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Biochar

REVIEW

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Biochar impact on soil health and tree-based crops: a review

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Abstract

Biochar produced from pyrolysis of biomass such as wood, canopy, animal manure, and agricultural waste is recognized for its stability and for being a benefactor of soil health and plant growth. Its application in forestry is an area with growing research interest due to its ability to enhance soil physicochemical properties, including structure, water retention, and nutrient availability, thereby boosting plant growth, drought tolerance, and resistance to pests and diseases. However, the effectiveness of biochar varies based on factors like biochar type, application rate, soil type, and tree species. Potential risks associated with biochar use include nutrient immobilization, increased pH in alkaline soils, and enhanced leaching of toxic elements. Despite its promise, challenges such as knowledge gaps, lack of site-specific studies, and concerns of economic viability hinder widespread adoption of biochar in forestry. This qualitative review compiles over 150 published works from the past two decades on biochar application in forestry. It assesses the impacts of biochar on soil health and tree crops, highlighting its potential to improve soil fertility and promote tree growth. The review identifies significant findings, such as the positive influence of biochar on soil and plant health and outlines existing knowledge gaps that need addressing. By synthesizing current research, the review proposes future directions to optimize biochar use in sustainable forestry management, emphasizing the need for tailored approaches and economic assessments to facilitate broader adoption. The findings underscore the potential role of biochar in enhancing forestry practices while calling for further studies to resolve uncertainties and improve its practical implementation.

Article Highlights

- Biochar improves soil health, structure, water retention, and tree resilience
- Unique biochar–tree interactions boost carbon storage and root-system benefits
- Tailored biochar use mitigates nutrient immobilization and pH-related challenges
- Long-term trials are vital to optimize biochar applications for forestry systems

Keywords Forestry, Soil health, Tree crops, Drought tolerance, Diseases mitigation

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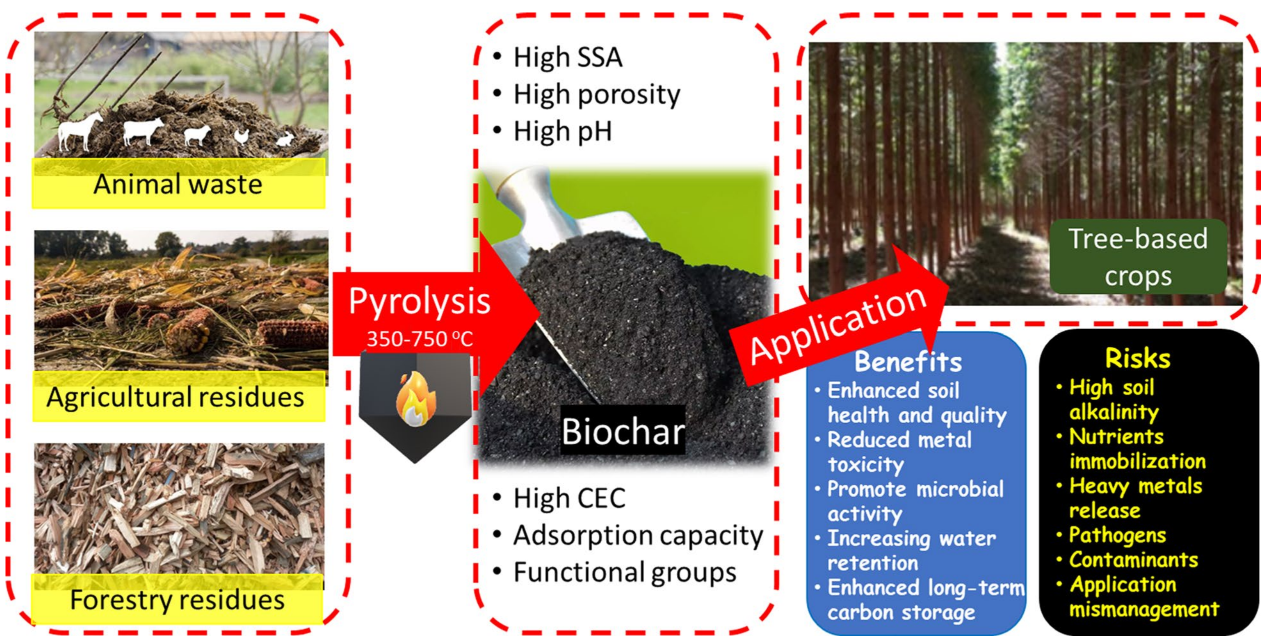
Graphical Abstract



1 Introduction

Biochar is a charcoal-like material and is mainly produced by pyrolysis (Biederman and Harpole 2013) which converts biomass into biochar under high temperature and limited oxygen supply. Biochar has rich physiochemical properties such as high fixed carbon content, surface area, porosity, stability (Atkinson et al. 2010). Biochar differs from charcoal, torrefied wood, hydrochar (produced by hydro-thermal carbonization), and natural pyrogenic carbon in its intended application, production processes, and properties. Regulatory definitions distinguish the agricultural and environmental applications of biochar from other materials primarily used for energy. The structure of biochar in molecular level is characterized by cross-linked aromatic rings formed during pyrolysis which contribute to its stability (Li and Tasnady 2023). Understanding these distinctions of biochar is vital for its proper regulatory categorization and effective utilization in various sectors, from civil engineering (i.e. additive to cement mortars) to environmental science, particularly in agriculture and carbon sequestration efforts (Kalderis et al. 2024). The global biochar market is valued at $177 million annually based on current pyrolysis plant capacities and a carbon price of $50 per ton of CO_2 (Han et al. 2021b).

Given the high carbon content and porosity, biochar facilitates the retention of soil water and nutrients, which provides benefits to soil health and crop production (Jiao et al. 2021). It can also help to mitigate climate change by sequestering carbon in the soil (Stavi and Lal 2013; Du et al. 2016). The properties of biochar, including its porosity, surface area, and chemical composition, are essential factors that influence its effectiveness in forestry applications (Lehmann and Joseph 2015).

The overall beneficial effects of biochar application in the soil include improvement of soil structure, plant available water, nutrient cycling, and control of soil erosion (Edeh et al. 2020; Nguyen et al. 2017). A study found that, in an agricultural setting, the application of biochar increased soil pH by 0.5 units and available phosphorus (P) by 20% (Joseph et al. 2021). Another study by Ventura et al. (2018) found that biochar application, depending on the dosage, increased soil aggregate stability by 50%, plant available water by 20%, and the growth of poplar trees (*Populus* spp.) by 20%. Despite these findings, while biochar benefits in agricultural systems are well-documented, its unique interactions with tree crops—such as prolonged carbon storage, root-soil-microbe dynamics, and its potential in forest sustainability—are less explored.

Unlike annual crops, which grow within a single season, tree crops have longer lifespans, complex roots, and high biomass, resulting in unique biochar interactions. Forest ecosystems, with multi-layered vegetation and diverse soil organisms, affect nutrient cycling and carbon storage over extended timescales (Lehmann et al. 2006). Biochar in forest settings must offer long-term stability, resilience to stress, and sustained nutrient release, distinct from shorter-cycle crops (Glaser et al. 2002). Trees face challenges like nutrient immobilization, a challenge that biochar can mitigate by improving soil structure, enhancing cation exchange, and supporting beneficial microbes (Lehmann and Joseph 2015). Thus, biochar research in forests requires a long-term view to understand benefits and risks. A literature review focused on tree crops addresses this gap by offering insights into how biochar applications can be optimized for sustainable, long-term management in forest ecosystems.

The effects of biochar on tree crops can be influenced by several factors, such as the type of biochar, the application rate, soil type, and tree species. Nevertheless, existing evidence supports the notion that biochar can serve as a valuable source for enhancing the growth and productivity of tree crops. Despite that, there remains a limited understanding of the biochar impacts on forest soil, particularly in comparison to agricultural soil (Gogoi et al. 2019), including their effects on tree crops. For instance, various studies conducted in different regions have yielded promising results. In Iran, the application of biochar resulted in a 26% boost in trunk diameter and shoot number in apple trees (*Malus domestica*) (Khorram et al. 2018). A meta-analysis of recent studies examining biochar responses in woody plants reveals significant potential for substantial tree growth enhancement with the addition of biochar, showcasing an average 41% increase in biomass (Thomas and Gale 2015). Notably, these responses are most prominent during early growth stages and demonstrate higher efficacy in boreal and tropical ecosystems compared to temperate zones, as well as in angiosperms compared to conifers (Thomas and Gale 2015).

The available data suggest that while biochar amendment may not serve as a universally applicable strategy for promoting forest health, it demonstrates clear benefits for trees thriving in nutrient-deficient soils and under challenging environmental conditions (Johanis et al. 2022). As mentioned earlier, the enhanced growth and productivity of tree crops resulting from biochar addition can be attributed to the addition of nutrients to the soil, improvements in soil structure, and increased plant available water (Zhang et al. 2020; Jeffery et al. 2017). In a collaborative effort, Zhang et al. (2022) established a reciprocal relationship, determining that the biochar generated from pyrolysis of both agricultural and forest residues was a valuable additive for rehabilitating degraded forest soils in China. In a concise summary, the authors delineated the advantageous impacts of biochar application, encompassing: (1) enhancement of the soil physicochemical properties; (2) mitigation of greenhouse gas emissions; and (3) augmentation of nutrient use efficiency, consequently fostering tree growth. These positive outcomes were attributable to factors such as the nature of the raw material, pyrolysis temperature, application rate, aging process post-application, and the specific characteristics of the soil and plantation involved.

Regarding disease tolerance, a study by Zwart and Kim (2012) found that amending potting media with 5% biochar effectively diminishes the expansion of necrotic lesions induced by *Phytophthora* spp. in seedlings of two prevalent landscape tree species. Therefore, biochar can assist in reducing the incidence of pests and diseases in tree crops by providing a physical barrier to pests, stimulating the growth of beneficial microbes, and increasing the resistance of trees to disease.

Forest plantations worldwide face the challenge of maintaining soil fertility (Liao et al. 2012), ensuring tree health, and promoting sustainability. Biochar, as a soil amendment, provides a possible solution to these issues by enhancing soil properties and supporting tree growth. It is well known that the myriad potential benefits of biochar in agriculture and forestry systems, ranging from enhanced soil health and plant growth to carbon sequestration and reduced greenhouse gas emissions, have garnered widespread attention and support. However, it is important to note that, despite the numerous positive outcomes reported, some studies in the literature have documented conflicting or contradictory results (Wang et al. 2020). This variability underscores the importance of considering specific conditions, including the type of biochar, application rates, soil characteristics, and crop species, which can significantly influence the effectiveness of biochar application. Consequently, a consensus in the scientific community emphasizes the necessity for systematic investigations to unravel the intricate relationships among biochar production technologies, biochar properties, and its performance in agricultural and forestry systems (Wang et al. 2020).

Against this backdrop, in addition to acknowledge other review articles and meta-analyses concerning biochar impacts on soil chemical and physical properties and tree growth (Bruckman and Pumpanen 2019; Gogoi et al. 2019; Lévesque et al. 2022; Li et al. 2018; Thomas and Gale 2015; Yadav and Solanki 2015; Zhang et al. 2022), this review holds particular significance by offering a qualitative examination of the advantages and the detrimental aspects of biochar applications in forestry systems. Therefore, the primary aim of this review is to critically evaluate and synthesize current research on biochar characteristics, with a particular emphasis on its applications in forestry systems. This includes an in-depth examination of its effects on soil health and tree-based crops. The review systematically explores biochar production processes from diverse feedstocks and their influence on biochar properties, as well as its application to forestry soils and its impacts on soil physicochemical attributes, microbial communities, carbon sequestration, and the management of pathogens and diseases. Additionally, this review addresses potential challenges associated with biochar use, such as unintended increases in soil pH, nutrient immobilization, and the heightened risk of environmental contamination. By offering a balanced and comprehensive analysis, this work provides critical insights to guide evidence-based decision-making in the sustainable application of biochar in forestry.

2 Methodology

A comprehensive review was conducted on Web of Science, Elsevier Science Direct, Google Scholar, Scopus, and ProQuest databases using the keywords 'biochar', 'tree', 'soil', and 'forest' in the title, abstract, and keywords, which identified a total of 599 sources. The search ended up comprising several forest and tree crops, which is beneficial to a global perspective. The search was not limited to a specific period. The oldest paper found was published in March 2003 while the newest one was published in September 2024 with the majority published in the last eight years. From the ProQuest database, which has 26 databases integrated, identical sources were eliminated, remaining 244 studies (out of 599). For this qualitative review, we meticulously selected over 150 published works focusing on biochar application within forestry contexts, analyzing its impact on soil health and the development of tree crops.

