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Biochar

REVIEW

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Influence of biochar on growth performances, yield of root and tuber crops and controlling plant-parasitic nematodes

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Abstract

Root and tuber crops are important sources of food and provide income for millions of people worldwide besides an observed high demand for organically produced harvests. Hence, recent attention has been given to utilizing biochar, a carbon-rich material produced from the pyrolysis of organic materials, which improves soil structure, water-holding capacity, and nutrient availability, as an amendment to produce organic root and tuber crops. These effects are caused by the formation of organic coatings on the surface of biochar, which decreases hydrophobicity and increases the ability to retain nutrients, acting as a slow-release mechanism delivering nutrients dependent on plant physiological requirements. However, comprehensive studies on the impact of biochar application on root and tuber crop growth, productivity, and effectiveness in eliminating soil parasites have not been extensively studied. Thus, the purpose of this review is to explore the use of biochar and biochar-based soil amendments and their potential applications for improving the growth, yield, and efficacy of controlling parasitic nematodes in a wide range of root crops. Most of the studies have investigated the effects of biochar on cassava, sweet potatoes, and minor root crops such as ginger and turmeric. It has been observed that biochar application rates (5–20 t ha^{-1}) increase the vine length and the number of leaves, tubers, and tuber weight. The addition of biochar demonstrates the ability to control plant-parasitic nematodes in a rate-dependent manner. While biochar has shown promising results in improving crop growth and yield of limited root and tuber crops based on a few biochar types, ample opportunities are around to evaluate the influence of biochar produced in different temperatures, feedstock, modifications and controlling parasitic nematodes.

Highlights

- Organically produced root and tuber crops are in urgent demand.
- Biochar demonstrates the ability to control plant-parasitic nematodes.
- Biochar application increased crop growth and yield of root and tubers.

Keywords Crop yield, Carbon materials, Organic fertilizer, Root and tuber crops, Nutrient retention, Nematodes

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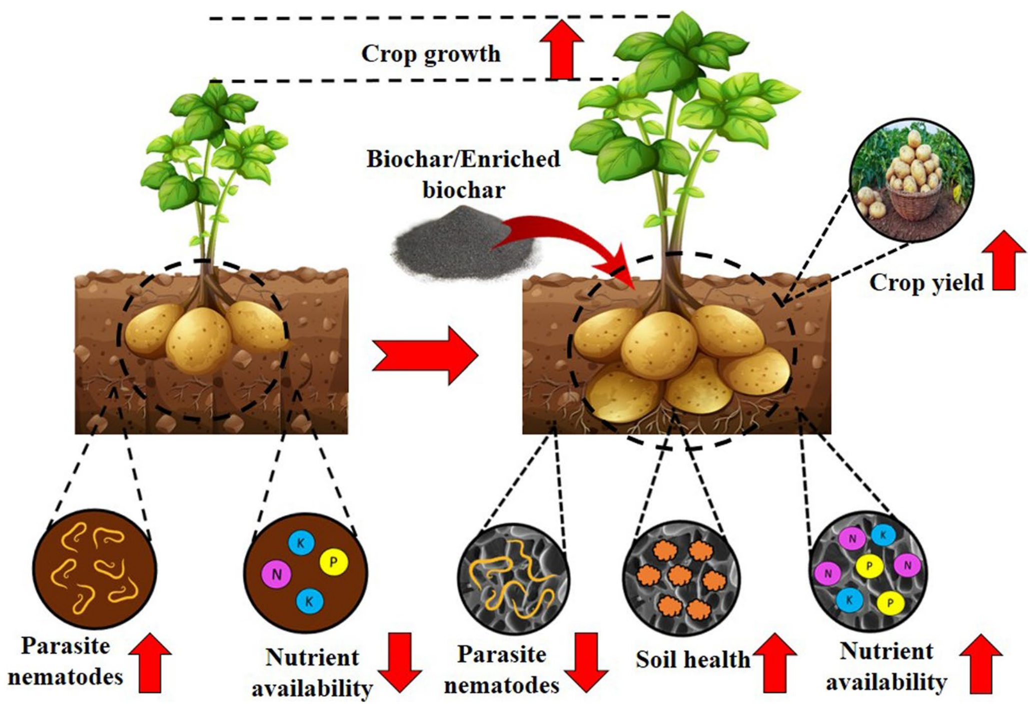
Graphical abstract



1 Introduction

Root and tuber crops are a major source of food and nourishment for many farmers and households in the developing world. They contribute significantly to the global food supply and are a major source for both domestic and commercial use as well as animal feed (Scott 2021). Soil health, which incorporates the chemical, biological, and physical properties of soil, influences both yield and quality in root and tuber crops such as potatoes, sugar beet, carrot and cassava, etc. (Aulakh et al. 2022). These plants have a high capacity for photosynthetic activity, a high yield potential, and the ability to withstand unfavourable climatic conditions. Conventional agriculture that uses chemical inputs produces larger yields nevertheless being environmentally unfriendly since it has a negative influence on the quality of the environment, water, soil, and food (Suja and Sreekumar 2014). The practice of "organic farming" promotes sustainable production, preservation of soil health, and environmental preservation while receiving an enormous demand. It recommends the avoidance of synthetic chemicals, a reduction in the usage of inputs purchased, and maximum utilization of resources produced on the farm (Manna et al. 2021). In general, tuber crops respond well to organic manures, and there is a lot of potential for organic production with these crops. Additionally, there is currently a high demand from affluent individuals in developed countries (Europe, The United States, and the Middle East) for organically grown roots and tubers like yams, sweet potatoes and cassava (Suja et al. 2012). The correct scientific utilization of numerous less expensive and more readily available organic sources of plant nutrients is the primary challenge in the production of tuber crops organically (Girija et al. 2016), however, leads to reduced parasite attacks as well (Ntalli et al. 2020).

