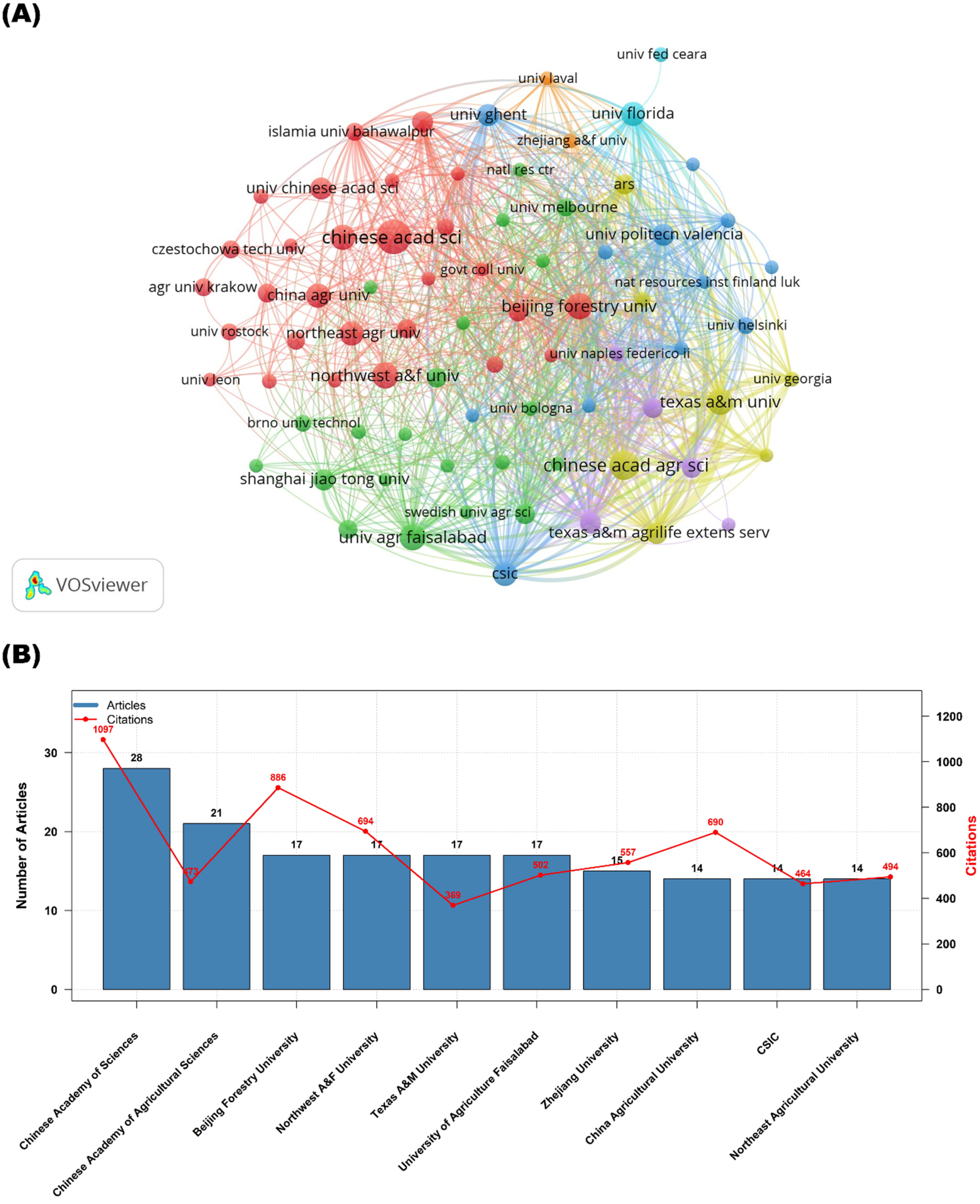

**Fig. 5** Mapping of the main institutions involved in research on biochar in plant growing media. (**A**) Institutional collaboration network, in which each node represents an institution, node size reflects its prominence in the network, links represent institutional co-authorship relationships, and colors indicate the main collaborative clusters. (**B**) Productivity and impact of the ten most relevant institutions, expressed as number of publications and number of citations, respectively

The Chinese Academy of Sciences (CAS) emerges as the principal collaborative nucleus, given its prominent node size and the high density of its connections, confirming its prominence in the institutional collaboration network in terms of collaboration strength and network centrality on this topic. This nucleus is strongly interconnected with related national institutions (China Agricultural University and Beijing Forestry University), forming a powerful Asian axis responsible for a substantial share of international cooperation. The network is further complemented by additional clusters involving European universities (University of Ghent, University of Bologna, and CSIC) and by American sub-networks (Texas A&M University) with strategic connections. The overall configuration of the network therefore reveals a multipolar cooperation system, dominated by Chinese institutions but supported by transnational interactions that foster knowledge dissemination and the consolidation of a global research agenda on biochar in plant growing media.