In this article, the terms "forest(ry)" and "forestry systems" are employed broadly to encompass not only traditional forests but also tree crops in agricultural settings and specific tree plantations such as *Eucalyptus* and *Pinus*. This inclusive terminology is justified by the expanding role of tree-based systems in both ecological and economic contexts. For instance, agroforestry, which integrates trees and shrubs into agricultural landscapes, has been recognized for its benefits in biodiversity conservation, soil health, and carbon sequestration (Jose 2009). Additionally, monoculture plantations of species like *Eucalyptus* and *Pinus* are significant in global forestry practices due to their economic value and rapid growth rates, contributing to timber, paper, and bioenergy industries (Richardson 1998). Finally, texts on agroforestry, such as "Agroforestry for Sustainable Agriculture" (Mosquera-Losada and Prabhu 2019), outline timber and other tree-based products under the general umbrella of tree crops, which includes trees cultivated for timber, fruit, nuts, and other purposes. By using these terms inclusively, the article aims to reflect the diverse applications and importance of tree-based systems across different landscapes and industries, aligning with contemporary perspectives in forestry research.

An initial bibliometric analysis was held to quantitatively illustrate the works published within the topic, where the number (#) of publications on biochar-amended soils and impacts on tree crops was also evaluated over time. For this, the search considered three of the most popular databases (Scopus, Science Direct, and ProQuest), where regression analysis considered 'year' as the independent variable and the '# of publications' as the dependent variable. The fitting line of publications from January 1, 2006 to December 31, 2022 was plotted using JMP Pro 15 after identifying the best trend model. The exponential relationship was successfully obtained and plotted with the combined database sources ($n = 51$). Data were combined since the analysis of covariance (ANCOVA) revealed a greater significance for the 'year' factor ($p < 0.0001$) in comparison to the interaction 'year × database' ($p < 0.0462$). Such interaction was close to $p = 0.05$ (non-significant) and it was linked to the Scopus database, which provided a minor # of publications (165) when compared to the other sources, Science Direct (190) and ProQuest (244), thus justifying the authors' choice of combining the data. The modeling considered only complete years, so 2023 was not added to the dataset since potential works conducted during this may be released only in 2024/25. Graphs were plotted using Excel.

3 Bibliometrics analysis on biochar use in forestry systems

Figure 1 shows the number (and percentage) of publications on biochar soil application and impacts on tree crops by field of research since 2010. During this period, significant attention has been directed toward research in environmental, energy, agricultural, and biological sciences due to their critical contributions to soil health, environmental quality, and silviculture. As a matter of fact, the utilization of biochar in forestry, encompassing aspects like vegetation, biodiversity, organic matter, and heavy metals, has evolved progressively with the sustained expansion of research focus in these areas (Chen et al. 2023). The integration of Earh and Planetary Sciences has made a slight contribution (Fig. 1). According to Chen et al. (2023), investigation into the utilization of biochar to enhance soil health, in conjunction with its impact on forestry systems, requires the interdisciplinary

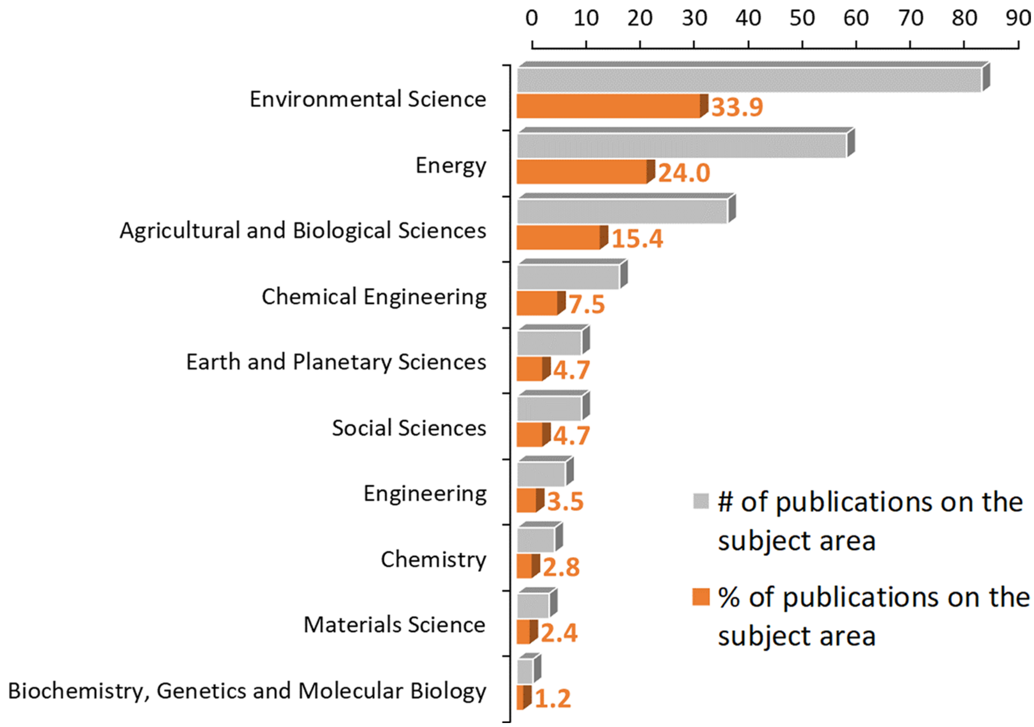


Fig. 1 Distribution of published works on biochar soil application and impacts on tree crops by field of research from 2010 to 2023 according to Science Direct (2023)

integration of ecology, botany, geology, environmental sciences, and geophysics. It is also important to acknowledge the inherent limitations in any bibliometric analysis, such as potential omissions of articles due to database restrictions and the constraints of machine searching. Furthermore, in the context of our review, noted parallels exist between the applications of biochar in forestry and agriculture, thereby expanding the scope of our search results.

Research on biochar application in forestry systems was mainly placed in the United States (14%), China (12%), Australia (11%), and Brazil (9%) (Fig. 2). This corroborates the bibliometric analyses recently raised by Chen et al. (2023), who highlighted that China and the United States set the standard for research output. Surprisingly, a reduced number of original research studies were produced when compared to review articles (Fig. 2). This discrepancy may stem from the selection of keywords used in our search strategy. Most review articles tend to incorporate only a subset of these keywords, rather than combining all of them into a single search. Consequently, as existing review articles do not comprehensively address the combined benefits of biochar application on soil properties, tree crop biomass, and wood quality, this highlights the need for further research on this topic.

Upon further analysis, studies on biochar application and its impacts on forestry systems exponentially increased in the last two decades, starting in 2006, which demonstrates a gradual increment over time until 2022 (Fig. 3). This aligns with the bibliometric analyses conducted by Chen et al. (2023), which systematically assessed published works spanning the period from 2002 to 2022. Their study highlighted that the exploration of biochar application in forestry soils remains in a robust phase of accelerated growth, progressing at a steady and moderate pace. This reinforces that more research must be performed to fill some gaps and to promote the use of biochar as a sustainable and efficient agricultural practice for the combined benefit of both soil quality and tree crops production.

4 Trade-offs among feedstock, process, and biochar properties

Pyrolysis is a thermal-chemical process that decomposes or transforms biomass into char, bio-oil (condensable volatile products), and gases (non-condensable volatile products, such as CO_2, CO, CH_4, H_2, C_2H_6 and C_2H_2-C_2H_4), the proportion of which depends on feedstock type, process temperature, residence time and highest temperature achieved. Based on the temperature, residence time, and heating rate, pyrolysis can

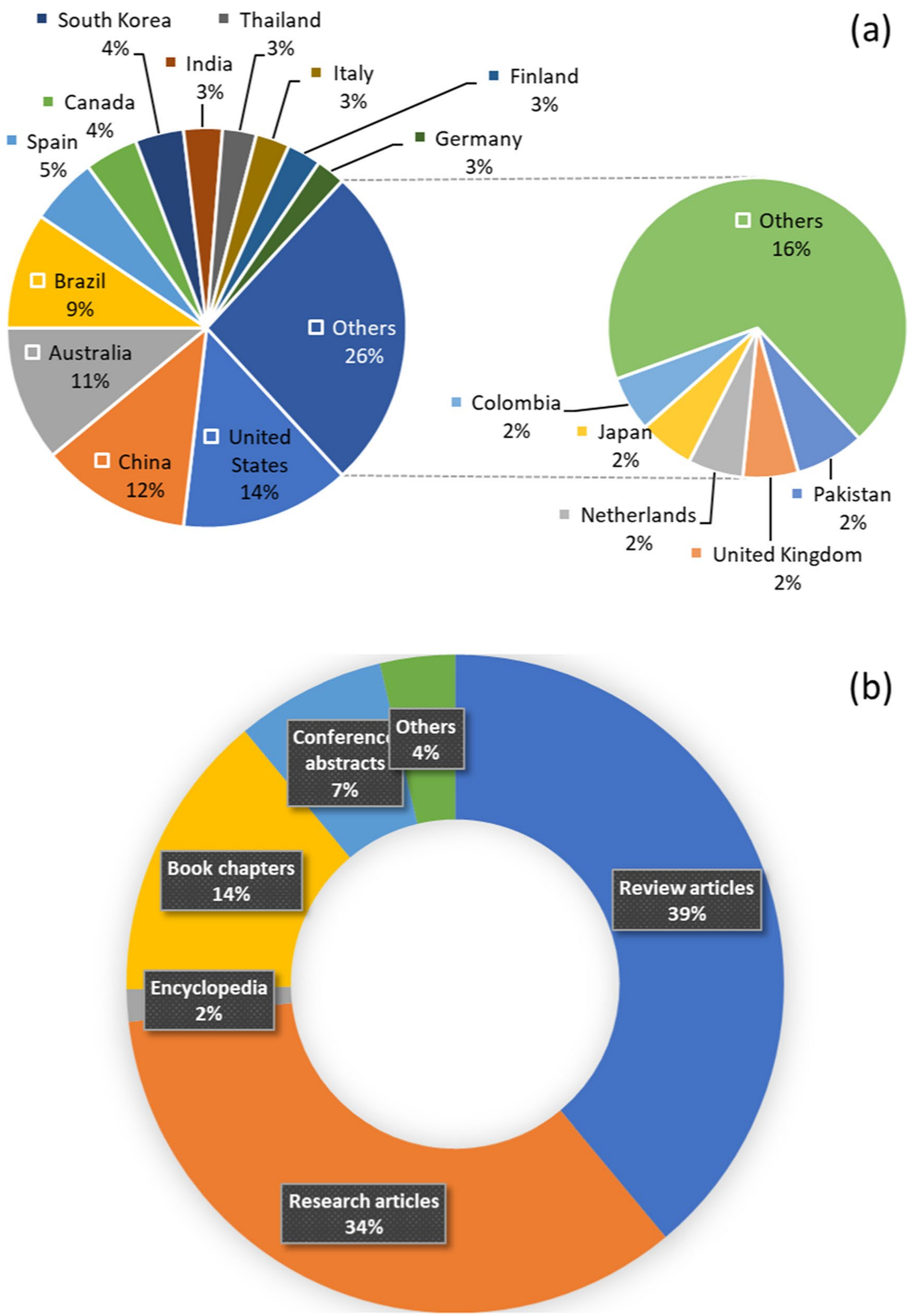


Fig. 2 Distribution of published works on biochar soil application and impacts on tree crops by country (**a**) from 2006 to 2023 (Scopus, 2023) and by publication type (**b**) from 2010 to 2023 (Science Direct, 2023)