Biochar is a solid substance rich in carbon that is made by pyrolysis of plant or animal biomass under a partial exclusion or limited oxygen condition (Bolan et al. 2022). Many feedstock types are used to produce biochar including agricultural residue and animal waste such as rice straw, corn cobs, wheat residues, animal waste, sewage sludge, municipal solid waste and biogas residues (Kumar et al. 2023). The feedstock and processing parameters, such as the pyrolysis temperature, rate of heating, residence time, particle size, reactor type, and pressure conditions, affect the chemical properties of biochar (Ahmad et al. 2014). As a result of its unique characteristics, biochar has been used for various applications, such as waste management, adsorption functions, soil amendment in agriculture, catalysis, carbon sequestration and storing energy (Wu et al. 2023). Biochar can increase the fertilizer's effectiveness for plant uptake and reduce soil nutrient loss. Nutrient loading onto biochar is essential to improve the fertilizer because pristine biochar has few nutrients (Rashid et al. 2021). In addition to enhancing the soil's physical, chemical, and biological properties, after a single application of biochar, Zhang et al. (2013) observed an increase in the population of soil nematodes and fungivore abundance along with a decrease in plant-parasitic nematodes.

According to George et al. (2016), *Pratylenchus penetrans*, a migratory endoparasitic nematode, is less prevalent in carrots when biochar is present. Other plant-parasitic nematodes are thought to be negatively or neutrally affected by biochar, including root-knot nematodes (*Meloidogyne* spp.) and the potato-cyst nematode (*Globodera* spp.) (Oladele et al. 2021). Even though there is a high demand for organically grown tuberous vegetables, cereals and grain legumes, research and development on biochar-based organic cultivation of tropical tuber crops are less concerned and less well established. At the same time, literature data demonstrated inconsistent results depending on the nematode, crop, and the biochar used (George et al. 2016). Therefore, a critical discussion on how biochar affects root and tuber crop yield, nutrient quality, and control of plant-parasitic nematodes is timely and important. Ultimately, this review offers a new viewpoint for understanding the effect of biochar relevant to the cultivation and production of different roots and tuber crops and controlling plant parasitic nematodes. In addition, the current constraints and need for future research are discussed.

2 Bibliometric analysis

A literature survey was conducted in the Scopus database using the terms "biochar" AND ("crop growth" OR "yield") AND ("root crops" OR "tuber crops" OR "sweet potato" OR "cassava" OR "ginger" OR "turmeric" OR "yams" OR "potatoes" OR "carrot" OR "radish" OR "onion") for research articles published between 2011 and 2023. The indexing terms were based on the search in "title", "abstract", and "keywords" of the articles. The search was further limited to research articles in scientific journals and the English language, resulting in 104 papers. VOSviewer software (version 1.6.18) was used to analyze the co-occurrence of the author keywords involved with the research on biochar and root crop growth or yield to form the network maps. The co-occurrence was examined with the minimum number of studies from keywords as 3. The data extracted from each study included: (i) feedstock type /biomass; (ii) pyrolysis temperature; (iii) enrichment material (including organic, inorganic fertilizers, clay minerals, rock phosphate); (iv) plant benefits; (v) experiment type; (greenhouse, pot or field (vi) type of crop; and (vii) biochar dose/application rate.

A total of 364 keywords provided by the author were extracted from the information base. These words co-occurred at least three times. Figure 1 displays a network consisting of 22 keywords that have been categorized into seven distinct clusters. The relationships between these keywords are illustrated through graphs that feature interconnected nodes and links. In this network map, nodes are used to represent the individual keywords, and the size of each node is proportional to the frequency with which that keyword appears in the documents being analyzed. Larger nodes indicate that the corresponding keyword appears more frequently within the analyzed documents. The connections between nodes in a graph are represented by links, also known as edges. The thickness or width of the link indicates the strength of the relationship between the nodes it connects. A thicker or wider link generally suggests a stronger relationship between the two nodes. Additionally, the weight or value of the link can be used to determine the strength of the relationship between nodes. These clusters of keywords were divided based on patterns of co-occurrence in the selected documents. The red, green and blue clusters are composed of the largest number of keywords, it can be seen that the keywords "compost", "yield" and "soil fertility" "pyrolysis", "soil properties" in those three clusters received the most attention. The largest node represented the keyword "biochar" and it had 56 co-occurrences. The keyword "poultry manure" showed 10 co-occurrences and was highly related to the keyword "biochar". Other small clusters are: cluster 4 (yellow) made up of three nodes, cluster 5 (purple) consists of three nodes and in this cluster, studies are focused on "poultry manure", "soil properties" and "sweet potato". The orange colour and ash colour clusters made up two nodes.

3 Agronomic benefits of biochar

Adopting sustainable agriculture is crucial to ensure an adequate supply of food for population growth and maintain economic, social, and environmental viability. As a consequence of its beneficial properties for sustainable agriculture, including the effects on soil fertility and crop productivity, research on the usage of biochar in the agricultural field has advanced significantly over the last two decades (Aziz et al. 2019; Hussain et al. 2017). Understanding the role of biochar in the soil and its potential advantages for sustainable agriculture requires an understanding of its agronomic properties. Biochar in particular has a high surface area and porosity that makes it possible to adsorb/retain nutrients/water or to offer habitats for beneficial soil microbes. Additionally, the