The productivity and scientific impact of the most active institutions are quantified in Fig. 5-B, based on publication output (number of publications) and citation impact (number of citations), confirming the strong concentration of influence within a limited number of organizations. CAS reaffirms its leading position with 28 publications and 1,097 citations, consolidating itself as the primary center for research and scientific dissemination, reflecting its substantial leadership capacity and global academic impact. This prominence is reinforced by the strong performance of other Chinese institutions (Chinese Academy of Agricultural Sciences and Beijing Forestry University), which confirm Asia's central role in scientific output and citation visibility. International institutions of relevance, such as Texas A&M University (369 citations) and CSIC (464 citations), exhibit high impact despite lower publication volumes, suggesting the notable quality and visibility of their contributions. In summary, the bibliometric results demonstrate that the advancement of knowledge is strongly supported by the performance of Chinese institutions, which stand out in both publication output and citation impact within the international research landscape on the use of biochar.

Supplementary Fig. 2 maps the collaborative connections among countries, authors, and institutions, highlighting the configuration of the main co-authorship and institutional affiliation networks in the field. A clear predominance of China and the United States as central hubs of production and collaboration is evident, reflecting their strong leadership and international influence in this research domain. Among the most productive and interconnected authors, Gu M.M., Yu P., Wang Y., and Zhang L. stand out, with contributions closely associated with globally recognized institutions. Researchers affiliated with the Texas A&M University System and Texas A&M University–College Station play a strategic role in articulating scientific networks, particularly through cooperation with Chinese authors, while the Chinese Academy of Sciences and the United States Department of Agriculture (USDA) emerge as key institutions providing technical–scientific support and contributing to the development of highly relevant studies.

This solid transnational integration, concentrated along Sino–American bilateral axes, has been decisive for theoretical and methodological advances in the field, consolidating institutional cooperation between universities and governmental agencies with strong potential for global scientific impact.

### 3.1.3 Scientific Impact and Relevance of the Studies

The publications listed in Table 1 represent the most cited records retrieved within the dataset and illustrate the thematic breadth of the field. Although the dataset includes studies directly focused on plant growing media, substrates, and peat substitution, it also encompasses highly cited publications from adjacent biochar-related domains, such as soil amendment, composting, anaerobic digestion, and environmental remediation. For this reason, the table should be interpreted as a citation-based overview of influential publications retrieved by the search strategy, whereas the more specific discussion of biochar in plant growing media is developed in the subsequent sections.

The most influential article in the field, with 596 citations, was conducted by Getachew Agegnehu et al. (2017) and is entitled "The role of biochar and biochar-compost in improving soil quality and crop performance: a review." The study establishes the importance of using biochar–compost mixtures to enhance agricultural sustainability. The review indicates that applying biochar–compost blends has proven more effective in improving soil properties and crop yields compared with the use of biochar alone. Biochar and biochar–compost mixtures can serve as viable alternatives for remediating degraded soils and enhancing their long-term productive potential. The leading study highlights the importance of these amendments in improving the physical and chemical properties of soil, such as total pore volume and water-holding capacity, as well as increasing soil pH, cation exchange capacity (CEC), total organic carbon (TOC), and nutrient availability.

Chenghao Luo et al. (2015) rank second, with 472 citations. In their study entitled "Application of eco-compatible biochar in anaerobic digestion to relieve acid stress and promote the selective colonization of functional microbes," the authors demonstrated that the addition of eco-compatible biochar alleviates acid stress and promotes the selective colonization of functional microbes during mesophilic

**Table 1** Most cited publications within the dataset, with emphasis on studies related to plant growing media, substrates, and adjacent biochar applications

| Ranking | Authors/year | Title | Source | Total Citations |
|---|---|---|---|---|
| 1 | (Agegnehu et al. 2017) | The role of biochar and biochar-compost in improving soil quality and crop performance: a review | *Applied Soil Ecology* | 596 |
| 2 | (Luo et al. 2015) | Application of eco-compatible biochar in anaerobic digestion to relieve acid stress and promote the selective colonization of functional microbes | *Water Research* | 472 |
| 3 | (Zhang and Sun 2014) | Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar | *Bioresource Technology* | 344 |
| 4 | (Zhou et al. 2013) | Sorption of heavy metals on chitosan-modified biochars and its biological effects | *Chemical Engineering Journal* | 339 |
| 5 | (Fagbohungbe et al. 2017) | The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion | *Waste Management* | 311 |
| 6 | (Gruda 2019) | Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems | *Agronomy-Basel* | 284 |
| 7 | (Schulz et al. 2013) | Positive effects of composted biochar on plant growth and soil fertility | *Agronomy For Sustainable Development* | 274 |
| 8 | (Yang et al. 2017) | Adding granular activated carbon into anaerobic sludge digestion to promote methane production and sludge decomposition | *Journal Of Cleaner Production* | 260 |
| 9 | (Doan et al. 2015). | Impact of compost, vermicompost and biochar on soil fertility, maize yield and soil erosion in northern vietnam: a three year mesocosm experiment | *Science Of The Total Environment* | 258 |
| 10 | (Zheng et al. 2012) | The effects of biochars from rice residue on the formation of iron plaque and the accumulation of Cd, Zn, Pb, As in rice (Oryza sativa L.) seedlings | *Chemosphere* | 244 |