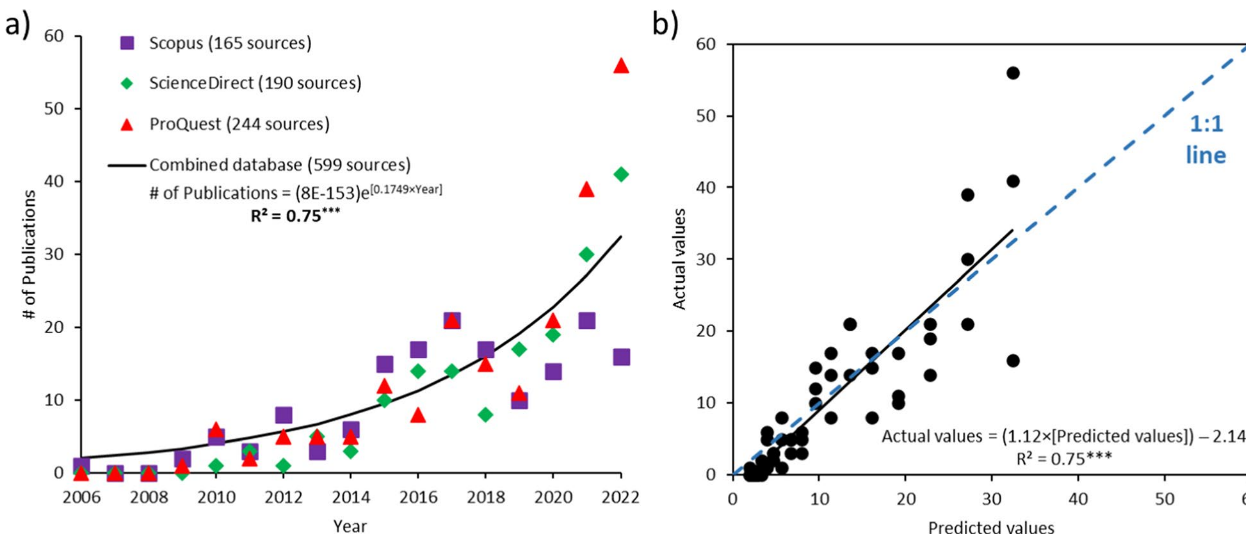


Fig. 3 The trend line of the number of publications from 2006 to 2022 successfully converged exponential regression, which shows the increased importance of the research subject (**a**); and diagnostic plot of '*predicted* x *actual*' values from the exponential model (**b**). The 'number of sources' inside parentheses (**a**) represents the cumulative number of publications through the years

be classified into slow pyrolysis (minutes to days), fast pyrolysis (< 5 s), and flash pyrolysis (< 0.1 s). Slow pyrolysis is usually carried out at relatively lower temperature (400–600 °C), lower heating rate (< 50 °C min^{-1}) and extended residence time, resulting in production of mainly solid biochar (< 35% char yield). Fast pyrolysis using relatively higher temperature (650–900 °C) and heating rate (< 1000 °C s^{-1}) with shorter residence time promotes biomass decomposition into mainly gaseous compounds (50–70% conversion efficiency). Temperatures and residence times used in between those of fast and slow pyrolysis can result in production of bio-oil (< 60% of bio-oil yield) (Bridgwater 2003; Liu et al. 2014; Wang et al. 2022a). The physical, chemical, and morphological properties of biochar are affected by feedstock type and pyrolysis conditions (Antonangelo et al. 2019). The type of feedstock appears as one of the primary factors determining the characteristics of the final product and its suitability for various agronomic applications (Domingues et al. 2017).

Biomass derived from forestry and agriculture crop residues is mainly composed of cellulose, hemicellulose, and lignin which are the major building blocks of plant cell wall, and extractives including terpenes, phenols and graxes and inorganic compounds that are not structure of plant cell wall (Demirbas 2004; Jung et al. 2015). There are also differences among molecular components of forestry and agriculture biomass (Welker et al. 2015; Yang and Lü 2021). The structural complexity of the plant cell-wall is among the important topics in the design and utilization of energy plants (Zeng et al. 2017) and the pyrolysis process (Yang et al. 2007).

Given the pyrolysis conditions and the corresponding physiochemical changes of biomass during pyrolysis, it becomes evident that the pyrolysis product—biochar can exhibit distinct characteristics. When a pyrolysis process starts, the hemicellulose begins to decompose earlier (at 160 °C) than other components while cellulose has a peak weigh loss rate at 350 °C, and the lignin, due to its higher thermal stability (from 200 to 800 °C), shows a longer residence time in furnace (Faleeva et al. 2022).

During the thermal conversion of raw material into biochar, substantial (and proportional) increases of carbon content, C:N ratio, inorganic compounds, porosity, and surface area are observed, rendering the formed biochar great potential of physical adsorption capacity for liquids and gases. According to Chen et al. (2017), the pyrolysis process firstly enables formation of abundant functional groups on biochar due to accelerated decomposition of surface molecular structures, followed by development of suitable porosity and functional groups on biochar at 500–700 °C. Furthermore, the enduring nature of biochar is associated with the prevalence of aromatic groups, a tendency that intensifies at elevated temperatures (Wang et al. 2016).

A general characterization of forestry and agricultural biochar pyrolyzed at different temperatures is available in Table 1. A range of raw materials which are classified into forestry, crops, and livestock residues, after converted into biochar, could have different agronomic applications (Tab. 1). Particularly, wood biochar has

Table 1 Physical and chemical properties of forestry and agricultural biochars. Search: Adapted from Rathnayake et al. (2023), Wang et al. (2022a), Chen et al. (2021), Higashikawa et al. (2016), Domingues et al. (2017), and Antonangelo et al. (2019)

Feedstock types	**Forestry**		**Crop residues**	**Livestock residues**
	Wood, sawdust, and bark		Sugarcane bagasse, coffee husk, rice husk, corn straw, soybean straw, switchgrass, sunflower husk	Poultry litter-derived, manure
Process				
Temperature (°C)	350–750		350–750	350–750
Char (%)	28.2–59.6		26.9–43.5	55.9–69.7
Properties	**Wood**	**Bark**		
%				
Moisture content	–	–	2.7–4.4	2.7–3.9
Ash	0.7–1.1	7.9–14.5	1.9–19.6	29.8–56.4
Volatile matter	6.5–36.9	6.0–38.5	7.7–35.0	26.5–36.9
Carbon fixed	62.2–92.4	53.2–79.4	52.5–90.1	11.1–17.0
C	70.4–90.9	67.6–86.3	60.5–90.5	24.7–31.2
H	1.52–3.81	1.16–3.73	1.57–3.92	0.67–1.97
O	5.6–24.0	19.1–28.7	4.3–19.5	10.9–16.3
N	< 0.30	< 0.30	0.1–3.5	1.0–4.5
S	0.01–0.04	0.01–0.04	0.03–0.23	0.29–0.44
g kg^{-1}				
P	1.05–1.09		< 2.73	3.71–4.28
K	0.24–0.26		0.87–13.65	3.05–3.13
Ca	1.77 –2.02		0.59–6.10	52.51–52.57
Mg	0.64–0.84		0.21–3.66	1.16–1.28
mg kg^{-1}				
Cu	9.22–17.83		1.12–11.01	11.42–12.35
Mn	44.20–54.28		31.65–106.10	48.0–63.86
Zn	10.68–22.44		7.15–38.52	77.80–85.30
Fe	485–501		51.83–10,141	431–555
B	23.35–36.53		7.25 –33.33	2.26–10.79
Na	1510–1918		180–587	1,259–1,475
$mmol_c$ kg^{-1}				
Cation exchange capacity	91–206	–	138–280	105–320
pH	7.48–7.59	–	8.44–9.17	8.21–9.96
μS cm^{-1}				
Electrical conductivity	59–73	–	227–1903	4013–4337

"–" Non-applicable

high carbon content and high aromatic structure, which could enhance the wood chemical stability and the persistence in soil. Biochar from crops and livestock residues has a high liming potential, also a high ash content, mainly comprised of potassium (K) and phosphorus (P), indicating a greater agronomic potential to tropical soils (Domingues et al. 2017).

Another parameter to consider is the particle size of biochar. The fractions of biochar with large particle size have porous structure within the material, while the fractions of biochar with smaller particle size (< 1 mm) have large surface area exposure. This as a result amplifies the accessibility of chemical compounds and enhances their reactivity. Some recent studies have focused on nanometric scale (1 to 100 nm) of biochar (nano-BC) via size reduction and particle screening and have signaled potential agronomic benefit, including environmental remediation of contaminants in soil, microbial metabolic activity, and crop performance (Li et al. 2023; Rajput et al. 2022; Song et al. 2022).

5 Potential benefits of biochar for soil health and tree crops

Soil health is the state of biological, chemical, and physical properties of soil that enable it to function as a vital ecosystem (Lehmann et al. 2020). It supports plant growth, nutrient cycling, and biodiversity, contributing to overall environmental sustainability. Key aspects include active and diverse microorganisms and soil fauna, adequate nutrient levels, balanced pH, low contaminants, good soil structure, balanced texture, and proper water retention and drainage. Additionally, healthy soil provides major ecosystem functions such as carbon sequestration, water filtration, and habitat support. Maintaining soil health involves practices like soil amendments with biochar (He et al. 2021), which promotes long-term productivity and environmental health. Numerous studies have reported the positive effects of biochar on soil health in forestry systems (Cui et al. 2021; Wang et al. 2020; Zhou et al. 2020; Li et al. 2018). Biochar acts as a soil conditioner, enhancing water retention, cation exchange capacity (CEC), pH buffering, and nutrient availability (Jeffery et al. 2011). Enhanced soil quality through increased water-holding capacity, nutrient availability, and soil enzyme activities promotes healthier and more robust root systems (Piccolo et al. 2022; Lee et al. 2022). These improvements in soil conditions, therefore, contribute to better physiological responses in trees, such as enhanced photosynthetic performance and faster recovery from drought stress (Piccolo et al. 2022), leading to improved overall soil fertility and resilience (Spokas et al. 2014) and positively impacting tree establishment and biomass production (Agegnehu et al. 2016). For example, in urban tree species like *Tilia × europaea*, trees grown in biochar-amended soils demonstrated a 22% increase in total biomass compared to control trees, highlighting the role of biochar in supporting tree vigor and overall productivity (Piccolo et al. 2022). Moreover, the use of biochar as a growth substrate for tree seedlings in nurseries has demonstrated its potential to enhance root development and transplant survival (Barros et al. 2019). Table 2 presents a summary of works showing the combined benefits of biochar application to soil health and tree crop production.

5.1 Improving soil structure

Soil structure plays a crucial role in determining the success of tree crop cultivation, as it directly influences root penetration, water movement, nutrient availability, and overall plant growth. Soil aggregates are fundamental units of soil structure, and their stability influences water retention and resistance to erosion (Wang et al. 2022b). Biochar improves soil structure by increasing aggregate stability and porosity, thus leading to better drainage, water retention, and aeration, which benefits tree growth. A study by Lehmann et al. (2006) demonstrated that biochar-amended soils exhibited increased macroporosity, promoting better water infiltration and root penetration. Moreover, the porous nature of biochar creates habitats for soil-beneficial microorganisms that contribute to soil aggregation (Atkinson et al. 2010).

Effects of biochar on aggregation stability vary based on feedstock type, pyrolysis conditions, and application rates. A study by Joseph et al. (2010) demonstrated that biochar produced from wood feedstock enhanced aggregate stability due to its porous structure and the promotion of microbial activity. Conversely, Teutscherova et al. (2020) reported mixed effects of biochar application on aggregation stability, emphasizing the need for site-specific considerations. Despite the contrasting results, biochar application as soil amendment led to improved aggregate stability and reduce the bulk density in forest soils, indicating potential for enhanced root growth and water movement (Sun et al. 2022). To reiterate, a recent literature review by Lévesque et al. (2022) highlighted that although only a few studies examined the impact of biochar on tree growth in temperate forests, the uppermost findings support that biochar addition led to enhanced soil aggregation, attributed to increased microbial activity and organic matter content, which favored the formation of soil stable aggregates.

The mechanisms driving biochar-induced improvements in soil structure and aggregation stability are complex. The surface chemistry of biochar fosters interactions with soil particles, promoting aggregation and stabilizing soil structure. While short-term studies highlight the potential benefits of biochar, long-term effects on soil structure and aggregation stability in forestry systems require further investigation (Hardy et al. 2019). It is crucial to assess the persistence of biochar-induced improvements and potential trade-offs. Environmental considerations such as biochar production methods, feedstock selection, and application rates should be carefully evaluated to minimize any adverse impacts on local ecosystems.