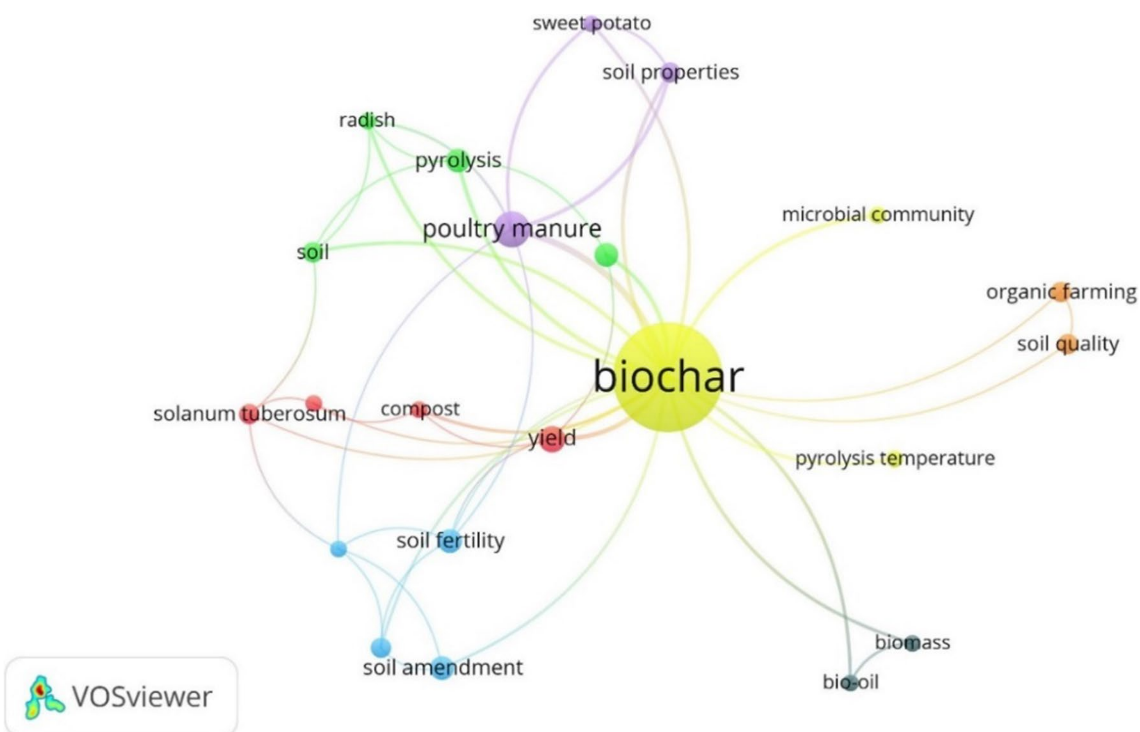


Fig. 1 Co-occurrence bibliometric map of author keywords from 2011 to 2023

porosity and surface area of biochar may have a significant impact on its ability to retain nutrients through the surface binding of both cations and anions. The biochar production process and some beneficial physical and chemical properties of biochar are illustrated in Fig. 2. Several studies were conducted to evaluate the benefits of biochar for soil and crop growth. Among those studies, Das et al. (2021) found it is extremely beneficial for improving soil organic C, water-holding capacity, soil microbe activity, and biomass. Not limited to the soil properties, Rombel et al. (2021) conducted studies relevant to crop growth and they found it can also reduce the leaching of fertilizers while increasing nutrient bioavailability and retention, soil aeration, and crop growth and yield. Further, the physical characteristics of the soil, including soil structure and texture, depth, bulk density,

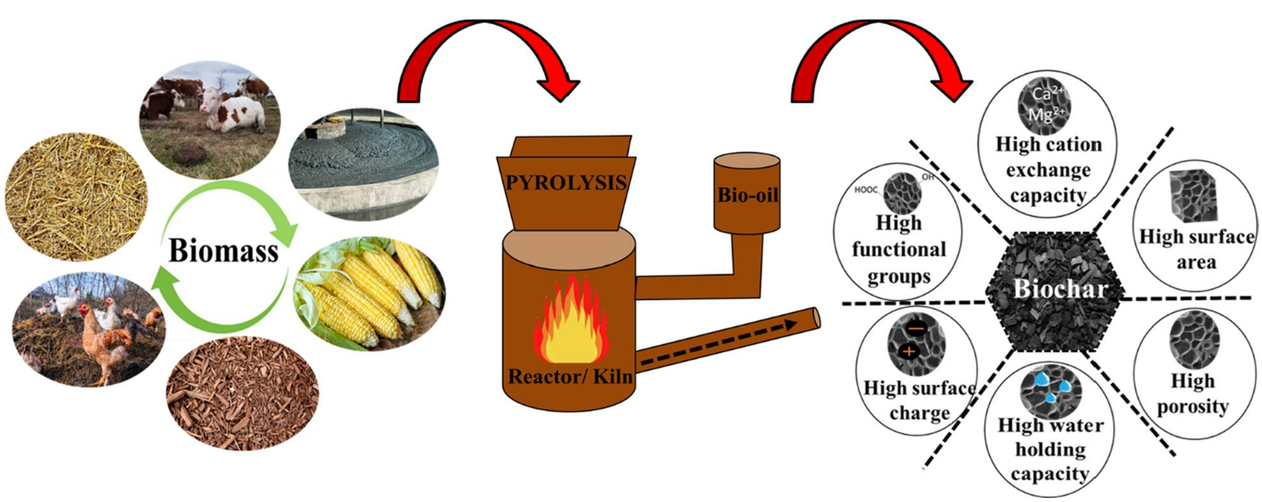


Fig. 2 The production process of biochar from different feedstock types and its beneficial properties

pore size distribution and hydraulic properties are significantly altered by the application of biochar to the soil matrix (Vithanage et al. 2013).

The physicochemical characteristics of soil, such as humus production, soil organic matter decomposition, soil substance transformation, and nutrient cycling, are closely associated with soil microorganisms and can be used as essential indicators for assessing soil quality and fertility (Yan et al. 2021). Biochar will aid in the provision of space for microorganisms in the soil and also aid in the binding of significant anions and cations since it has a larger porosity and more surface area (Rehman and Razzaq 2017). Finally, incorporating biochar into agricultural methods is strongly advised because it will have numerous long-term advantages for the environment, agriculture, and economy (Osman et al. 2022).