anaerobic digestion (AD). The incorporation of biochar significantly shortened the methanogenic lag phase and increased the maximum methane production rate. Biochar functions as a substrate for the adhesion and growth of methanogenic consortia, selectively enriching functional microbes such as Methanosarcina.

Lu Zhang and Xiangyang Sun (2014), ranked third, investigated the co-composting of green waste with spent mushroom compost (SMC) and biochar (BC) in a two-stage process that optimized physical, chemical, and microbiological properties. The optimal combination (35% SMC and 20% BC) resulted in the production of a high-quality compost in only 24 days—significantly faster than traditional methods. In this context, biochar helped reduce N loss and increase nutrient retention.

Regarding heavy-metal remediation, the fourth most cited article is “Sorption of heavy metals on chitosan-modified biochars and its biological effects,” authored by Yanmei Zhou et al. (2013). In this study, modified biochars exhibited a higher capacity to remove metals ($Pb^{2+}$, $Cu^{2+}$, and $Cd^{2+}$) compared with unmodified biochar. Moreover, and particularly relevant in the agronomic context, the chitosan–biochar containing adsorbed lead reduced plant lead uptake by approximately 60% and decreased toxicity during seed germination and seedling growth.

Michael O. Fagbohungbe et al. (2017), ranked sixth, reviewed key challenges in anaerobic digestion (AD), such as substrate-induced inhibition (SII) and nutrient loss in the digestate. The authors propose biochar as an adsorbent to optimize AD performance by adsorbing inhibitory compounds, enhancing the buffering capacity of the system, and promoting the immobilization of bacterial cells.

Some articles explore the unique properties of biochar in more specific contexts, such as the work by Nazim S. Gruda et al. (2019) (284 citations), which reviews the growing need for sustainability in soilless culture systems (SCS). Biochar is identified as a promising biobased component for growing-media formulations, particularly as an alternative to peat and rockwool, as it enhances cation exchange capacity and water retention. The incorporation of biochar into peat-based substrates can significantly reduce the carbon footprint and mitigate greenhouse gas emissions ($CO_2$, $CH_4$, and $N_2O$).

Hardy Schulz et al. (2013), with 274 citations, demonstrated in their study entitled “Positive effects of composted biochar on plant growth and soil fertility” the beneficial effects of composted biochar on oat plant growth and soil fertility. Biomass growth and seed weight were optimized with increasing amounts of composted biochar and with a higher proportion of biochar in the mixture.

The authors concluded that composted biochar combines the high carbon-sequestration potential of biochar (a stable material with low nitrogen content) with the fertilization potential of compost (labile organic matter rich in mineralizable nutrients).

The study by Yafei Yang et al. (2017) focused on how Granular Activated Carbon (GAC), a conductive and adsorbent carbon material, can optimize the anaerobic digestion (AD) of waste activated sludge (WAS). GAC proved to be a simple and effective strategy, resulting in an increase in methane production of up to 17.4% and raising the sludge degradation rate by 6.1% points (from 39.1% to 45.2%).

Thuy Thu Doan et al. (2015), ranked tenth, conducted a three-year mesocosm experiment in Vietnam and observed that vermicompost and biochar had a positive and variable influence on maize yield. Notably, vermicompost improved maize resistance to water scarcity, and when the vermicompost–biochar mixture was applied, additional improvements in growth and yield were recorded. Moreover, both vermicompost and biochar reduced water runoff, soil detachment, and nitrogen (N) losses.

A set of prominent articles addresses the use of carbon-based materials, including biochar, to optimize Anaerobic Digestion (AD), a key process in organic waste management for biogas production.

The study entitled “The effects of biochars from rice residue on the formation of iron plaque and the accumulation of Cd, Zn, Pb, As in rice (*Oryza sativa* L.) seedlings” by Rui-Lun Zheng et al. (2012), focuses on the effects of biochars derived from rice residues (straw, husk, and bran) on the mobility and accumulation of heavy metals (Cadmium – Cd, Zinc – Zn, Lead – Pb) and the metalloid Arsenic (As) in rice seedlings (Oryza sativa L.) grown in historically contaminated soil under flooded conditions.

The study by Zheng et al. (2012) demonstrates the potential of biochar as an environmental remediation agent. However, the mobilization of As shows that biochar is not a universal solution and requires caution and case-specific optimization, with outcomes depending primarily on the feedstock and the contaminant under investigation.