In summary, biochar application in forestry systems offers a promising avenue for improving soil structure and aggregation stability. Enhanced porosity, microbial activity, and interactions with soil particles contribute to the positive effects of biochar on soil properties. However, variability in outcomes across studies emphasizes the need for site-specific assessments and long-term monitoring. As the the role of biochar in sustainable forestry systems continues to evolve, an understanding of its impacts on soil structure and aggregation stability will be essential for informed decision-making.

Table 2 Biochars applications on soil attributes and tree-based crops

Biochar feedstock	Production	Amount added	Soil type	Location	Effects on soil	Tree crop	Effects on tree crop	References
Sewage sludge (biosolids)	Thermal degradation of biosolids through pyrolysis	20 to 80 Mg ha^{-1}	Loamy, kaolinitic, thermic Grossarenic Kandiudults (Soil Survey Staff)	North Florida Research and Education Center, Quincy, Florida	Sewage sludge-derived biochar performed better than the raw organic amendment as a soil conditioner	*Eucalyptus grandis* W. Hill ex Maiden	Improved seedlings' quality, growth, and morphological traits of the Eucalyptus seedlings (20 to 40 Mg ha^{-1}) and increased plant height by 35% (80 Mg ha^{-1}) after 60 days of cultivation	Gonzaga et al. (2018)
Wood chips and rice husk	Wood roaster carbonization at 200 to 250 °C	20% (volume basis)	*Not mentioned*	Chungnam National University, Daejeon, South Korea (36° 22′ N, 127° 21′ E)	Improved soil quality	*Zelkova serrata*	Improved several parameters of tree growth in nursery system	Cho et al. (2017)
Sawdust from native species obtained from timber industries (activated biochar)	Slow pyrolysis at 650 °C	25 to 100% (volume basis)	*NA*	Sinop, Mato Grosso, Brazil (11° 52′ 23″ South, 55° 29′ 54″ West)	*NA*: substrates were used instead of soil. The activated biochar (AB) substrate demonstrated better results on biometric variables of the tree crop	*Eucalyptus urophylla × E. grandis*	Biometric values such as plant height, stem diameter, leaf number and Dickson Quality Index (DQI), fresh and dry biomass accumulation, and nutrient concentration in the aerial part were improved at 90 days after staking	Barros et al. (2019)
Biochars produced from several feedstocks comprised the meta-analysis	Several production process comprised the meta-analysis	Several rates comprised the meta-analysis	*NA*	*NA*	Biochar-amended soils showed contrasting results from meta-analysis and might not be effective in all systems	Several woody plants comprised the meta-analysis	Positive effects of biochar on woody plant biomass	Juno and Ibáñez (2021)
Macadamia nut shells	Highest temperature treatment (HTT) of 450–480 °C	(0–100 Mg ha^{-1})	Brown Dermosol (Australian Soil Classification system)	Horticultural Research Centre at the Sandy Bay Campus of the University of Tasmania; and Florentine Valley, South-West Tasmania (42° 38′ S, 146° 27′ E; Forestry Tasmania coupe FO031Z)	Soil potassium (K), sodium (Na), and nitrogen (N) contents increased in response to biochar treatments while calcium (Ca), magnesium (Mg), and manganese (Mn) decreased	*Eucalyptus nitens*	Seedling growth did not reveal clear trends in response to biochar application	Wrobel-Tobiszewska et al. (2016)

Table 2 (continued)

Biochar feedstock	Production	Amount added	Soil type	Location	Effects on soil	Tree crop	Effects on tree crop	References
Wood	Pyrolysis under several batch technologies	Up to 2.75 Mg ha^{-1}	Several	Florida, USA	Carbon (C) sequestration effectiveness in the long-term	*Eucalyptus* spp.	Cost of C sequestration in *Eucalyptus* is around $5 per mt of biochar added per ha	Rockwood et al. (2020)
Rubber wood	Retort method (furnace temperature at ≥ 600 °C)	0, 1 and 2% (w/w)	Ultisol, *Agalawatta* series (Typic Hapludults)	Dartonfield Estate (N 6° 30.278′ and E 80° 10.091′), Agalawatta, Rubber Research Institute of Sri Lanka	Soil pH increase from 5.3 to 6.3 and to 6.6 with, respectively, 1% and 2% biochar application	*Hevea brasiliensis*	Aboveground dry matter accumulation increased by 81%; combined application of biochar + N and Mg fertilizers increased N, P, Mg and Ca uptake by plants	Dharmakeerthi et al. (2012)
Eucalyptus wood	Slow pyrolysis at 400 °C and 600 °C for 150 min	0.5, 1, 2, and 5% (w/w)	Multimetal (Cr, Zn, Ni, and Co) Contaminated Soil (Study area: *Bera* project)	Longitude 86° 25′49.41″ E and latitude 23° 45′41.82″ N, Bastacolla, Dhanbad district, Jharkhand, India	Up to 5% of biochar loading increased cation exchange capacity (CEC), pH, available nutrients, organic matter (OM), enzymatic activity, and decreased metals phytoavailability	*Acacia auriculiformis*	Combined application of biochar and fertilizer substantially reduced metal toxicity and water stress in plants	Chandra et al. (2022)
Wheat (*Triticum* L.) straw	Continuous carbonizer at 600 ℃ for 3 h	20 t hm^{-2}	Acidic Metabolic Red Soil	Nanning, Guangxi, China (107° 45′ 108° 51′ E, 22° 13′ 23° 32′ N)	Maintenance of soil sustainability in Eucalyptus plantations	*Eucalyptus* spp.	Increased soil N, K, and moisture level contributed to plant and microbial nutrients and water supply to improve *Eucalyptus* plantations outcomes	Ren et al. (2020)
Fresh sawdust of tropical native species	Slow pyrolysis at 650 °C	25 to 100% (volume basis)	*NA*	Sinop, Mato Grosso, Brazil (11° 52′ 23″ S, 55° 29′ 54″ W), 384 m altitude	Soil-based substrate demonstrated increased soil water retention capacity	*Tectona grandis*	Increased plant seedlings both for height and stem diameter, and provided growth performance comparable to a nursery substrate	Rezende et al. (2016)

Table 2 (continued)

Biochar feedstock	Production	Amount added	Soil type	Location	Effects on soil	Tree crop	Effects on tree crop	References
Wood from native savanna species	Brick kiln (traditional charcoal-making practice) with temperatures ranging from 200 °C to 500 °C under low oxygen	0 to 20% (volume basis)	Oxisol	Mato Grosso, Brazil (14° 41′ 44″ S and 52° 21′ 01″ W, 305 m a.s.l.)	Soil conditions were not improved, except by a possible effect of increased water holding capacity, due to a long-term effect only	*Hybrid Eucalyptus variety (Eucalyptus urophylla* S. T. Blake × *Eucalyptus grandis* W. Mill ex Maiden) and *T. vulgaris* L.G. Silva & H.C. Lima	Neither species responded to biochar application since it did not affect tree survival or productivity	de Farias et al. (2016)
Hornbeam wood chips	Slow pyrolysis at temperature range of 450–500 °C	0 to 30 g kg^{-1}	Clay loam soil	Agricultural and Natural Resources Research Center (ANRRC), northern Iran (37° 35′ N; 52° 02′ E, 25 m a-s-l.)	Alleviated the negative effects of water deficit, enhanced soil water retention, CEC, nutrient availability, and microbial activity	*Quercus castaneifolia* C.A.M	Improved the growth of *Q. castaneifolia* seedling by increasing photosynthesis, growth, and biomass of seedlings (at rate of 30 g kg^{-1})	Zoghi et al. (2019)
Mistletoe (*Loranthus europaeus*)	Electrical furnace at 550 °C for 4 h	0 to 30 g kg^{-1}	Medium texture soil	Research Nursery of the Forest Sciences Department of Ilam University, Iran	Amelioration of the soil water holding capacity and reduced loss and leaching of nutrients	Oak (*Quercus brantii* Lindl.)	Increased photosynthetic rate, photosynthetic pigments, leaf area and growth of oak seedlings	Heydari et al. (2023)
Acai fruit (*Euterpe oleracea*)	Pyrolysis	7.5% (w/w)	Amazon forest soil	Para state, Amazon forest, Brazil	Increased soil porosity, induced water and nutrients use efficiency by roots (vascular cylinder diameter increased by 52%)	*Eucalyptus urophylla*	Dry matter content of leaf, root, stem, total and stem diameter respectively increased by 67, 37, 90, 61 and 20%; plants photosynthetic machinery was stimulated	Melo et al. (2022)
Sewage sludge, orange bagasse, and coconut shell	Pyrolysis at process 400–500 °C for 2 h for sewage sludge biochar and 1 h for dry coconut shells and orange bagasse	0, 1, and 2% (w/w)	Red Yellow Argissolo (water resources digital atlas of sergipe state)	Universidade Federal de Sergipe, São Cristóvão, Sergipe, Brazil	Improved physical and chemical soil quality under formulated substrates	*Moringa oleifera* Lam	Promoted a better development of plant seedlings; increased shoot dry matter and improved seedling height and stem base diameter in 10.5 and 0.83 mm, respectively	Soares et al. (2019)

Table 2 (continued)

Biochar feedstock	Production	Amount added	Soil type	Location	Effects on soil	Tree crop	Effects on tree crop	References
Chicken manure and sawdust	Step-wise procedure under limited-oxygen conditions using a slow-pyrolysis reactor at 200 to 400 °C for 16 h	2.4 kg m^{-2}	Ultisol	Forest at Liujiazhan Town (116° 56 E, 28° 12′ N), Yingtan City, Jiangxi Province, China	Increased soil pH, total N, total P, total K, available phosphorus (P) and K	*Pinus elliottii*	Chicken manure biochar increased net primary production of tree plant by ~ 180%, fertilizer nitrogen use efficiency, and was more efficient for tree C fixation	Lin et al. (2017)
Myscanthus sp.	Pyrolysis at 450 °C	3.5, 10, and 20 Mg ha^{-1}	Typic Udorthent (Soil Survey Staff)	Atlantic side of the Basque country (northern Iberian Peninsula)	Increased soil organic carbon (SOC) stocks	Mature *Pinus radiata* and young *Quercus pyrenaica*	Nickel (Ni) uptake increased in biomass of the *Pinus radiata*; increased K uptake by *Quercus pyrenaica*	Moragues-Saitua et al. (2023)
Wood residues of *Acacia mangium* Willd	Slow pyrolysis with residence burning times from 11 to 14 h at temperatures between 350° C and 400° C	0, 40, and 80 Mg ha^{-1}	Oxisol	Planas, department of Meta, Colombia (4° 05′–5° 08′ N, and between 74° 05′ and 73° 30′ W)	Increased CEC, N, soil organic matter (SOM), carbon (SOC), did not change pH and levels of calcium (Ca) and K	*Acacia mangium* Willd	Good seedling quality was assured; increased uptake of Ca and K by plants; and 130% + increase in the Dickson index (DQI) was observed	Moreno et al. (2021)
Biochar produced from several feedstocks	Pyrolysis	*NA*	Several	Boreal, temperate, and tropical forests	Restored forest soil health, enhanced CEC, SOM, and water infiltration	Several species of boreal, temperate, and tropical forests	Mitigate climate change and potentially increase productivity, particularly on marginal land	Bruckman and Pumpanen (2019)
Spruce	Slow pyrolysis at 650 °C	0, 5, and 10 Mg ha^{-1}	Haplic podzol (IUSS Working Group WRB)	Juupajoki, close to Hyytiälä Forestry Field Station (61° 51′ N, 24° 17′ E, 181 m above sea level), Southern Finland	Increased soil C stocks, soil available N, and NUE by forest trees	Young boreal Scots pine (*Pinus sylvestris* L.) forests	Increased tree biomass production; increased the diameter growth of dominant trees by 25% and the height growth by 12% in a three-year study	Palviainen et al. (2020)

NA not applicable

5.2 Increasing water retention and drought tolerance

Water scarcity and drought stress continue to pose significant challenges to global agriculture and silviculture, especially in regions where tree crops are cultivated (Albaugh et al. 2013; Little et al. 2009). Innovative approaches are needed to enhance soil water retention and improve drought tolerance in these crucial agricultural/forestry systems. Biochar has a promising role in addressing these challenges. Given the high capacity of biochar to absorb and hold water, it maintains the soil moisture levels for longer period, especially in dry areas. Additionally, the porous structure of biochar supports water regulation within the soil profile (Fellet et al. 2011). Hence, biochar-amended soils may show improved drainage properties, preventing waterlogging.