3.1 Biochar-based fertilizers

Fertilizers based on biochar are gaining vast attention since they are made from agricultural waste like organic materials and biochar fertilizers usually feature a slow release of nutrients when compared with compost and other commercial fertilizers (Wang et al. 2022). The adsorptive nature of biochar is influenced by porosity and reactive surfaces, which have been used to create formulations for controlled-release fertilizers. The surface functional groups of biochar play a significant role via sorption and chemical interaction, even though the physical features of biochar have been used to manufacture biochar-based slow-release fertilizers (Conte et al. 2021). Compared to quick-release fertilizers, slow-release fertilizers offer a longer nutrient delivery. As a result of the slow release of nutrients into the fixing media throughout the process of fixation in the soil, controlled or slow-release fertilizers enhanced the availability of nutrients (Rashid et al. 2021). According to research conducted by Khajavi-Shojaei et al. (2020), the coating substance and structure of biochar-based slow-release nitrogen fertilizer improve the slow-release of nitrate and ammonia within biochar pores or surface functional groups. Based on the literature, there are various examples of using pristine biochar as soil fertilizers (Osman et al. 2022; Rombel et al. 2021). However, due to its physicochemical characteristics, such as a negatively charged surface, a small specific surface area, and the absence of acidic functional groups, pristine biochar has some limitations as an effective fertilizer such as limiting the soil nutrient (NO_3^- and PO_4^{3-}) releasing properties (Marcińczyk et al. 2022). Production of nutrient-enriched biochar is one of the methods used to improve the nutrient content and increase the efficiency of biochar and it may result in lower application rates.

There are three main biochar enrichment methods including direct treatment, pre-treatment and post-treatment enrichment methods (Karim et al. 2022). In the direct treatment process, the initially nutrient-rich feedstock goes through gradual pyrolysis, which encourages nutrient enrichment in the biochar. The pre-treatment method is another method of producing nutrient-enrich biochar fertilizer. Here, biomass is treated with a nutrient-rich mineral source before the pyrolysis step. These components also assist in enhancing the functionality of biochar by increasing its moisture retention and the ability to stabilize heavy metals (Ndoung et al. 2021). In the post-treatment process, nutrient sources such as mineral fertilizer, clay, rock compounds, and composts are mixed with biochar after the pyrolysis process usually at room temperature or control temperatures. This process enhances biochar properties such as nutrient contents, and cation exchange capacity, increasing the pH, surface area, and functional groups. Regulating the type and amount of particular nutrients that will improve the biochar-based fertilizer is another benefit of post-treatment techniques (Joseph et al. 2013). Many studies reported that the application of biochar-based fertilizers for different fields has improved soil quality parameters, and increased crop growth and productivity (Agegnehu et al. 2017; Gao et al. 2022; Ndoung et al. 2021). Hence biochar-based fertilizers fit in with the current tendencies of sustainable development including the production of environmentally friendly fertilizers.

3.2 Effects on soil fertility and nutrient cycling

To maintain proper biodiversity, a sustainable soil environment requires regular nutrient recycling. Variations in the soil ecosystem's levels of nitrogen, phosphorus, and sulphur are influenced by biochar and biochar-based fertilizer. The availability of nutrients to plants is impacted by biochar, which is also important for biogeochemical processes in soil, particularly in the dynamics of nitrogen cycling (Lehmann et al. 2011). The ability of biochar to slowly release nutrients into the soil sets them apart from conventional organic fertilizers. As a result, there is a large decrease in the loss of these nutrients through leaching or volatilization, which increases the effectiveness of nutrient uptake (Puga et al. 2020b). The capacity of biochar to store carbon can be increased or decreased depending on how effectively or poorly the native soil carbon is primed by the addition of biochar. The priming effect is described as an alteration in the rates of soil organic carbon (SOC) mineralization as a result of soil treatments (Lu et al. 2014). Because of better nitrogen adsorption and higher unaccounted nitrogen, adding biochar to subtropical farmland soil may be able to reduce nitrogen leaching (Zhao et al. 2014). The chemical structure and surface properties of biochar have a major role in the way they affect soil phosphorus. Increased phosphorus availability with the addition of biochar to the soil is generally shown by higher soil pH and direct release of phosphorus from biochar (Jin et al. 2016). Lustosa Filho et al. (2019) noted a shift occurred in the soil pH, leading to the emergence of microsites characterized by a decreased capacity of soil particles to adsorb phosphorus. This nutrient release is occurring gradually, which may be caused by several mechanisms. An et al. (2020) stated that the slower the release of nutrients, the smaller and more regular the pores and channels in the biochar fertilizer. Moreover, the interactions among biochar, clays, and minerals aid in regulating the permeation and diffusion of moisture into the structure of biochar fertilizers, resulting in the retention of nutrients (Liu et al. 2019). The utilization of biochar enhances soil fertility by two means: supplementing soil nutrients (such as potassium, to a restricted degree phosphorus, and numerous micronutrients) or preserving nutrients from external origins, which includes nutrients from the soil.

3.3 Impact on crop growth, productivity, and harvest

One of the main nutrients that affect how well plants grow is carbon. When biochar was added to tropical and subtropical soils, there were generally observed substantial increases in plant growth and yield. By immobilizing and mobilizing plant nutrients, biochar acts as a soil conditioner to improve plant growth (Antonangelo et al. 2021). Biochar-based fertilizers improve soil health, it has also been demonstrated that they improve plant performance in contrast to unenriched biochar or conventional organic fertilizers (Wang et al. 2023). Compared to their respective controls, the application of mineral-enriched biochar to each cow urine or either cow urine or NPK fertilizer increased the crop yield (Schmidt et al. 2017). The nutrient carrier effect of biochar, which results in a gradual nutrient release, more evenly distributed nutrient fluxes, and decreased nutrient losses, may account for the yield gains (Puga et al. 2020a). A rise in biomass production in the granular biochar-mineral urea combination indicates an increase in the fresh mass of the root, volume and shoot (Shi et al. 2020). After adding phosphorus-enriched biochar, maize plants had longer shoots and roots, as well as increased dry mass and phosphorus uptake. A greater phosphorus availability was the cause of the growth acceleration under the phosphorus-enriched biochar (Ahmad et al. 2018). The capacity of enriched biochar to enhance plant growth at several stages, including germination, seedling, blooming, and harvest, is another consequence. Overall, the addition of biochar can increase plant growth, nutrient uptake, and other properties such as crop yield and eliminate plant pathogens and illnesses.