Taken together, the highly cited publications retrieved in the dataset reveal that research on biochar spans both direct applications in plant growing media and adjacent domains involving soil improvement, waste valorization, environmental remediation, and bioenergy-related processes. Within the specific scope of this manuscript, the most relevant trend concerns the consolidation of biochar as a multifunctional material for substrate improvement, peat substitution, and plant performance enhancement, while the presence of adjacent domains also reflects the broader interdisciplinary expansion of biochar research.

#### 3.1.4 Conceptual Structure, Thematic Evolution, and Maturity of the Research Field

The term co-occurrence network shown in Supplementary Fig. 2-A demonstrates that biochar occupies a central position, linking distinct research lines. One major group of studies relates the use of biochar to terms such as “compost,” “peat replacement,” “circular economy,” “soil,” and “horticulture,” confirming its role as a component of growing media. Another cluster concentrates terms associated with the chemistry and nutrition of the growing medium, such as “nutrients,” “pH,” “salinity,” “fertilizer,” and agro-industrial residues such as “sugarcane bagasse”. A further grouping focuses on agronomic and biological effects, including “soil fertility,” “growth,” “microbial activity,” and “nitrification.” An additional block highlights discussions on “sustainability” and the use of biochar as an alternative substrate. Another cluster is associated with waste processing and valorization, including “composting,” “anaerobic digestion,” “biogas,” and “organic waste.” Finally, a nucleus of studies addresses “phytotoxicity” and related materials such as hydrochar and charcoal. Overall, the map identifies biochar as a multifunctional material used both in the formulation of growing media and in strategies for waste management and soil-quality improvement.

The temporal evolution of terms associated with the use of biochar between 2014 and 2023 is presented in Supplementary Fig. 2-B. The early years concentrate studies focused on material properties and interactions with the growing medium, reflected in terms such as “cellulose,” “nutrition,” and “soils”. Beginning in 2016, the focus broadens to management and productivity aspects, with emphasis on “composts,” “productivity,” “peat,” and “growing media”. In 2019, the consolidation of biochar as an agricultural input becomes evident, marked by the recurrence of “biochar,” “compost,” “growth,” and “amendment”. In recent years, approaches oriented toward sustainability and system performance have emerged, including “circular economy,” “life-cycle assessment,” and “optimization.” In terms of frequency, the most common terms are “biochar”

(537), "soil" (200), "compost" (163), and "growth" (162), reinforcing the predominant focus on agricultural application and plant responses.

The overview of the conceptual and thematic evolution of research on biochar in plant growing media (2011–2024) is depicted in Supplementary Fig. 4. The analysis of Supplementary Fig. 4-A establishes the relationship between impact and centrality of the main terms, outlining two fundamental axes of development. The first axis groups "biochar," "pyrolysis," and "compost," which exhibit high frequency but low centrality, indicating that these concepts form the structural foundation of the field, oriented toward fundamental principles and production processes. The second axis concentrates "growing media" and "peat," which display higher centrality, revealing a recent trend toward the practical application of biochar as a substitute for conventional growing media. This shift reflects a transition from a primarily chemical and technological focus to a more agronomic and environmental perspective.

Supplementary Fig. 4-B reinforces this progression by organizing the themes according to their density and relevance. The topics "soil," "compost," and "growth" position themselves as motor themes—highly integrated and central within the literature—confirming the prominence of research on the effects of biochar on plant growth parameters and on the quality of the growing medium. In contrast, "biochar," "pyrolysis," and "carbon" remain basic themes, conceptually supporting the broader set of investigations. Other groups, such as "anaerobic digestion," "methane production," and "co-digestion," emerge as developing themes, whereas "heavy metals," "bioavailability," and "amendments" persist as specialized niches, demonstrating the diversification and interconnectedness of agriculture, remediation, and bioenergy research.

Complementing the previous interpretation, Supplementary Fig. 4-C presents the keyword co-occurrence analysis, which delineates four distinct thematic clusters. The first, predominantly agronomic, groups terms such as growth, yield, compost, media, peat, and substrate, reflecting the consolidation of biochar use in growing media and its relationship with plant development parameters. The second concentrates words associated with physicochemical properties and production technologies, such as pyrolysis temperature, hydrothermal carbonization, and heavy metals, highlighting the continued interest in material optimization and its environmental functions. The remaining clusters link biochar to biotechnological processes such as anaerobic digestion and methane production, reinforcing its potential for integration into circular and sustainable systems.

Taken together, the results of the three figures substantiate the proposed overview, which is structured around four interdependent axes. The analyses confirm that the literature has evolved from a solid conceptual foundation concerning the fundamentals and properties of biochar toward applied investigations focused on its impact on plant growth and its potential to replace traditional growing media such as peat and compost. This trajectory reveals a maturing field that seeks to balance agronomic performance, environmental viability, and methodological standardization, essential aspects for the scientific and technological advancement of biochar use in plant growing media.