Studies have consistently demonstrated that biochar-amended soils exhibit higher plant available water due to the porous nature and high surface area of biochar particles (Atkinson et al. 2010; Graber et al. 2010; Leng et al. 2021). These porous structures facilitate water infiltration and reduce evaporation rates, leading to increased availability of soil moisture for tree crop roots during dry periods. Research by Zhang et al. (2021a) confirmed the positive impact of biochar on soil water retention. In the authors' scenario, biochar (produced from the Pacific Northwest timber harvesting residues) raised plant-available water with increased application rates, the effect of which was especially evident in silt loam soil for absolute increases and in sandy soil for relative changes. Curiously, biochar particle size had a limited effect on gravimetric plant-available water yet affected volumetric content in silt loam and clay soils, not in sand soil (Zhang et al. 2021a). Hence, the effects of biochar on plant-available water hinge on soil texture and biochar particle size.

In terms of improved drought tolerance, several mechanisms are involved. As mentioned, the porous structure of biochar acts as a reservoir for water, ensuring a steady supply of water to plant roots during drought stress (Agegnehu et al. 2016). Additionally, biochar promotes the development of a more extensive and efficient root system, allowing plants to explore deeper soil layers for water sources (Rajkovich et al. 2012). Furthermore, the positive impact of biochar on soil microbial communities enhances nutrient cycling and facilitates plant stress responses, ultimately aiding tree crops in coping with water scarcity (Lehmann et al. 2011).

Other studies conducted in various agroecosystems have consistently supported the positive effects of biochar on soil water retention and drought tolerance in tree crops, as highlighted by Deng et al. (2017). For instance, Guo et al. (2022) demonstrated that biochar-amended soils in a citrus (*Citrus* spp.) orchard exhibited increased soil moisture, reduced soil moisture fluctuations, and enhanced tree growth during drought periods. Similarly, Jeffery et al. (2011) reported increased survival rates and growth of tree seedlings in biochar-amended soils subjected to water stress in a reforestation context.

This optimistic response to enhanced tree adaptation for coping with drought stress is a recurring phenomenon within urban settings (Somerville et al. 2019). Numerous other studies underline the significance of such adaptations amid water scarcity. For instance, in Canada, Robertson et al. (2012) conducted a study that demonstrated the beneficial impact of biochar on the initial growth phases of tree seedlings. Their findings revealed that pine [*Pinus contorta* (Douglas)] and sitka alder (*Alnus viridis* spp. sinuata) seedlings exhibited greater biomass in biochar-treated conditions. Similarly, in Finland, Palviainen et al. (2020) documented elevated height and diameter growth in Scots pine (*Pinus sylvestris* L.) with the implementation of biochar treatments (Table 2). Furthermore, the work of Somerville et al. (2019) highlighted the augmentative effects of biochar and/or compost on the growth of spotted gum (*Eucalyptus maculata* Hook) within urban areas, particularly in the warm temperate climate of Australia. Finally, biochar amendments led to increased tree growth in secondary forests shading non-timber forest product (NTFP) plantations of *Ocotea quixos* (Lauraceae), *Myroxylon balsamum* (Fabaceae), and their mixture. Specifically, plots amended with kiln biochar exhibited a 29 ± 12% increase in aboveground biomass, while those with traditional mound biochar showed a 23 ± 9% increase compared to control plots (Ríos Guayasamín et al. 2023).

5.3 Enhancing nutrient availability and soil physicochemical properties

The presence of water-soluble minerals in crop-, weed-, and tree-derived biochars suggests its potential as a valuable source of plant nutrients (Das et al. 2021). Das et al. (2021) demonstrated that such green waste-derived biochars are rich in essential micronutrients, such as iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn), which can serve as readily available nutrients for plants in nutrient-deficient soils. Additionally, those biochars also contain significant amounts of P and calcium (Ca), macronutrients that can be utilized for the reclamation of acidic soils, according to the authors. Biochar, given its organic properties, also increases soil available nutrients to trees indirectly because of its behavior as a slow-release fertilizer, releasing nutrients over time. Initially, biochar binds nutrients until it reaches its maximum adsorption capacity, after which it gradually releases them into the soil solution for plant uptake (Hossain et al. 2020). In forest soil, it is known that soil fertility remains high due to the continuous deposition of tree leaves and the favorable conditions for soil microorganisms (Kyaschenko et al. 2017). However, with the ability of biochar to improve the soil nutrients retention, leaching losses are prevented and nutrients are made more available to plants and microorganisms.

The biochar properties can influence its ability to adsorb and retain nutrients in the soil. The impact of biochar on nutrient availability in root zones of tree crops is complex and depends on factors beyond the biochar type, including soil categories, application rate, and tree species. Many studies have found that biochar exhibits the capacity to increase the retention of essential nutrients, notably nitrogen (N), P, and K, within the soil matrix, thereby mitigating nutrient losses through leaching. The work of Zoghi et al. (2019) revealed that increased rates of hornbeam wood chips-derived biochar increased the N, P, and K availability to *Quercus castaneifolia*, and that was accompanied by the increase in the soil CEC (Fig. 4). Nutrient retention is indeed facilitated by the high CEC of biochar, which enables the sequestration and gradual release of cations such as Ca, magnesium (Mg), and K, consequently providing an extended nutrient reservoir for the benefit of tree crops. Additionally, the potential of biochar to influence soil pH towards neutrality is a critical mechanism that affects the solubility and subsequent availability of nutrients to tree crops.

The positive influence of biochar extends to the domain of micronutrients, where it may enhance the availability of essential elements such as Fe, Zn, and Mn. Yadav and Solanki (2015) asserted that micronutrients are poised to assume a pivotal role in supporting both the productivity and quality of the production system over the forthcoming decades, with a particular focus on tropical fruits. These micronutrients exist in two primary forms: non-chelated (sulfate) and chelated. The chelated forms, where biochar predominantly contributes to improving their availability, represent intricate compounds where specific cations form complex bonds with organic molecules. An additional mechanism through which biochar influences micronutrient availability is by elevating the levels of dissolved organic matter (DOM) within the soil (Hartley et al. 2016). This augmented DOM can effectively serve as a chelating agent for micronutrients, rendering them more accessible to tree crops.

The response of tree crops to biochar application varies based on species, age, and specific growing conditions. Some tree crops, such as fruit trees, have shown positive responses to biochar in terms of growth, yield, and fruit quality (Table 2). The response of biochar to soil nutrient status and citrus fruit quality has been evaluated by Zhang et al. (2021b). The authors proved that soil physicochemical properties, such as pH, organic matter, nutrient contents, had positive responses to biochar application, which was reflected in favorable citrus fruit indexes, such as peel, edibility, soluble solid-to-titratable acidity ratio, and soluble solids. Sarauer et al. (2019) found no impact on tree growth after applying biochar at a rate of 25 Mg ha^{-1} to forest soil in the northwestern United States. On the other hand, biochar was effective in soil carbon sequestration and had no negative impact on soil and plants (Sarauer et al. 2019). Soil type and texture must also be considered in the decision-making process. According to Alkharabsheh et al. (2021), biochar amendments have a greater potential to enhance crop productivity in coarse-textured and sandy soils than in fine-textured, fertile soils. This is likely because the low

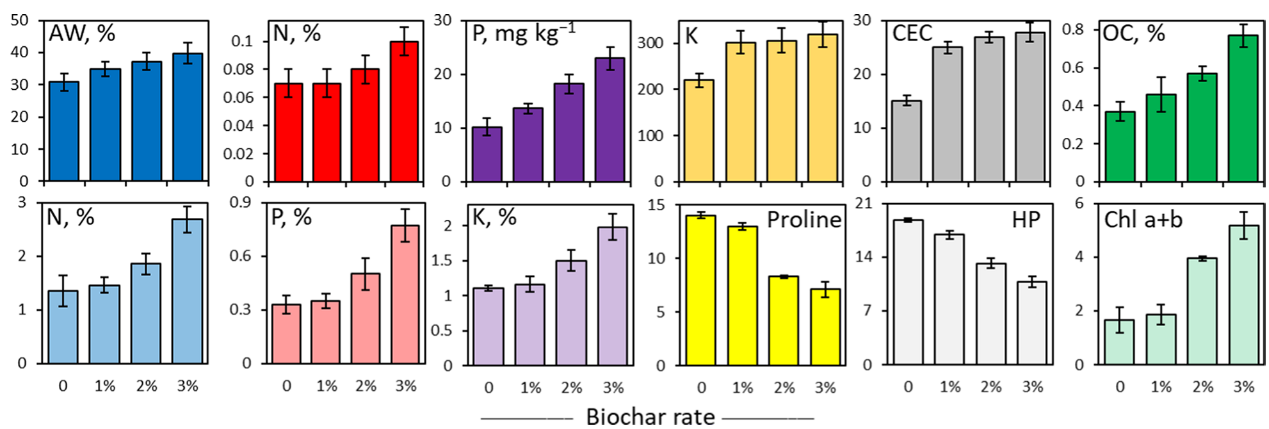


Fig. 4 Increased biochar application increases soil physicochemical attributes (top), nutrient contents in plant tissues and chlorophyll, and decreases stress indicators (Proline and HP, μmol g^{-1}) in tree plants (bottom). AW: available water. N: nitrogen. P: phosphorus. K: potassium, mg kg^{-1} (soil). CEC: cation exchange capacity, meq. 100 g^{-1}. OC: organic carbon. HP: hydrogen peroxide. Chl a+b: chlorophyll a+b, mg g^{-1}. Bars are the standard error of the mean. Graphs were created from the work reported by Zoghi et al. (2019), using hornbeam wood chips-derived biochar and cultivating *Quercus castaneifolia*

CEC, water and nutrient retention are not limiting factors in heavy-textured (clayey) soils. As a result, biochar is expected to have a more pronounced positive effect in coarse-textured soils.

These findings collectively underscore the intricate interplay between biochar and nutrient dynamics, emphasizing the need for tailored approaches contingent upon various environmental and crop-specific factors for maximizing the benefits of biochar in tree crop management. The enhanced soil nutrient availability facilitated by the application of biochar is intricately linked to the promotion of beneficial microbial activity and the suppression of diseases in tree crops. This highlights the significance of biochar as a valuable tool in sustainable agriculture and agroforestry practices.

5.4 Influencing microbial activity

Biochar offers significant advantages in enhancing soil microbial activity and benefiting tree crop production in amended soils (Mitchell et al. 2016). Because it creates a favorable environment for microbial communities, the positive effects of biochar on plant performance have been associated with increased bacterial diversity in the rhizosphere, as well as improved utilization rates of carbohydrates and phenolic compounds (Kolton et al. 2017). The porous structure of biochar provides a stable and hospitable habitat for soil microorganisms (Domene et al. 2014), protecting them from environmental stresses and predators. Additionally, the ability of biochar to improve soil structure, including aeration and moisture retention, fosters a more conducive environment for microbial growth (Zhu et al. 2017). Aerobic microbes play an important role of nutrient cycle in soil and root zone. Biochar applied in soil enhances aeration and alleviates anaerobic conditions, therefore, promoting aerobic microbial activity in the rhizosphere. The study by Mitchell et al. (2016), performed in a controlled environment, supported that the changes in microbial activity and soil organic matter (SOM) composition from a temperate forest soil were more distinct from the control at the two highest biochar concentrations, suggesting that these responses are dependent on the biochar application rate. The authors also emphasized that future work should investigate whether native SOM composition is altered during biochar amendment at the field scale under the influence of factors such as climate, vegetation inputs, and soil biota.