3.4 The potential of biochar in controlling plant parasite nematodes

In addition to enhancing plant growth and increasing crop yields, adding biochar to soil may also improve plant health and disease resistance (Hussain et al. 2017). Nematodes including root knots and root lesions are major crop pests that cause significant economic harm around the globe. Infections typically cause host plant growth reductions, decreased yields, and, in extreme cases, mortality due to unspecific illness symptoms resembling those brought on by physiological stress (George et al. 2016; Yaman et al. 2021). Biochar is thought to have a variety of effects on different plant-parasitic nematodes, including neutral, adverse, and both on root-knot nematodes (Meloidogyne spp.) and neutral effects on the potato-cyst nematode Globodera spp. (Domene et al. 2021). Most of the current research is still limited to certain pest species and indicates short-term consequences in greenhouse settings (Ogura et al. 2021). According to research by George et al. (2016) and Kamau et al. (2019), biochar decreases the prevalence of the migratory endoparasitic nematode *Pratylenchus penetrans* in carrots and the stubby-root nematode *Trichodorus* spp. in maize and increases the prevalence of the reniform nematode *Rotylenchulus reniformis* in cowpeas (Rashad et al. 2019). Additionally, it has been discovered that adding biochar to potting soil or agricultural soil can help control the infestation of root-knot nematodes on mungbean and is a good alternative to synthetic nematicide (Ikwunagu et al. 2019). Biochar produced from olive mill waste at 300 °C, hindered the survival of the *Meloidogyne incognita*. However, toxicity decreased at elevated pyrolysis temperatures (Marra et al. 2018). Similar results were obtained by Martínez-Gómez et al. (2023) for biochar derived from grape pomace at 300 °C, and 700 °C. There is not much documentation on the use of biochar against plant parasitic nematodes, however available studies have hypothesized many potential nematode control methods, such as changes in soil nematode biodiversity, induction of plant defences, or direct toxicity (Poveda et al. 2021). Huang et al. (2015) discovered that using oak wood biochar reduced *Meloidogyne graminicola* infection in rice plants, which was linked to the stimulation of plant defenses (local H_2O_2 buildup and transcriptional increase of ethylene-related genes). Although the direct use of biochar from charred log wood in an in vitro study resulting in a mortality rate of the nematode *Pratylenchus coffeae* comparable to chemical nematicide due to the direct toxicity effect of biochar by Rahayu and Sari (2017), George et al. (2016) found that carrot plants were more resistant to

Pratylenchus penetrans, most likely due to the induction of plant defences, while changes in soil pH or direct toxicity could not be ruled out.

4 Benefits of biochar for root and tuber crops

Crops with starchy roots, tubers, rhizomes, corms, or stems are classified as root and tuber crops. The most significant food crops for direct human consumption in South Asia, Africa, and the Pacific Ocean Islands are root and tuber crops, such as yam, cassava, potato, and sweet potato. These crops contribute to the nutritional requirement and the social, and economic security of these regions. They are mostly utilized to make animal feed, human food (either raw or processed), starch, alcohol, and fermented drinks like beer (Nanbol and Namo 2019). Due to the increased adaptability of tuber starch for a variety of uses in the industrial sector, some of these crops have been elevated to a commercial scale in some nations. They are grown in a variety of agroecologies and production techniques, from low-lying, arid places vulnerable to drought or flooding to densely inhabited highlands (Alemayehu and Bewket 2017). Even though these crops are adapted to poor soils, manures and fertilizers have a significant impact on boosting tuber yield and quality. Although the three main nutrients; nitrogen, phosphorus, and potassium are needed in large amounts for normal growth and development of tubers, some reports suggested that other nutrients, such as sulphur, calcium, and magnesium, as well as micronutrients like copper, manganese, boron, and zinc, are becoming depleted and inadequate in major crops (Koch et al. 2020).

Agbede and Oyewumi (2022) reported that tropical soils have low levels of organic matter and readily available nutrients, and their productivity and sustainability gradually deteriorate over time. This is a result of the same land being continuously farmed, which depletes the nutrients in the soil, causes physical degradation, and reduces yield. To increase crop productivity, soil amendments must be applied to correct the anomalies or reverse the negative nutrients and maintain productivity. Therefore, adding organic materials like compost, animal manures, and mulches may be possible to replace nutrients and improve the quality of tropical soils. Additionally, using more durable substances like biochar may be one of the solutions for managing soil (Rombel et al. 2021). Biochar amendment is preferable to other organic materials in two ways: first, it has a high stability against decomposition, which allows it to stay in the soil for longer while still giving long-term benefits to the soil; second, it has a greater ability to retain the nutrients (Rawat et al. 2019). In particular, compost-enriched biochar, nutrient-enriched biochar, biochar with mycorrhizal fungi, biochar with rock phosphate, and biochar with vermicompost have shown promising results in improving the yield and quality of root and tuber crops (Aziz et al. 2019). Biochar's effect on soil properties and its effect on root and tuber crops are illustrated in Fig. 3. By enhancing the physical and chemical characteristics of the soil, biochar promotes crop development and reduces plant parasitic nematodes. These biochar and biochar-based fertilizers not only improve soil fertility but also promote sustainable agriculture practices by recycling organic waste materials.

Several feedstock types and enrichment materials used to produce biochar and biochar-based fertilizers are presented in Table 1. Since different biochar produced from different feedstock, at different temperatures have been used in various studies; Adekiya et al. (2022) (Hardwood at 580 °C), Farrar et al. (2022) (Bamboo, chicken litter, and barley straw at 450 °C), Jabborova et al. (2021) (Black cherry wood at 450 °C), Navarro et al. (2020) (Walnut shell at 900 °C), Higashikawa et al. (2023) (Eucalyptus wood at 350 °C), it is difficult to say whether low temperature biochar is good or bad for a particular root crop. As well, whether hardwood biochar, softwood, manure-derived biochar, or crop waste biochar is the best source for relevant roots and tubers.

4.1 Biochar influence on root and tuber crop growth

Sweet potato (*Ipomea batata*) is a crucial root and vegetable crop in many countries in Africa and Asia. Producing sweet potatoes has various advantages over growing other tuber or root crops like yams, cassava, and cocoyam, including a shorter growing season of three to four months and a higher yield. Several studies have investigated that biochar application alone or in combination with mineral fertilizer has increased growth parameters such as sweet potato vine length and number of leaves per hill (Adekiya et al. 2022; Liu et al. 2014; Walter and Rao 2015). This was due to a straight change in the soil chemistry and physics of the soil by biochar due to its intrinsic properties. Bulk density is essential to tuberization, soil water movement, root spreading and function, and therefore, water and nutrient uptake and plant growth. Walter and Rao (2015) have used comparatively lower biochar application rates (5 t ha^{-1}) compared with Adekiya et al. (2022) who applied biochar rates at 10 and 20 t ha^{-1}. However, both biochar treatments positively affected the growth response of *Ipomea batata*.