## 3.2 *Overview: Biochar in Plant Growing Media*

Biochar has become established as a strategic component in plant growing media due to its multiple agronomic and environmental benefits (Kumar and Bhattacharya 2021). Its adoption is strengthened by its ability to reduce dependence on peat while simultaneously improving crop performance by enhancing substrate physical structure, water retention, and nutrient availability (Tian et al. 2012). Recent studies on sustainable substrates identify biochar, either alone or combined with organic amendments, as a promising alternative (Venkataramani et al. 2023). However, its effectiveness depends on careful calibration, as its performance is governed by production and formulation parameters that must be adjusted to the specific requirements of each crop (Fascella et al. 2018).

This section presents a scientometrically informed narrative synthesis of biochar use in plant growing media, explicitly grounded in the conceptual, thematic, and keyword-based patterns identified in the preceding analyses, particularly in Supplementary Figs. 3 and 4. The bibliometric results indicate a predominance of studies linking biochar to substrate optimization, plant growth responses, peat replacement, and sustainability-oriented production systems. Accordingly, the following subsections synthesize the literature around the most recurrent and analytically supported thematic axes of the field, rather than presenting an independent traditional review. Figure 6 schematically summarizes the main topics addressed in this section.

### 3.2.1 Fundamentals, Production, and Essential Properties of Biochar

As indicated by the conceptual and thematic analyses presented in Supplementary Figs. 3 and 4, the structural properties, production pathways, and functional attributes of biochar form one of the foundational axes of this research field. Biochar exhibits structural and chemical properties that make it suitable for environmental and agricultural applications (Bhatta Kaudal et al. 2018; Sun et al. 2024). Its matrix consists of a recalcitrant organic carbon fraction of aromatic nature that resists rapid mineralization, conferring

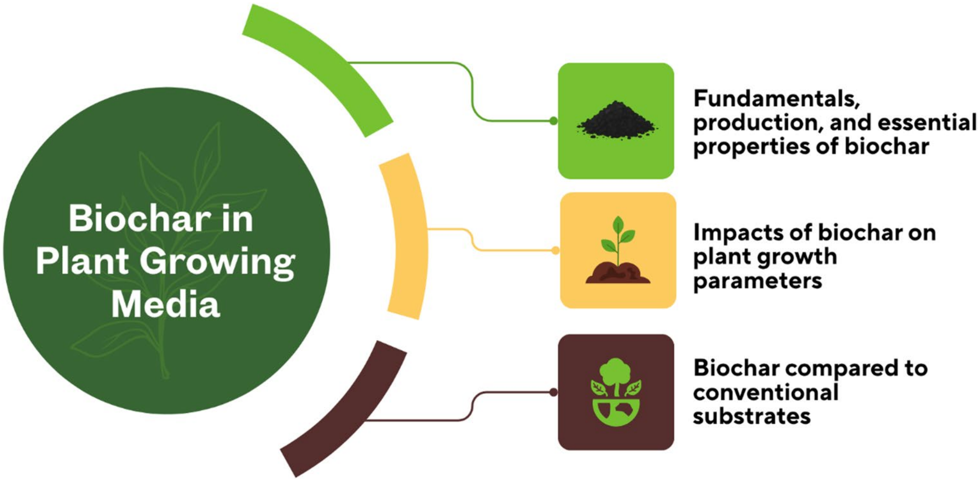

**Fig. 6** Key topics on biochar in plant growing media

high specific surface area, porosity, stability, and substantial cation exchange capacity (CEC), in addition to the ability to adsorb ions and molecules (Zhang and Sun 2014; Shang et al. 2018). A wide variety of organic residues can be used as feedstocks for biochar production, including agricultural wastes (prunings, corn straw, rice husks, and cashew shells), forest and aquatic biomass, the organic fraction of municipal solid waste, and sewage sludge (Wang and Wang 2019).

Studies indicate that feedstocks with a high cellulose content tend to produce biochars with superior performance, greater specific surface area, and enhanced nutrient adsorption and retention. In this context, the conversion of organic residues into biochar represents a sustainable management strategy that simultaneously adds value to these wastes and provides a beneficial input for soil quality (Lehmann and Joseph 2009; Ban et al. 2023). The selection of feedstock and processing conditions is therefore crucial for determining the properties of the final product, requiring precise calibration among raw materials, the production pathway, and operational parameters (Kumar and Bhattacharya 2021).