Zhang et al. (2021b) assessed the impact of wheat straw-derived biochar on microbial communities in citrus production soils. Biochar enhanced soil bacteria's richness, evenness, and diversity, while slightly reducing fungal evenness. Bacteria's pivotal role in the metabolic environment of soil was evident, with all biochar treatments enriching beneficial bacteria. Additionally, the proliferation of nutrient-cycling saprophytic fungi enriched post-biochar application, underscoring the holistic benefits of biochar integration. Zhang et al. (2021b) also observed that the bacteria, which were primarily enriched in both shallow and deep soil layers, underwent a shift in community composition from the *Proteobacteria* phylum to *Acidobacteria* and *Chloroflexi* after biochar application. This transformation was likely driven by changes in soil pH, nutrient availability, and microbial habitat conditions induced by biochar. This shift accentuates an augmentation in biodiversity. In addition to the *Acidobacteria* playing a crucial role in the soil carbon cycle, notably in the breakdown of plant residues (Eichorst et al. 2007), some species of *Chloroflexi* are engaged in mercury (Hg) methylation, chemical oxygen demand reduction, and naphthalene removal (Azaroff et al. 2020). However, additional research is still indispensable for the optimization of biochar application methodologies, dosages, and their alignment with varying tree species and soil profiles. For example, Noyce et al. (2015) concluded that the addition of biochar at a rate of 5 Mg ha^{-1} exerts neutral effects on soil microbial communities within a northern hardwood forest environment characterized by acidic soils. Their findings suggest that biochar applications can serve as a viable strategy for carbon sequestration without imposing detrimental impacts on the soil microbial community dynamics. In a boreal pine forest study, biochar produced at 500 °C reduced the abundance of *Actinobacteria* and *Verrucomicrobia*, while biochar produced at 650 °C increased the abundance of *Conexibacter* and *Phenylobacterium* (Ge et al. 2022). At the higher production temperature (650 °C), application rate of 0.5 kg m^{-2} resulted in a greater abundance of *Cyanobacteria*, *Conexibacter*, and *Phenylobacterium* compared to the 1 kg m^{-2} rate. These findings suggest that biochar application influences the relative abundance of specific bacterial groups, such as *Actinobacteria*, *Verrucomicrobia*, and *Cyanobacteria*, potentially impacting nutrient cycling in boreal pine forests (Ge et al. 2022). The authors emphasize the need for long-term field monitoring to understand the sustained effects of biochar on microbial communities, given the stability and persistence of biochar in soil.

Biochar demonstrates a noteworthy ability to act as a pH amendment in soil, effectively optimizing pH levels within the range favorable for microbial communities (Maestrini et al. 2014; Sheng et al. 2016; Sheng and Zhu 2018). This pH-regulating capacity arises from the inherent alkalinity of biochar. This, in turn, fosters a discernible increase in the population of gram-negative bacteria, alongside a concurrent decrease in the proportions of gram-positive bacteria and fungi, as documented in the studies of Pietri and Brookes (2009) and Rousk et al.

(2009). Biochar derived from softwood chips raised soil pH and exchangeable cations in two sub-boreal forest soils underneath pine (*Pinus contorta* var. latifolia) or sitka alder (*Alnus viridis* ssp. sinuata) cultivation (Robertson et al. 2012). Such enhancement on soil fertility was responsible for increasing the abundance of ectomycorrhizal morphotypes, which in turn provided greater biomass of pine. However, when biochar is applied to calcareous alkaline soils in arid regions, the effect may be minimal on soil pH or even counterproductive, as the inherited high soil pH could limit the ability of biochar to further increase pH.

The capability of biochar to increase soil microbial activity leads to improved nutrient cycling and soil health. As afore mentioned, biochar functions as a nutrient retention and recycling agent, adsorbing and gradually releasing essential nutrients like NPK, which benefits tree crops through efficient nutrient cycling (Frąc et al. 2023), thus enhancing soil fertility. This stable organic carbon source, provided by biochar, also serves as a substrate for soil microorganisms, stimulating their activity, which in turn will contribute to soil nutrient recycling. The erosion-reducing properties, enhanced water retention capacity, and potential for suppressing soil pathogens of biochar further contribute to its beneficial impact on tree crop production.

5.5 Reducing pests and diseases

The well-being of trees in various ecosystems is constantly threatened by the detrimental effects of pests and diseases. These challenges often lead to reduced growth, diminished vitality, and even the death of trees, causing significant ecological and economic losses. As traditional chemical-based approaches of controlling pests and diseases raise concerns about environmental impact and long-term sustainability, seeking for alternative solutions has become new focus by researchers. Biochar has emerged as a promising tool due to its ability to suppress the growth of pathogens (Zhang et al. 2021b). The anti-pathogenic properties of biochar can be attributed to its complex physical and chemical characteristics such as high surface area, porous structure, and the presence of functional groups which render biochar the capability of adsorbing and immobilizing a wide range of pathogens (Jaiswal et al. 2018). Additionally, biochar exhibits a highly alkaline pH, which can be unfavorable for the growth of many harmful microbial species. These attributes collectively lead to the potential of biochar in mitigating pest and disease pressures in trees.

The mechanisms behind the ability of biochar to suppress the growth of pathogens are worth investigating. The adsorption of pathogens on to the surface of biochar limits their movement and access to the host trees, therefore reducing infection rates. In contrast, as recently stated by Zhang et al. (2021b), the soil without biochar treatment originally contains harmful pathogenic fungi, such as the species of the *Ophiostomatales* order in shallow soil and the species of the *Ophiostomataceae* family in deep soil, and both are hazardous to citrus production (Veilleux et al. 2020).

Beyond its direct anti-pathogenic properties, biochar has been shown to enhance nutrient retention and availability in soils, as previously elucidated. This can lead to improved tree vigor, allowing trees to better withstand pathogenic attacks. Zoghi et al. (2019) exemplifies the role of biochar in promoting nutrient uptake and increasing overall plant health (Fig. 4 and Table 2). The increased biochar application improved soil quality, enhanced nutrient availability, and boosted plant health by retaining water, improving soil structure, increasing nutrient retention, and promoting chlorophyl-II production which, in turn, reduced plant stress indicators (Zoghi et al. 2019). It is then assumed that such improvements collectively suppress pathogens and diseases through altered microbial communities, increased soil pH, and induced systemic resistance, bolstering plant defense mechanisms. However, proper integration with other agricultural/silvicultural practices is crucial, and local conditions should guide biochar application rates for optimal results.

Utilizing biochar for pest and disease management aligns with sustainable agricultural and forestry practices. Unlike conventional chemical treatments, biochar is a renewable resource and can be produced from various organic materials, including agricultural wood and crop residues, agro-industrial co-/by-products, animal manure, municipal solid wastes, etc. (Karthik et al. 2020). Furthermore, the incorporation of biochar into soil systems can contribute to carbon sequestration and soil fertility enhancement, providing additional ecological benefits. The anti-pathogenic properties of biochar offer a promising path for minimizing the incidence of pests and diseases in trees. Its abilities to suppress pathogen growth, enhance nutrient availability, and contribute to overall tree vigor make it a valuable tool in sustainable pest and disease management strategies. However, as previously mentioned, further research is needed to optimize biochar application methods, dosages, and their compatibility with different tree species and soil types. As we move towards more environmentally conscious approaches to agriculture and forestry, biochar stands out as a multifaceted solution with the potential to revolutionize pest and disease management in trees.

5.6 Carbon sequestration and climate change

Strategies for carbon stock have been adopted in the face of climate change and the biochar applications in soil can be an interesting solution in the short- and medium-term. Biochar increases the soil organic carbon (SOC), promotes beneficial interactions among soil microbial communities, improves soil quality and increases water and nutrient retention capacity (Jeffery et al. 2011; Zhang et al. 2021b). These benefits not only increase agricultural productivity, but also give ecosystems resilience, especially in the face of climate change. Previous works demonstrated an average increase in SOC stocks via biochar application between 11.5–14.6 Mg ha^{-1} (26–33% of relative increase) (Gross et al. 2021; Luo et al. 2023). The stability of biochar not only supports carbon storage but also delivers ecosystem-level benefits. For instance, biochar application in forest plantations, such as *Eucalyptus*, has been shown to enhance carbon sequestration both above and below ground, improving tree growth and survival rates (Rockwood et al. 2020; Xu et al. 2020). Similarly, its use in Moso bamboo forests has increased ecosystem carbon sequestration by enhancing soil and vegetation carbon stocks, while reducing non-CO_2 greenhouse gas emissions (Xu et al. 2020). Ohtsuka et al. (2021) proposed that the application of biochar could potentially enhance carbon sequestration in oak forests under field conditions, particularly with a dosage of 10 Mg ha^{-1}.

Wood-derived biochar offers dual benefits, serving as both a soil amendment and a long-term carbon sequestration strategy. In forest plantations, its application has been shown to promote more robust tree growth and improve survival rates, as demonstrated by Grau-Andrés et al. (2021). Rockwood et al. (2020) investigated the effects of wood-derived biochar, both alone and in combination with other fertilizers, on the performance of forest and agronomic crops in Florida, USA. Their findings highlighted the economic feasibility of applying biochar in *Eucalyptus* plantations, estimating carbon sequestration at 2.5 g C ha^{-1}, with costs ranging from \$3.30 to \$5.49 per Mg of carbon sequestered.

Díaz et al. (2024) revised different co-products from thermochemical technologies (such as, gasification, pyrolysis, and hydrothermal carbonization), and suggested that 75% of pyrochar (char from pyrolysis) can remain unmineralized for over 100 years thereby improving SOC stocks. The same authors explained that resistant carbon undergoes chemical alterations during thermochemical processes into various aromatic groups and, in contrast, biochemical processes selectively eliminate the labile carbon from the biomass, leaving the recalcitrant fraction unchanged compared to the original raw material (Uchimiya et al. 2013). This increases the stability of organic carbon in the soil, reducing carbon cycle to the atmosphere, thus contributing to climate change mitigation. The proximate analysis of biochar, characterized by a higher fixed carbon content than its raw material, suggests a greater potential of resistance to degradation, making it a promising option for climate change mitigation (Li and Tasnady 2023). Wood-based biochar holds a slight advantage over other biochar and is recommended for this carbon sequestration purpose.

Although the mechanisms of interaction between biochar and soil still need further clarification, the use of biochar as an interesting alternative for combating climate change has been evident. Woolf et al. (2010) illustrated that the sustainable production of biochar, coupled with its incorporation into soils, has potential to avoid emissions of the order of 1.8 Pg CO_2-C equivalent annually over the century, possessing the technical capability to significantly contribute to the goals of abating climate change. Application in apple orchards has also been found to reduce greenhouse gas emissions, mitigate climate change impacts, and decrease net global warming potential by increasing soil organic carbon stocks (Han et al. 2021a, b).

Numerous empirical inquiries have delved into the ramifications of biochar incorporation on soil carbon sequestration in forestry contexts. Examples include a global review by Jeffery et al. (2017) who furnished additional evidence affirming the favorable impact of biochar on soil carbon sequestration. In agricultural settings, the sequestration potential of biochar varies with soil texture and composition. Medium- to fine-grain textured soils with higher C/N ratios exhibit greater increases in carbon storage compared to coarse-grain soils (Gross et al. 2021). In urban environments, biochar amendments improve soil quality, facilitate CO_2 sequestration, and enhance plant responses to environmental constraints, making it a sustainable strategy for successful tree establishment (Piccolo et al. 2022).

The existing literature deliberates on the potential of biochar in contribution of climate change mitigation when implemented in forestry systems. With respect to the nexus between biochar and nitrous oxide emissions, Spokas et al. (2009) underscored the role of biochar in curtailing such emissions, thereby fortifying its stature as a potential viable strategy for climate change mitigation. A long-term study by Cui et al. (2021) illuminated that while biochar exhibited no statistically significant impact on the overall global warming potential of forest soil, it demonstrated potential of alleviating climate change through a notable 26% increase in soil carbon content in the presence of litter. According to the authors, biochar application was observed to augment soil available P and dissolved organic carbon (DOC) concentrations, alongside fostering an increase in soil microbial biomass, particularly under warmer environmental conditions. The findings presented by Gundale et al. (2015) emphasized the potential efficacy of biochar application in boreal forest ecosystems for both carbon sequestration and augmentation of available ammonium (NH_4^+) in soil.

Interactions of biochar with soil microbial processes also play a critical role in carbon dynamics. While long-term biochar addition can increase ligninase activity, facilitating the breakdown of recalcitrant carbon compounds, it may suppress cellulase activity, potentially limiting the persistence of sequestered carbon in the soil (Feng et al. 2023). Additionally, biochar has been suggested to be more efficient for soil carbon sequestration compared to crop residues, although it may not always be the most cost-effective approach (Majumder et al. 2019). Despite these promising findings, the long-term effects of biochar on soil biological processes and organisms remain underexplored. Improved standards, comprehensive assessments, and long-term field studies are needed to fully understand and maximize its benefits for carbon sequestration, greenhouse gas mitigation, and soil improvement (Kuppusamy et al. 2016; Luo et al. 2023). To date, the overwhelmingly extant literature posits that biochar application in forestry systems holds promise for enhancing soil carbon sequestration, fostering tree growth, and substantively contributing to climate change mitigation.