Ginger (*Zingiber officinale*) and turmeric (*Curcuma longa*) are minor root crops grown for their culinary and medicinal benefits. To maximize growth, ginger, and turmeric require regular fertilization with nitrogen, phosphorus, and potassium (Seyie et al. 2013). Numerous research studies have recently looked into how adding

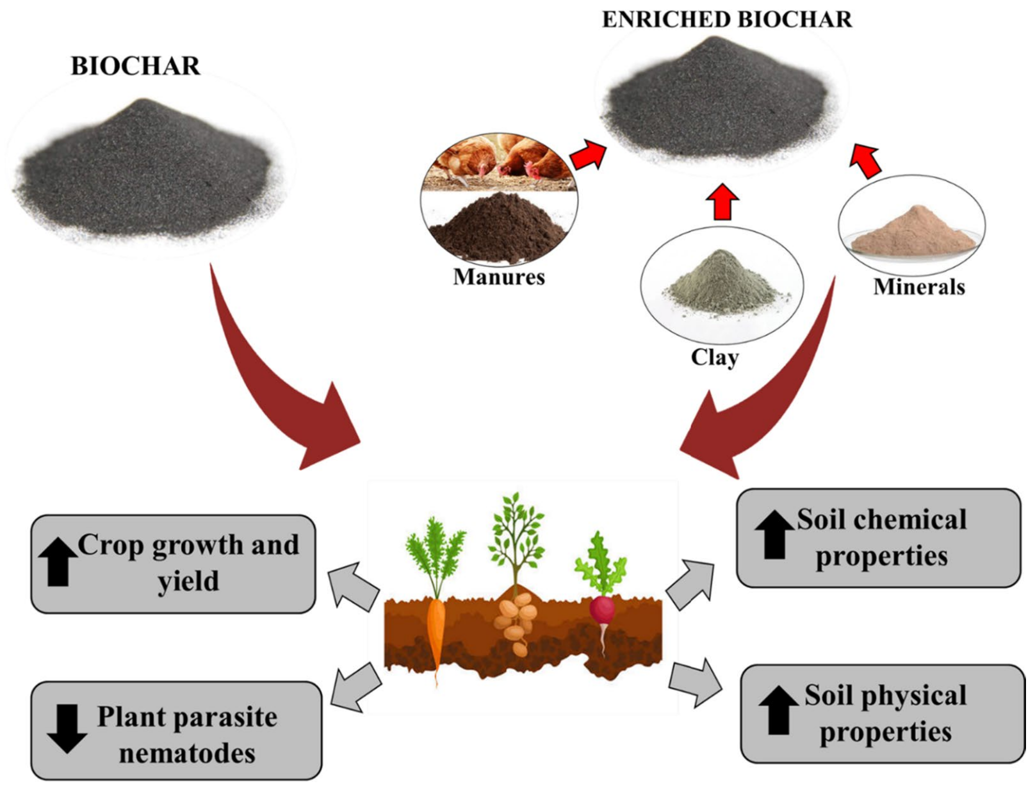


Fig. 3 Effect of biochar and enriched biochar on different soil properties and its benefits for roots and tuber crops

poultry manure to biochar boosted the ginger plant's height, number of leaves, and number of tillers (Adekiya et al. 2020a; Mardiansyah et al. 2020). In addition to poultry manure, the use of NPK fertilizer with biochar was tested by Adekiya et al. (2020a). Although biochar and chicken manure had better physical soil characteristics, biochar with NPK increased ginger yield and growth in comparison to biochar with poultry manure. Among several studies, Jabborova et al. (2021) investigated the effect of biochar on promoting the germination and growth of ginger seeds in addition to growth parameters. In comparison to the control, seed germination was significantly raised by both biochar amendment amounts (2% and 3%) used. Further, as a comparison to the control, plant height improved by 53% with the 2% biochar treatment and by 78% with the 3% biochar treatment. Farrar et al. (2022) developed organo-mineral biochar using bamboo, chicken litter, lime, rock phosphate, potassium sulphate, granular boron and clay. They tested different pristine and enriched biochar type's effect on turmeric crop growth. The organo-mineral biochar treatment enhanced the number of primary fingers per plant more than commercial biochar fertilizer and co-applied pristine biochar.

4.2 Effect of biochar on root crop yield and controlling plant parasitic nematodes

The increase in yield under biochar compared to the conventional organic fertilizer could also be the result of modifications made to the soil by the biochar, such as nutrient addition, an increase in soil pH, nutrient availability, and the preparation of chemically active surfaces that could have influenced the dynamic nature of soil nutrients (Kizito et al. 2019). Effects of biochar and biochar-based fertilizers on plant properties of different root and tuber crops are shown in Table 2. Cassava (*Manihot esculenta* Crantz) is the most important tuber crop and the third important food crop after rice and maize. Cassava yields may rise with the use of inorganic fertilizers, although yield stability cannot be sustained over a prolonged period. The potential of biochar for managing soil organic matter in cassava-based farming systems, paying particular attention to its impact on crop output, yield stability, and remaining soil fertility was studied by (Islami et al. 2011). When compared to yield without organic amendments, biochar treatment significantly increased the cassava yield.

Different types of biochar and enriched biochar have been used to increase crop yield in sweet potato, hardwood biochar with mineral fertilizer (Adekiya et al.