Biochar production pathways have been continuously refined to improve both yield and quality. The most commonly used method is pyrolysis—either fast or slow—with controlled temperature, heating rate, and residence time to modulate microstructure (Bu et al. 2022a; Sun et al. 2024). In addition to pyrolysis, gasification has also been employed to generate biochars with characteristics comparable to those obtained in retort systems, with potential to replace peat in growing media (Gascó et al. 2018a). Hydrothermal carbonization, in turn, produces hydrochars whose agronomic suitability may require post-processing treatments—such as acidification and salt leaching—to eliminate phytotoxicity and adjust pH and electrical conductivity (Gascó et al., 2018a).

Among its applications, biochar stands out as a promising climate-change mitigation strategy due to its capacity to stabilize carbon in soils over long periods and to partially replace inputs and processes dependent on fossil fuels (Alvarez et al. 2018; Singh et al. 2014). In thermochemical routes, coproducts such as syngas and bio-oil can be used for heat and electricity Generation (Yousefian et al. 2023). Biochar itself exhibits broad functional versatility, serving as an adsorbent in gas and wastewater purification, a reducing agent in metallurgical processes, a conditioner and carrier of nutrients in agriculture, an input in livestock systems, and a component in construction materials. Furthermore, when activated or functionalized, it can be applied in environmental remediation processes and energy-storage systems (Santos et al. 2025).

### 3.2.2 Impacts of Biochar on Plant Growth Parameters

The relevance of plant growth responses within this research field is supported by the scientometric analyses presented in the previous sections, particularly the keyword and thematic maps, in which terms such as “growth,” “compost,” “media,” “peat,” and “substrate” appear among the dominant and highly integrated themes. Biochar has emerged as a promising input for improving cultivation conditions, as it modifies chemical, physical, and biological substrate properties in ways that may favor plant development. Among the main reported effects are increases in pH and electrical conductivity, enhanced nutrient availability and uptake, improved photosynthesis, and stimulated biomass accumulation.

Although these responses depend on feedstock type, pyrolysis temperature, and application rate, the literature frequently reports positive effects across ornamental and horticultural species under specific cultivation conditions. Supplementary Table 1 presents representative examples from the literature on the effects of biochar on plant growth parameters, including crop type, biochar source, application dose, and the main responses reported. This subsection offers a qualitative synthesis of representative evidence from the literature, highlighting recurrent response patterns and the diversity of agronomic contexts in which biochar has been associated with plant growth improvement.

The incorporation of biochar into substrates has produced positive and consistent effects on plant growth. Studies indicate that adding 20% biochar derived from the pyrolysis of wheat straw at 350 °C, as well as incorporating biochar/compost mixtures into peat-based substrates, increased pH and electrical conductivity and resulted in higher foliar levels of N, P, and K, increased chlorophyll content, and higher net photosynthetic rates in Syngonium podophyllum, outperforming the control (Zulfiqar et al. 2019).

In vegetables, coconut-fiber mixtures enriched with biochar increased shoot dry mass and improved the mineral profile of spinach, indicating simultaneous gains in yield and quality compared with the pure reference medium. Similarly, a greenhouse trial with Rosa rugosa showed that incorporating 25% conifer-wood biochar into the substrate maintained growth, water-use efficiency, and ornamental quality equivalent to cultivation in 100% peat (Fascella et al. 2018). Similar results were observed in urban rooftop agriculture, where compost-based substrates enriched with biochar increased the productivity of tomato, lettuce, and Swiss chard compared with peat, improved the nutritional stability of the medium, and, in some cases, produced fruits with quality comparable to open-field cultivation. These findings highlight the potential of biochar as a sustainable, high-performance component in horticultural systems. (Picca et al. 2025).

The magnitude of these benefits depends on both the dose and the quality of the material. In *Rhododendron delavayi* Franch., the incorporation of 20% woody-waste biochar and 30–40% rice-husk biochar increased plant height, leaf area, root attributes, and photosynthesis (Bu et al., 2022b). In summary, reviews indicate that biochar tends to improve porosity, bulk density, water retention, and nutrient availability, resulting in enhanced vigor and growth, provided that the feedstock, pyrolysis conditions, and substrate formulation are appropriate for the cultivation system (Yu et al. 2023b).

Evidence obtained under real production conditions indicates that biochar is compatible with the management of plant growth regulators. In poinsettias, violets, and begonias, the incorporation of 15% and 30% biochar into a peat-based substrate did not alter the efficacy of paclobutrazol applied by drench, when compared with perlite at the same proportions. Thus, despite the high adsorptive capacity of biochar, under the evaluated conditions and concentrations there was no impairment of growth control, suggesting that levels of up to 30% do not interfere with plant responses to the regulator (Veazie et al. 2024; Venkataramani et al. 2023).