6 Potential risks of biochar for soil health and tree crops

The overall literature reviewed suggests that biochar can be an important soil ameliorator beneficial for tree crops as illustrated in Fig. 5. However, everything has two sides, so it is important to use it carefully and to be aware of the potential risks, as discussed in the following sections.

6.1 Excessive elevation of soil pH

Biochar produced from pyrolysis is generally characterized by its alkaline mineral content and elevated pH, making it a valuable tool for ameliorating soil acidity when introduced to low-pH soils. This alkalinity is primarily attributed to the presence of surface organic groups, soluble organic compounds, carbonates, and inorganic alkalis including oxides and hydroxides (Fidel et al. 2017). The capacity of biochar to neutralize soil acidity proves beneficial in enhancing nutrient availability within acid soils (Laird et al. 2010). However, it is important to recognize that different crops have specific pH requirements for optimal growth. For tree crops, maintaining a slightly acid to neutral pH range, typically around 6.0 to 7.0, is essential (Marinari et al. 2000). Deviations from these pH levels, leading to excessive alkalinity, may pose a threat to tree crop cultivation. The work of Scharenbroch et al. (2013) pointed out that tree sapling (*Acer saccharum* and *Gleditsia triacanthos*) growth was favored when biosolids were applied as it decreased soil pH, enhanced available N, N mineralization, and microbial respiration, in

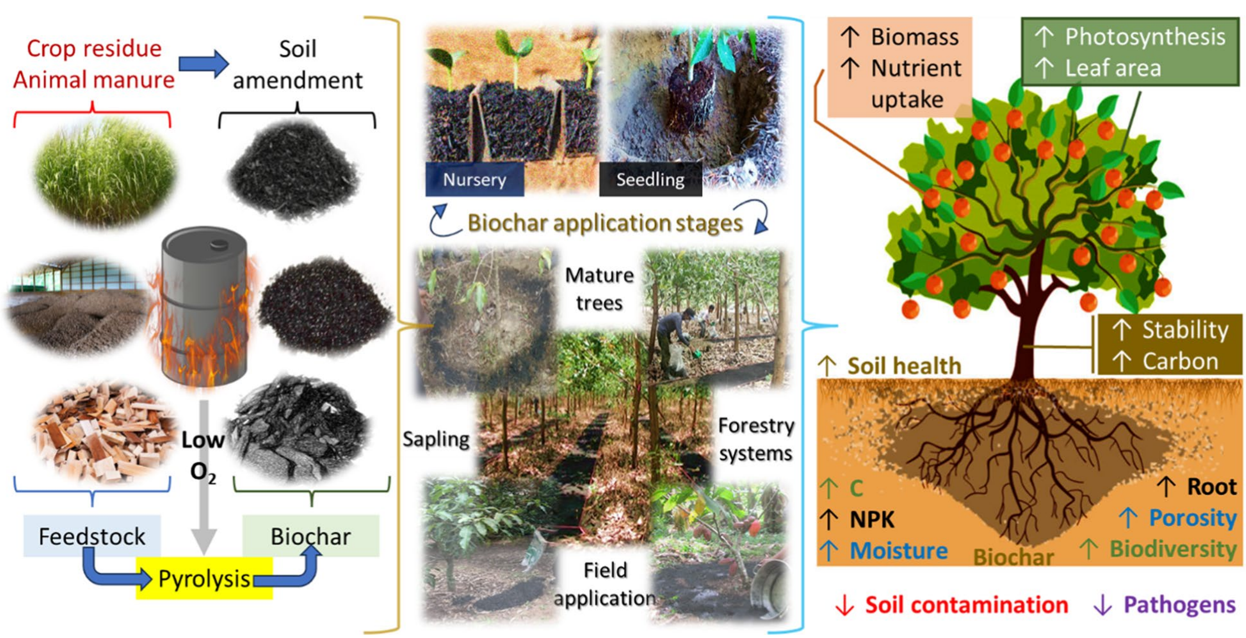


Fig. 5 Illustration depicting the path from pyrolysis feedstock selection and biochar production to its application in various stages of tree crops within forestry systems, showcasing benefits to soil quality, ecological parameters, carbon stock, and forest crop development

comparison to the scenario when biochar derived from pine feedstock was applied.

The study conducted by Gao et al. (2020) has provided valuable insights into the complex relationship between biochar applications, soil acidity, water use efficiency (WUE), plant water use efficiency (PWUE), and leaf water use efficiency (LWUE). First, it is worth understanding that WUE is a general measure of how effectively water is utilized in a given system, expressed as the ratio of output to water input; PWUE narrows this focus to assess the efficiency of water use specifically in plants, calculated as the ratio of plant output to water consumed; and LWUE delves further into the plant level, examining how efficiently leaves use water during photosynthesis, determined by the ratio of photosynthetic rate to transpiration rate. The authors revealed that the introduction of biochar to acid soils leads to an overall enhancement of WUE, primarily attributed to the liming effect of biochar. However, it is noteworthy that this increase in WUE is not mirrored by a significant improvement in PWUE. Conversely, in alkaline soils, the incorporation of alkaline biochar triggers stronger sodium (Na) toxicity effects and ammonia (NH_3) volatilization, resulting in a notable increase in PWUE (Gao et al. 2020). However, this positive effect on PWUE is counterbalanced by a decline in LWUE. This intricate mechanism has been aptly termed by the authors as 'the addition of alkaline biochar to alkaline soils'. Their findings highlighted the importance of recognizing that the pH of biochar alone cannot serve as a straightforward indicator to predict WUE responses, particularly when it results in an excessive elevation of soil pH.

The non-desired initial properties of biochar could be addressed by processing and modifying the biochar. For example, chemically engineered biochar treated with 0.1–1.0 M NaOH increases surface area and pore volume, while acidic modifiers enhance the presence of acidic functional groups (Boguta et al. 2019). However, the pH may either decrease or increase, necessitating a balance between optimal chemical properties and safe usage (Boguta et al. 2019). To effectively manage and mitigate the risks associated with excessive pH increases linked to biochar, careful selection of biochar with low alkalinity and adherence to the specific pH requirements of tree crops is indispensable. Incorporating biochar in combination with other organic materials and implementing regular soil pH monitoring can be effective strategies for addressing these concerns (Gai et al. 2014). Additionally, it is crucial to consider the interactions among biochar type, initial soil pH, and the species of tree crops involved, as these factors can influence the impact of biochar applications. Local soil variations and the preferences of specific tree crops should be considered when contemplating biochar utilization.

6.2 Immobilization of soil essential nutrients

While biochar is acknowledged for its capacity to improve soil fertility and nutrient retention, concerns have emerged regarding its ability to immobilize essential nutrients (Joseph et al. 2021; Ndoung et al. 2021; Zulfiqar et al. 2022), potentially making them less available to tree crops. Therefore, its capacity to immobilize essential nutrients, including N, P, and K, has raised questions regarding its impact on tree crop growth.

Highly reactive surface functional groups in biochar will bind to soil essential nutrients, making them unavailable to trees. This can be aggravated if biochar is over-applied. In a recent study, Slesak and Windmuller-Campione (2024) investigated the impact of biochar application combined with periodic irrigation on the growth of jack pine (*Pinus banksiana*) seedlings in the northern region of Minnesota, US. Their findings revealed that the sole application of biochar led to a reduction in leaf Ca concentration compared to treatments without biochar (Slesak and Windmuller-Campione 2024). This decrease is attributed to heightened nutrient immobilization, a phenomenon observed when biochar is applied independent of a nutrient source.

Additionally, excessive soil pH increments, primarily driven by biochar applications, can disrupt the soil chemical equilibrium and lead to imbalances in nutrient availability. In such conditions, certain micronutrients, such as Fe and Mn, tend to become less accessible to tree crops, potentially impacting their growth and productivity. The reduced sensitivity to low soil pH among some tree crops is due to their increased tolerance to aluminum (Al) toxicity compared to other crop varieties (Kochian et al. 2004). These tree crops favor the uptake of essential micronutrients that are more soluble at low pH, which is unfavored when biochar promotes soil pH increase. The average concentrations of Cu, Fe, boron (B), K, Mg, and P in peach tree leaves exhibited a notable decrease when biochar alone was applied, as opposed to the combined application of biochar and organic fertilizer (Frąc et al. 2023). A supportive study by Sifton et al. (2023) demonstrated that wood-derived biochar and organic fertilizer (biofertilizer) combinations enhanced growth and nutrient uptake in silver maple grown in an urban soil by effectively addressing issues of nutrient limitations of both macronutrients (N, P, K, Mg, and Ca), and micronutrients (B, Fe, Mn, Mo, Na, S, and Zn) (Sifton et al. 2023). This effect might be a consequence of chelates formed between micronutrients and DOM as promoted by the addition of organic fertilizers, making micronutrients more available even at a higher soil pH.

On the other hand, biochar only application can immobilize essential nutrients through several mechanisms. First, it exhibits a high CEC, allowing it to adsorb cations Ca and Mg, as well as other essential nutrients. Second, biochar can sorb soluble nutrients and promote their precipitation, leading to reduced nutrients availability. For instance, phosphate can form insoluble complexes with biochar, making P less accessible to plants. The P immobilization by biochar is through chemical interactions, such as precipitation with Ca and Al ions, as well as surface adsorption (Kochian et al. 2004). Third, biochar can modify the microbial community in the rhizosphere (Heydari et al. 2023; Ren et al. 2020), enriching microbiota that compete with tree crops for essential nutrients, thereby further diminishing nutrient availability.

The immobilization of essential nutrients by biochar can have diverse effects on tree crop growth. Some studies suggest that, under specific conditions, nutrient immobilization can lead to reduced growth and yields (Joseph et al. 2021; Ndoung et al. 2021; Zulfiqar et al. 2022). For instance, inadequate N availability can limit photosynthesis and overall tree health. On the contrary, biochar-induced nutrient immobilization may have positive effects in specific contexts. It can curtail nutrient leaching and enhance nutrient retention in the rhizosphere, potentially improving nutrient use efficiency in the long term.

In summary, the extent of nutrient immobilization by biochar is influenced by several factors. The type of feedstock used for biochar production can impact its nutrient immobilization potential. For example, biochar derived from manure may immobilize nutrients differently compared with biochar produced from wood. Additionally, the conditions during pyrolysis, including temperature, duration, and atmosphere, can alter biochar properties and its nutrient immobilization potential. The properties of the soil itself, such as pH, organic matter content, and nutrient levels, play a significant role in the interaction between biochar and nutrients. To mitigate the negative effects of nutrient immobilization by biochar, various strategies can be employed. One approach is to mix biochar with complementary amendments, such as nutrient-rich organic matter or fertilizers, to counteract nutrient immobilization effects. Selecting biochar types with low nutrient adsorption properties may also be beneficial for nutrient-rich soils. The timing of biochar application is crucial; applying it well in advance of planting or between cropping seasons allows for appropriate nutrient release from biochar.

6.3 Increasing risks of environmental contamination

The highly reactive surface of biochar is prone to be loaded with heavy metals and other pollutants. This can be a problem in forestry systems if the biochar is not properly produced or handled. As discussed, the reactivity of biochar is primarily determined by its surface area, porosity, functional groups, pH, CEC, etc. The pyrolysis conditions, feedstock type, and post-production treatments significantly affect these properties. In general, biochar produced at high temperatures and from feedstocks rich in lignin tend to have higher surface areas and more functional groups (Lehmann and Joseph 2015). These properties make biochar highly attractive for the adsorption of heavy metals and other pollutants.

Several mechanisms are involved with the reactivity of biochar with heavy metals. Physical adsorption, involving van der Waals forces and ion–dipole interactions, can occur on the surface of biochar due to its high surface area. Chemical adsorption may take place when functional groups like carboxylic and hydroxyl groups react with metal ions. Ion exchange and complexation reactions also play a role in binding heavy metals to biochar (Xiao et al. 2023). However, specific complexation reactions (i.e., formation of coordination bonds) between biochar and metal ions have not been elucidated. Overall, these mechanisms collectively make biochar an effective adsorbent for heavy metals in soils, but over time may promote their further exchangeability into the soil solution. From a microbial perspective, although the utilization of biochar-immobilized microbes in the context of nutrient management and the remediation of contaminated soils is prevalent, it is imperative to consider the potential secondary toxicity resulting from contaminants persisting in the biochar, as well as the direct toxicity of the biochar itself (Bolan et al. 2023).