Table 1 Different feedstock types and enrichment materials used for biochar and biochar-based fertilizer

Feedstock/biomass	Pyrolysis temperature (°C)	Enrichment material	Crop type	References
Hardwood	580	Potassium fertilizer	Sweet potato (*Ipomea batata*)	Adekiya et al. (2022)
		Poultry manure	Radish (*Raphanus sativus* L.)	Adekiya et al. (2019)
		Poultry manure	Ginger (*Zingiber officinale*)	Adekiya et al. (2020a)
		NPK fertilizer	Carrot (*Daucus carota* L.)	Agbede (2021)
	500	N/A	Cocoyam (*Xanthosoma sagittifolium* (L.)	Adekiya et al. (2020b)
Grass Chat waste	250 1100	N/A N/A	Onion (*Allium cepa*)	Aneseyee and Wolde (2021)
Bamboo Chicken-litter Barley-straw	450	Gypsum, lime, rock phosphate, potassium sulphate, granular boron, Clays (kaolinite and bentonite)	Turmeric (*Curcuma longa*) Ginger (*Zingiber officinale*)	Farrar et al. (2022)
Tobacco	N/A	N/A	Sweet potato (*Ipomea batata*)	Indawan et al. (2018)
Farmyard manure Cassava stem	300 370	N/A N/A	Cassava (*Manihot esculenta* Crantz)	Islami et al. (2011)
Black cherry wood	450	N/A	Ginger (*Zingiber officinale*)	(Jabborova et al. 2021)
Wheat straw	350–550	N/A	Sweet potato (*Ipomea batata*)	Liu et al. (2014)
Eucalyptus wood	350	N/A	Onion (*Allium cepa* L.)	Higashikawa et al. (2023)
Walnut shell	900	N/A	Sweet potato (*Ipomea batata*)	Navarro et al. (2020)
Barley straw	535	Compost (mixed green and table waste)	Potato (*Solanum tuberosum* L.)	Mawof et al. (2021)
Mesquite weed	575	N/A	Onion (*Allium cepa* L.)	Khan et al. (2019)
Pigs and cattle manure Sludge	400–500	N/A	Potato (*Solanum tuberosum* L.)	Kassaye et al. (2022)
Oil palm shell	N/A	Chicken manure	Red ginger (*Zingiber officinale* Rosc.)	Mardiansyah et al. (2020)
Coffee husk	N/A	NPS blended fertilizer	Potato (*Solanum tuberosum* L.)	Gebre et al. (2020)

2022), tobacco biochar (Indawan et al. 2018) and wheat straw-derived biochar (Liu et al. 2019). The addition of biochar increased the number of cations, which improved the fertility and availability of soil nutrients, specially potassium, which is necessary for sweet potato tuber expansion (Agbede and Oyewumi 2022) although Indawan et al. (2018) stated there was no effect between sweet potato cultivars and tobacco biochar dose. Liu et al. (2019) found that biochar produced from wheat straw pyrolyzed at 350–550 °C, increased sweet potato yield and the highest yield resulted when the amount of biochar was 40 t ha^{-1}. Moreover, the interaction between biochar and nitrogen fertilizer was tested by Adekiya et al. (2019), and a significant interaction between biochar and nitrogen fertilizer was found, showing that a higher radish (*Raphanus sativus* L.) yield increase was seen with increasing rates of biochar application in the presence of nitrogen fertilizer, emphasizing the function of biochar in enhancing the plant's ability to utilize nitrogen fertilizer. Further, González-Pernas et al. (2022) showed a similar effect on radish yield with pinewood biochar.

Low soil nutrients, particularly nitrogen and phosphorus, have been challenged by the decreased yield trend of minor root crops in the tropics. The combined application of biochar and animal manure positively affects the productivity of two different minor root crops, ginger (Adekiya et al. 2020a; Mardiansyah et al. 2020) and turmeric (Farrar et al. 2022). All the above studies concluded similar findings; biochar treatments considerably increased the fresh rhizome number and rhizome weight of ginger and turmeric. In contrast with the above-mentioned studies, Mardiansyah et al. (2020) stated that crop yield was affected by the biochar dose. Potato (*Solanum tuberosum*) was planted under different biochar and mineral fertilizer treatments in a field experiment (Mollick et al. 2020; Upadhyay et al. 2020). Adding biochar to soil and plants had a considerable favourable impact by increasing the plant height, tuber weight and yield. Upadhyay et al. (2020) evaluated the response of a few types of biochar (*Lantana camara*, *Ipomoea carnea*, rice husk, sawdust) on the growth and yield attributes of potatoes. However, all biochar positively influenced total yield.

Although roots and tuber crops are the most vulnerable species for nematode attacks including cyst nematodes,

Table 2 Effects of biochar and biochar-based fertilizer on root crop growth and productivity

Crop type	Biochar/fertilizer type	Type of study	Application rate (t ha^{-1})	Effect of growth and yield	References
Sweet potato (*Ipomea batata*)	Hardwood biochar with potassium fertilizer	Field experiment	0, 10, and 20	Increased the vine length and number of leaves and number of tubers and tuber weight	Adekiya et al. (2022)
	Tobacco biochar		5	Increasing the storage root yield by 8–45% to control	Indawan et al. (2018)
	Rice husk biochar and kunai grass biochar with mineral fertilizer (NPK)		5	Improvement of leaf number and vine numbers per hill improved marketable tuber yield	Walter and Rao (2015)
	Wheat straw		0, 2.5, 5, 10, 20, 30 and 40	40 t ha^{-1} treatment increased crop yield by 53.77%	Liu et al. (2014)
Ginger (*Zingiber officinale*)	Black cherry wood biochar	Pot experiment	1, 2, and 3%	Improved plant height, leaf length, leaf number, leaf width, as well as shoot and root weight of ginger	Jabborova et al. (2021)
	Bamboo biochar-based organo mineral enrich biochar		10 and 30	Increased root mass fraction and plant height	Farrar et al. (2021)
	Hardwood biochar and poultry manure, Hardwood biochar and NPK fertilizer	Field experiment	15	Improved soil physical and chemical properties, growth and ginger yield (number of rhizomes and fresh rhizome yield) compared with control	Adekiya et al. (2020a)
Red ginger (*Zingiber officinale* Rosc.)	Oil palm shell biochar with chicken manure		5, 10 and 15	Increased the height of ginger plants at all ages, number of tillers and rhizome fresh weight	Mardiansyah et al. (2020)
Black ginger (*Kaempferia parviflora*)	Cocopeat and sugar cane baggase biochar	Greenhouse experiment	3.4 kg cocopeat with 600 g sugar cane biochar	Increased the number of leaves, plant height, fresh and dry weight (leaves, rhizomes, and roots), leaf area, and leaf area index	Ws (2018)
Turmeric (*Curcuma longa*)	Organo mineral biochar (Bamboo biochar, chicken litter and clay)	Pot experiment	8.6	Increased the number of primary fingers per plant, the fresh and dry weight of mother rhizomes compared with commercial biochar fertilizer and the control	Farrar et al. (2022)