### 3.2.3 Biochar Compared with Conventional Substrates

The comparative assessment of biochar and conventional substrates is one of the most recurrent applied themes identified in the scientometric analyses, particularly in association with the terms “peat,” “growing media,” “substrate,” and “compost” in Supplementary Figs. 3 and 4. Peat, widely used as a substrate in horticulture, is characterized by high water-holding capacity, low pH, low nutrient content, and low bulk density. However, as a limited resource, its extraction generates significant environmental impacts, including biodiversity loss and greenhouse gas emissions, which justifies the search for more sustainable alternatives (Atzori et al. 2021; Méndez et al. 2017).

Biochar can be used as an alternative to peat in the production of poinsettias, aiming to reduce climate-change impacts, increase productivity, and mitigate problems associated with the loss of ecosystems that harbor rare species. It provides multiple advantages, such as improving nutrient availability in the soil and removing toxic substances and enzymes produced by pathogenic microorganisms (Yu et al. 2023a).

Several studies have investigated alternatives to partially or fully replace peat with biochar. Guo et al. (2018) evaluated the growth of poinsettia (*Euphorbia pulcherrima*) in substrates containing different proportions of biochar (0%, 20%, 40%, 60%, 80%, and 100%). The results indicated that biochar represents a viable option for reducing peat use, with the 20% proportion being the most effective in increasing plant dry mass. A concentration of 40% sustained growth comparable to that obtained with the commercial substrate, whereas proportions of 60% and 80% reduced dry mass without compromising the growth index or final visual quality. Thus, up to 80% biochar could be used as an additive in peat-based root substrates with an acceptable reduction in growth and no alterations in quality.

Nieto et al. (2016) found that the addition of biochar to peat substrates can partially replace peat, highlighting that biochar produced at 500 °C performed best, resulting in greater lettuce biomass compared with pure peat. Ma et al. (2020), evaluated how adding biochar to a peat substrate influences cucumber seedling growth and plug mechanical strength. The study showed that 10% biochar improves seedling and root development, whereas concentrations of 40% and 50% impair growth. Additionally, substrates containing 10% and 20% biochar exhibited higher compression resistance, meeting the requirements for automated harvesting. Thus, biochar stands out for simultaneously enhancing seedling vigor and plug stability.

Other studies combining biochar and peat have also been conducted. Martins et al. (2023) sought to reduce or eliminate the use of peat by replacing it with coconut husk, municipal organic compost, and acacia biochar. The results demonstrated that these renewable, locally sourced inputs (compost and acacia biochar) are efficient and sustainable, provided that formulations are properly balanced (Martins et al. 2023). Mendéz et al. (2017) investigated the impacts of incorporating sewage sludge and biochar derived from this material into peat-based substrates, assessing both growing-media quality and the development of lettuce (*Lactuca sativa*). Some results indicated that the incorporation of biochar increased microbial biomass as well as lettuce production. In addition, shoot length increased by 137% to 147%.

Studies show that combining biochar with other compounds yields additional benefits. Ravindran et al. (2022) investigated the co-composting of food waste and poultry manure with different doses of rice-husk biochar (0, 3, 5, and 10% w/w), sawdust, and salts. The results showed that both biochar and salts enhanced and prolonged the thermophilic phase and accelerated the biodegradation and mineralization of the mixture. Thus, the study demonstrated the effectiveness of using these inputs for co-composting these residues.

In addition, the literature includes studies linking biochar to vegetable seedling production. Santos et al. (2024) investigated the use of biochar derived from sewage sludge (SSB) and organic compost (COM) as inputs for the production of yellow passion fruit seedlings. Nine treatments were tested, including a control and four concentrations of each material. Both inputs improved seedling performance compared with the control; however, organic compost produced superior results, especially at the 10% dose. The authors suggest further investigations into residual effects and possible combinations of SSB and COM in future research.

Eskandari et al. (2019) evaluated the use of hydrochar produced by hydrothermal carbonization of paper-mill biosolids as a partial substitute for peat in substrates for pine seedlings. The study showed that adding 20% hydrochar, combined with a 50% reduction in liquid fertilizer, decreased the need for fertilization in nurseries. This approach contributes to recycling nutrients from industrial residues and reducing the use of peat and chemical fertilizers. In addition, hydrochar promoted increases in stem diameter and mycorrhizal formation, potentially improving seedling survival after transplantation.

### 3.2.4 Methodological Gaps and Future Perspectives

This scientometric study provides a comprehensive overview of the scientific production related to the application of biochar in plant growing media. However, methodological limitations should be acknowledged. First, this study relied solely on publications indexed in the Web of Science Core Collection, which means that the patterns identified here reflect the coverage, indexing profile, and structural characteristics of this database rather than the totality of global scientific production on the subject. Consequently, the observed distributions of publications, countries, institutions, and collaboration networks should be interpreted as representative of the Web of Science-indexed corpus analyzed in this study. Relevant studies available in other databases such as Scopus or Google Scholar may therefore not have been captured. Future scientometric research on biochar in plant media should integrate multiple databases in order to broaden coverage, improve data completeness, and reduce indexing bias.