The underlying mechanisms are elucidated in Fig. 6 and are intricately linked to the recent findings of Xiao et al. (2023). Their study attributed the unique capacity of bone-derived biochar (BC) to the enhanced accumulation of heavy metals (HMs) in *Salix jiangsuensis* '172' (SJ-172). Notably, the application of BC resulted in remarkable uptakes of 115%, 162%, 285%, and 219% of cadmium (Cd), lead (Pb), Mn, and Cu, respectively, at a 4% BC application rate, compared to alternative treatments. The authors highlighted the synergistic effect on enhanced HM accumulation in SJ-172, affirming the the inherent phytoaccumulative capabilities of trees, which were further potentiated by the introduction of biochar (Fig. 6).

In the same study, BC was administered to acidic soil characterized by an abundance of hydrogen ions (H^+) in the solution. This environment facilitates the neutralization of negative charges on the biochar surfaces by H^+,

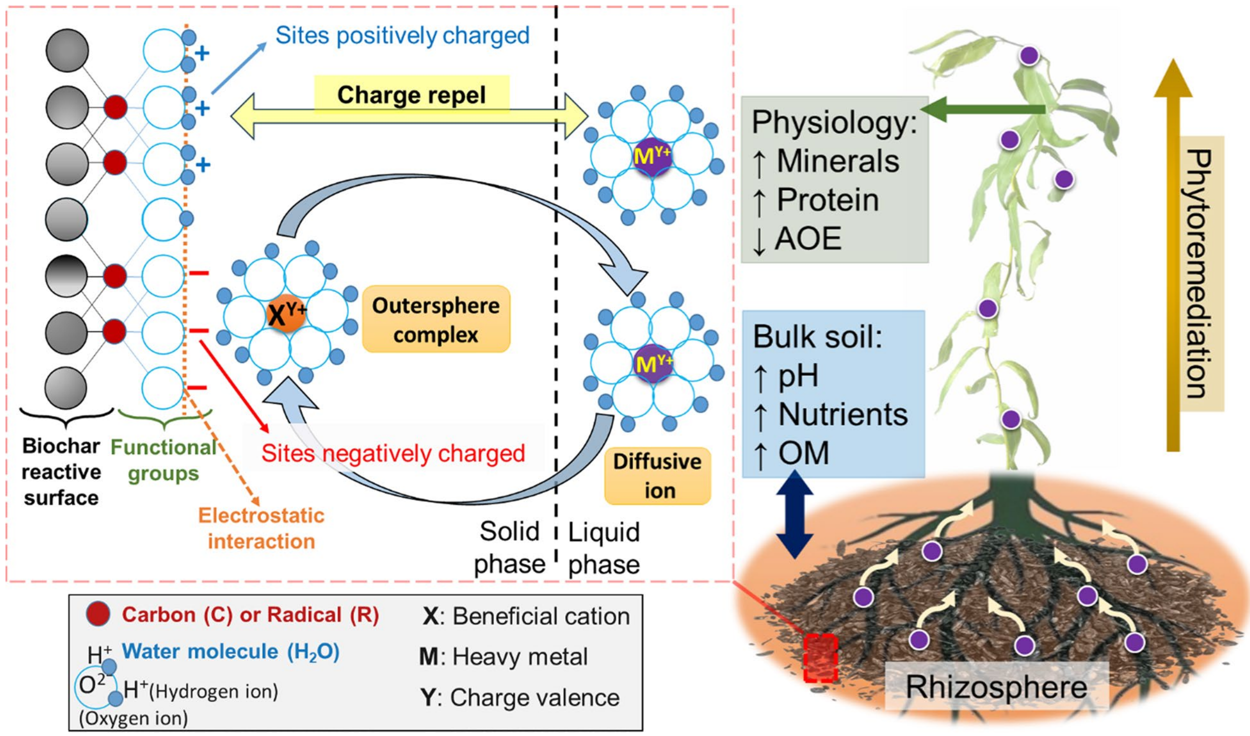


Fig. 6 Schematic representations illustrate the intricate interplay among biochar (BC), beneficial cations, and heavy metals (HM) in both the soil solid phase and solution (left) and the soil-root-plant uptake interaction (right). Heavy metals engage in low-affinity exchanges with calcium (Ca^{2+}), magnesium (Mg^{2+}), and other beneficial cations, facilitated by water molecules enveloping ions (hexahydrate cations forming outer sphere complexes). Protonation of BC's surface functional groups repels cationic metals into the soil solution, contributing to enhanced HM exchangeability and bioavailability through diffusive ion mechanisms. This physicochemical interaction mitigates heavy metal accumulation in the soil, as HMs are absorbed by trees during phytoremediation. Biochar's positive effects on the soil–plant interface enhance physiological activities in plants, concurrently facilitating heavy metal sequestration in plant tissues. The figure was created based on the works of Xiao et al. (2023) and Antonangelo and Zhang (2020). *OM* organic matter, *AOE* antioxidant enzymes

potentially leading to their protonation as additional H^+ ions migrate to the solid fraction in pursuit of establishing chemical equilibrium (Xiao et al. 2023). Consequently, these charged interactions serve to repel cationic metals into the soil solution, rendering them more bioavailable to plants (Fig. 6). To corroborate this observation, the survival and growth of Jack pine were found to be optimal at low to mid-level wood-ash biochar concentrations, whereas higher doses resulted in elevated levels of toxic metals in both tailings and tree tissues (Williams and Thomas 2023). Specifically, according to the authors, trace amounts of the toxic metal/loids (i.e.: arsenic–As, Cd, Cu, and Pb) detected in wood ash did not lead to significantly elevated concentrations in sapling tissues at lower to moderate dosages. However, in certain instances, tissue contaminant levels were observed to rise at the highest dosage investigated (30 Mg ha^{-1}). Finally, Bieser and Thomas (2019) concluded that, although high-carbon wood biochar can have beneficial effects on soil properties, it may also increase the levels of toxic metals in boreal forest soils, potentially adversely affecting early tree growth.

Improperly produced or handled biochar presents a series of concernable problems. One of the major issues is contaminant mobilization. When biochar is not adequately cleaned during production, it can become tainted with heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other toxic compounds. Consequently, it inadvertently introduces these pollutants into the environment when this contaminated biochar is applied to soils (Inyang and Dickenson, 2015). Moreover, there are leaching concerns associated with biochar, as it can release adsorbed contaminants when exposed to environmental conditions, thus posing contamination risks if not managed properly (Yang et al. 2019). Additionally, the use of contaminated or poorly produced biochar may result in regulatory challenges and public perception concerns, potentially impeding the widespread adoption of biochar in forestry systems.

7 Final considerations and future perspectives

I. The type of biochar used can affect its effectiveness. For example, manure-based biochar, or even crop residue-derived biochar, has been demonstrated more effective than wood-based biochar in improving soil quality. Further consideration should be given to the selection of appropriate materials and production methods for biochar, considering both economic and safety factors. This ensures the development of an optimized solution tailored to the specific requirements of each target region (Johanis et al. 2022).

II. The quantity of biochar applied can also affect its effectiveness. Biochar overloading to soil can be harmful to trees because it could increase soil electrical conductivity (EC) and salinity. In that sense, a threshold of biochar application rate or loading rate must be verified from preliminary studies and should be considered with respect to economic and practical feasibility and availability of biochar feedstock. For example, the application of 3–6 Mg ha^{-1} of biochar to degraded tropical Ultisols in the Amazon did not affect tree growth or litterfall during the dry season (Gonzalez Sarango et al. 2021). Consequently, the application of biochar negatively impacted the benefit–cost ratio of the tree plantations, as the costs associated with amending the soil with biochar were not offset by any observable benefits (Gonzalez Sarango et al. 2021).

III. To reduce high dose rates of biochar in tree crops, application methods can be optimized by using band placement around root zones, which minimizes the amount needed while targeting the roots. Adjusting the incorporation depth to place biochar within the root zone can enhance its effectiveness without requiring large surface applications. Precision application techniques, such as variable rate application (VRA) or GPS-guided equipment, enable targeted use based on specific soil needs. Additionally, blending biochar with fertilizers, compost, or other organic amendments can help balance the overall soil improvement. Timing applications to coincide with critical nutrient uptake periods and leveraging moisture retention strategies further optimize biochar use, ensuring its benefits while reducing excessive doses.

IV. The soil type affects the effectiveness of biochar. Thus, biochar application in sandy to clay soils must be verified so does the response of tree crops to the biochar application that is better adapted to a particular soil texture. The tree species can also affect the effectiveness of biochar. Some tree species are more responsive to biochar than others. Therefore, the targeting tree species should be carefully evaluated before applying biochar.

V. While the benefits of biochar application in forestry systems are evident, potential environmental concerns should be addressed. In that scenario, the aging effect of biochar linked to the common pedogenic process due to the weather conditions should be properly evaluated and modeled.

VI. Biochar exhibits seemingly contradictory effects on microbial activity due to its diverse interactions with microorganisms. The porous structure and high surface area of biochar contribute to both antimicrobial properties and the promotion of microbial activity. Antimicrobial effects arise from the adsorption and immobilization of harmful substances, reduced nutrient availability, and alterations in soil pH that inhibit specific microorganisms. Conversely, biochar serves as a habitat and nutrient source, creating micro-environments favorable for microbial colonization and growth. The apparent contradiction highlights the complexity of biochar–microbe interactions, emphasizing the need to consider specific environmental conditions and microbial communities when assessing their impact on soil ecosystems.

VII. The exploration of lasting impact of biochar necessitates ongoing studies to unravel its fate in soils and elucidate its intricate interactions with soil microorganisms and nutrient cycles. Despite a clarion call for such investigations over a decade ago by Luo et al. (2011), comprehensive understanding is still evolving. Additionally, tailored site-specific studies become imperative to assure the optimal biochar dosage and application frequency, a critical step in mitigating potential adverse environmental effects, as highlighted by Biederman and Harpole (2013). This imperative holds true not only for agricultural lands but also extends to forestry systems, given the nuanced environmental processes surrounding and within soil profiles, distinguishing these systems from traditional agricultural landscapes.

VIII. Finally, the commercialization of biochar requires cost-effective production techniques, including advances in pyrolysis, gasification, and hydrothermal carbonization (HTC). Utilizing low-cost feedstocks like agricultural residues, organic waste, or even urban waste can help reduce production costs. Localized, small-scale biochar production units can further decrease transportation costs and improve cost-effectiveness. In agroforestry systems, the benefits of biochar, such as improving soil fertility, water retention, and nutrient cycling, can be optimized by tailoring it to specific crops or soils, while also serving multiple purposes like water filtration or livestock feed additives. Leveraging biochar for carbon credit can offset its costs, and government incentives can encourage adoption. Long-term benefits, such as improved yields and reduced input costs, further justify the investment, especially when biochar is integrated into broader ecosystem services.

8 Conclusions

Biochar is a promising tool for long-term carbon sequestration and offers significant root-specific benefits for trees. It improves soil properties, enhances tree growth, and increases resilience to environmental stresses. These attributes make biochar a valuable amendment for both carbon management and tree health. Further research is still required to ascertain the most effective biochar application rates and delve into the enduring impacts of biochar on tree crops. While biochar shows significant potential for various forestry applications, its large-scale implementation is hindered by the likely need for specialized machinery, which requires further exploration to enhance its commercial accessibility. To enhance the cost-effectiveness of biochar, it is crucial to invest in R&D, train farmers on its optimal use, and standardize quality control to ensure consistent benefits. By scaling production, improving energy efficiency, and demonstrating multifunctional uses of biochar, agroforestry systems can integrate biochar sustainably while minimizing upfront expenses. Moreover, comprehensive investigation into the physiochemical attributes of biochar, stemming from various feedstocks and diverse pyrolysis conditions including temperature, heating rate, residence time, and oxidizing agents remains essential. It is still needed to fully understand the effects of biochar on tree crops under different conditions. Since biochar application is propitious for sustainable soil amendment in forestry systems, future directions must focus on addressing remaining knowledge gaps, such as assessing direct impacts on wood quality, mainly in commercial forest plantations; optimizing biochar production methods; and developing region-specific guidelines for its application. Harnessing the potential of biochar in forestry management will lead to more sustainable and productive forest ecosystems.

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Data availability
The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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