Table 2 (continued)

Crop type	Biochar/fertilizer type	Type of study	Application rate (t ha^{-1})	Effect of growth and yield	References
Potato (*Solanum tuberosum* L.)	Biochar and mineral fertilization N, P, K)	Field experiment	7.5	7.5 t ha^{-1} biochar along with the recommended dose of NPK fertilizer resulted highest tuber yield (35.76 t ha^{-1}) and quality parameters like % dry matter content (25.33) and specific gravity (1.12)	Mollick et al. (2020)
	Biochar (*Lantana camara*)		2	Produced the highest number of tubers (6.1 tubers $plant^{-1}$), the greatest weight of tubers (286.1 g $plant^{-1}$)	(Upadhyay et al. 2020)
	Wood biochar		0, 1.25, 2.5 and 5 m^3/fed	Increased plant growth, leaf photosynthetic pigments, minerals content and tuber yield	Youssef et al. (2017)
Cassava (*Manihot esculenta* Crantz)	Farmyard manure biochar	Field experiment	10 to 20 Mg ha^{-1}	Increased the cassava yield (21.66 Mg ha^{-1}) compared with yield without organic amendments	Islami et al. (2011)
Onion(*Allium cepa*)	Grass biochar and chat waste	Field experiment	0.5 kg/m^2	Increased onion yield is equal to the supply of inorganic fertilizer	Aneseyee and Wolde (2021)
Carrot (*Daucus carota* L)	Wood biochar	Field experiment	0, 5, 10, or 20 t/ac	Positive effect on marketable carrot weights in the 5 t/ac treatment	Carpenter and Nair (2014)
Radish (*Raphanus sativus* L.)	Hardwood biochar and poultry manure	Field experiment	0, 25 and 50	Improved soil physical and chemical characteristics, leaf nutrient concentrations and yield components of radish	(Adekiya et al. 2019)
	Pinewood biochar		10 and 20	Significantly improves the mean fresh weight of radish (10 and 20 t ha^{-1} by 35.4% and 70.7%)	González-Pernas et al. (2022)

root-knot nematodes and root-lesion in potatoes, sweet potatoes and carrot-like crops, studies on this subject are still limited despite the current significant research on many aspects of biochar and the ecological and agronomical significance of nematodes. Due to the altering and mortality of the carrot as well as the shrinking in size and branching of the tap root, infections with root-lesion nematodes of the genus *Pratylenchus* typically result in lower yields of marketable carrot tap roots. Root-lesion nematode (*Pratylenchus penetrans*) infection rates and related carrot biomass loss were decreased by biochar (George et al. 2016). However, applying biochar at 0.3 and 1% levels was insufficient to stop any cyst nematode species from surviving or breeding in potatoes (Ebrahimi et al. 2016). Hence, more research is needed for the development of biochar compounds and the dosage as a nemato-repellent. Finally, adding biochar to root and tuber crops improves plant growth, plant chemical compositions, tuber yield and its components, while increasing the net return of tuber production, maintaining a good tubers quality and keeping the environment less polluted.

5 Future perspectives

The use of biochar and biochar amendments to enhance root crop growth and yield is a relatively new approach. However, the majority of research studies conducted on this topic have been carried out in laboratory and greenhouse settings over a short period. Therefore, it is important to conduct more long-term field studies to confirm the findings and investigate any potential negative impacts of biochar application on soils. Additionally, there is a need for further research to understand how biochar affects different soil types, climates, and plant species, and to investigate application methods, rates, surface or incorporated application, incorporation depth, and in-furrow application. Examining biochar's effects on nematodes that parasitize plants is also critical. A single macronutrient, typically nitrogen, phosphorus, or potassium, is the subject of the majority of recent studies on biochar` enrichment. However, it could be required to add chemical fertilizer to the enriched biochar for optimum efficiency. Moreover, a series of tests will be required to determine the best temperature and feedstock of biochar for a certain root or tuber crop in terms of growth and yield. If not used appropriately, enriched biochar, which has high quantities of nutrients like nitrogen and phosphorus, can contaminate soil and water. Heavy metals, which can build up in soils and make their way into the food chain and endanger human health, can also be found in biochar. Therefore, it is crucial to control the application of enriched biochar and make sure that the risk of soil and water contamination is kept to a minimum. The application of biochar can be carefully monitored and managed to maximize its positive effects while minimizing its negative consequences. In general, there is much to learn about the potential advantages and difficulties of utilizing biochar as a soil supplement for tuber crops. The future perspectives for study on biochar and tuber crop growth and yield are extensive. To enhance the development of cropping systems that are sustainable and productive, it is essential to address the research gaps that currently exist.

6 Conclusion

A wealth of data from the reviewed literature supports the use of biochar as a soil amendment to improve root and tuber crop growth and yield. Biochar has the potential to improve the physical, chemical, and biological properties of soil, thereby enhancing crop performance. One key benefit is its ability to enhance water and nutrient retention in the soil, which are vital for crop growth. However, it's important to note that the impact of biochar on crop performance depends on various factors such as the type of biochar, how it's produced, its particle size, application rates, and environmental conditions like soil type, climate, and management practices. To optimize the application of biochar for specific crops, soil types, and environmental conditions, more research is needed. Additionally, it is crucial to study how biochar affects the management of plant parasitic nematodes, which can damage tuber crop roots and reduce yields. Understanding these aspects is essential for the responsible and sustainable use of biochar as a soil amendment.

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