Another methodological limitation concerns the absence of a formal sensitivity test of the search query. Although the search string was iteratively refined to ensure broad thematic coverage, alternative keyword combinations may have retrieved a partially different set of publications. Therefore, the final corpus should also be interpreted in light of the selected search strategy adopted in the Web of Science Core Collection. Future scientometric studies should evaluate query robustness through formal sensitivity analyses, including alternative keyword combinations and cross-database comparisons.

The results of this analysis revealed that research on biochar use in plant growing media has expanded rapidly over the last decade, reflecting the increasing interest in sustainable and alternative substrates for plant production. Keyword trend analysis indicated that earlier studies primarily focused on identifying suitable biomass feedstocks and optimizing biochar production processes for agricultural use. Considerable attention has also been given to evaluating the effects of biochar on soil physical, chemical, and biological properties, as well as on plant growth, nutrient uptake, and crop yield, often in comparison with traditional substrates such as peat and compost (Siedt et al. 2021; Baronti et al. 2024; Chrysargyris et al. 2024b).

More recently, studies have begun to explore the integration of biochar applications with environmental and economic assessments (Casson Moreno et al. 2020; Das et al. 2023; Patel and Panwar 2024). Future research should therefore emphasize evaluating biochar from a sustainability perspective by considering feedstock sustainability together with its long-term environmental, agronomic, and economic impacts. In addition, future investigations should address the role of biochar in plant–microbe interactions and the potential benefits of combining biochar with microbial inoculants to enhance plant productivity and resource efficiency (Awasthi et al. 2020; Bolan et al. 2023; Caldara et al. 2024; Jin et al. 2024). Advances in these directions will contribute to a more robust and comprehensive understanding of biochar performance in plant growing media, while also supporting the methodological maturation of this research field.

## 4 Conclusions

This scientometric analysis revealed a marked increase in scientific production on the use of biochar in plant growing media between 2011 and 2024, indicating the consolidation and progressive maturation of this research field. The results highlight the leading role of China, followed by the United States and Australia, as well as the relevance of institutions such as the Chinese Academy of Sciences, within an increasingly interconnected international collaboration network.

Taken together, the scientometric patterns identified in this study suggest that biochar has become a highly relevant research topic in the search for more sustainable growing-media formulations. At the same time, the literature still reveals important challenges related to feedstock heterogeneity, variability in production conditions, and the lack of methodological standardization, all of which affect the predictability and comparability of results. Future investigations should therefore prioritize standardized experimental designs, long-term validation studies, life-cycle and economic assessments, and deeper analyses of plant–microbe interactions, in order to support the robust and scalable use of biochar in plant growing media.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s42729-026-03345-y.

**Acknowledgements** The authors are grateful for the financial support received from Petronas (Project ANP n. 25181-9), Mandacaru Energia, the National Council for Scientific and Technological Development – CNPq (Process n. 141456/2023-0), the Coordination for the Improvement of Higher Education Personnel – CAPES, and the Human Resources Program of the National Agency of Petroleum, Natural Gas and Biofuels (PRH-ANP), coordinated by the São Paulo Research Foundation – FAPESP (Process n. 2025/02752-7). The authors also extend their thanks to Geowellex for the technical assistance provided.

**Author Contribution** Gthielly Maira Fernandes: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Project administration, Validation, Supervision, Writing - original draft. Betelhem Fetene Admas: Conceptualization, Investigation, Methodology, Visualization, Validation, Resources. Emanuelly Kelly Gomes de Oliveira: Validation, Formal analysis, Writing - review & editing. Kadidja Ianne do Vale Almeida: Formal analysis, Investigation, Methodology. Lívia Christina de Araújo Silva Moura: Formal analysis, Investigation, Methodology. Lucrécia Pacheco Batista: Validation, Writing - review & editing. Luiz Augusto Galdino Melo: Validation, Writing - review & editing. Maria Helena Lima da Silva: Validation, Writing - review & editing. Darliane Cristina Soares de Souza: Validation, Writing - review & editing. Eulene Francisco da Silva: Validation, Formal analysis, Writing – review & editing. Daniel Valadão Silva: Validation, Formal analysis, Writing - review & editing. Rafael Oliveira Batista: Validation, Writing - review & editing. Frederico Ribeiro do Carmo: Validation, Writing - review & editing. Luiz Fernando de Sousa Antunes: Conceptualization, Supervision, Validation, Writing – review & editing.

**Funding** This study was carried out with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES) — Financing Code 001, Brazil and Conselho Nacional de Desenvolvimento Científico (CNPq).

**Data Availability** All data generated or analyzed during this study are included in this published article.

## Declarations

**Ethical Approval** Not applicable.

**Consent to Participate** All authors consented to participate.

**Consent to Publish** All authors read and approved the final manuscript.

**Competing interests** The authors declare that they have no conflict of interest.

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