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Review Article

Advancing Horticultural Productivity Through Biochar Application: A Critical Review

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Abstract

Biochar is a black carbon produced by the pyrolysis of organic biomass in a pyrolysis environment and is used as a soil amendment. Its raw materials include forest mass, animal and municipal solid waste, crop residues, and algae. It has large surface area, high cation exchange capacity, microporosity, high carbon content, and chemical stability, making it effective in adsorbing organic and inorganic pollutants, including antibiotics, pesticides, volatile compounds, and PAH. It contributes to carbon sequestration, soil restoration, and water and sewage purification by absorbing polar pollutants with charged functional groups, stabilizing the pollutants and reducing their uptake by plants. In soil, it improves oxygen, water retention, moisture, adsorption area, bulk density, porosity, and pore size, raises CEC, EC, organic carbon, nutrient retention and efficiency, and reduces weeds, metal toxicity, and greenhouse gas emissions. It also provides an excellent environment for microbes, acting as a carrier of PGPB bacteria that promote plant growth, especially in vegetables and fruits. In summary, its physical, chemical, and biological properties greatly influence the growth of horticultural crops.

Keywords: Biochar; Pyrolysis; Soil Improvement; Horticultural Plants; Fruit and Vegetable Crops.

Introduction

Currently, sustainable agriculture uses environmentally friendly practices (1). Sustainable agriculture ensures the production of adequate food to satisfy existing requirements, without limiting the capabilities of subsequent generations to meet their demands. This can be done by conserving biodiversity, using natural resources responsibly, and minimizing any adverse impacts that come along with agricultural operations. Sustainable farming practices include crop rotation, organic manure usage, effective irrigation techniques, and natural pest control. Sustainable agriculture is also known for providing support to rural communities, strengthening resilience to changes in agriculture, and improving adaptation to climate change, as well as striking a balance between environmental sustainability, socio-economic development, and agricultural production. By 2050, it is anticipated that sustainable economies will enable Europe to be the world's first continent to reach zero CO_2 emissions (2). Biofertilizers and soil ameliorants offer a more sustainable option than mineral fertilizers because biofertilizers enrich soil without the harmful consequences of using excessive minerals (3). Excessive mineral fertilizers have resulted in deteriorated soils; continuous fertilization of plants has been done with different inputs to

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ensure they receive all necessary Key nutrients involved in sustaining plant growth and overall development. Levels of most nutrients may drop because of numerous reasons or simply due to the leaching, runoff, or any other phenomenon leading to high fertilizer loss. Hence, the necessity to minimize fertilizer losses during soil fertilization, including organic matter loss (4). Biofertilizers stimulate microorganisms living in soil and increase its capacity to retain nutrients and moisture. Moreover, it is an environmentally sustainable method, as biofertilizers decrease greenhouse gas emissions and prevent contamination of groundwater sources (5).

Horticulture is one of the agricultural branches dealing with the cultivation of fruits and vegetables. Fruits and vegetables undergo several stages, including harvest, handling, processing, and distribution to consumers., perennial, tuberous, aromatic, and other crops. In particular, horticulture represents intensive agricultural systems and proper crop management during cultivation, harvesting, and post-harvesting periods aimed at enhancing crop quality, taste, and appearance. Hence, horticultural crops have become very important components of modern agricultural practices since these crops integrate scientific, art, and technological methods in growing crops that meet people's nutritional needs and requirements (6). Horticultural crops and, in particular, fruits and vegetables play an essential part in increasing the country's revenue since these crops are necessary for satisfying the basic food needs of a growing population. Excessive production of these products may be exported to earn foreign currency. Therefore, despite using less land compared with field crops, horticultural crops play an important role in promoting prosperity within a country. The living standards of any community can be measured in terms of per capita production and consumption levels of horticultural crops. Also, these crops known for having high productivity per unit area and being a good a rich Provides significant amounts of vitamins together with key minerals, including calcium, phosphorus, and iron etc. (7). The prolonged reliance on chemical fertilizers and pesticides has contributed environmental contamination, soil deterioration, & health concerns, encouraging the implementation of sustainable farming systems. Biofertilizers and organic amendments improve soil fertility, nutrient availability, and microbial functioning while enhancing field crop growth & productivity. Previous studies demonstrated that organic farming systems can achieve yields comparable to conventional agriculture under suitable conditions. The application of beneficial microorganisms, including PGPR and mycorrhizal fungi, has shown positive effects on fruit quality, nutrient uptake, and plant resistance to stresses and diseases. Therefore, integrating organic and biological inputs represents an effective strategy for sustainable horticultural production and environmental conservation (8). Horticultural crops are grown on small and large farms and demand intensive farm management as well as a high level of professionalism. These crops are used by consumers either for eating or directly, and their purposes are food, ornamental, medicinal, and industrial. These crops include fruits, vegetables, ornamental, medicinal, and aromatic crops, as well as trees and shrubs grown in gardens and orchards. This article will mainly concentrate on horticultural crops (9). This development in agriculture has been based on the increased use of various inputs in agriculture in order to increase production and yields. For example, chemical fertilizer application increases costs as well as leads to the pollution of soil and water sources. Agricultural practices have changed, and nowadays farmers are more interested in sustainability in agriculture. The concept of sustainable agricultural production systems is becoming widely accepted in agricultural practices. In the last fifteen years, biochar has become a key instrument for mitigating climate change all over the world. These

technologies help to achieve food security and sustainable agricultural production systems (10).

Biochar is described as a black carbon product created using a variety of organic materials by undergoing thermal decomposition reactions at high temperatures and low amounts of available oxygen. Thermochemical conversions processes involved in biochar production processes using low-oxygen thermochemical processes, including pyrolysis, torrefaction, gasification, and hydrothermal carbonization of biomass. conditions (11). Among many other elements, the elemental composition of biochar includes hydrogen, carbon, oxygen, and phosphorus, comprising sulfur, nitrogen, and small quantities of micronutrients such as copper, zinc, and manganese. Iron different amounts in the biochar, which depend on the biochar type and source (12). Biochar is an inexpensive amendment for soils that features a considerable specific surface area and acts as a promising substitute for adsorption of multiple types of pollutants of organic and inorganic origin, including antibiotics, agricultural pesticides, VOCs, PAHs, and others. Due to its distinct physical and chemical characteristics, as shown in Table 1 below, biochar demonstrates high CEC, high adsorbing capacity, porous structure, high C content, and chemical stability. Because of its unique properties, biochar is extensively used for carbon capture, soil remediation, and the purification of water and wastewater (13). Additionally, biochar surfaces contain functional groups with charge, which leads to, it has a distinct property of binding polar chemicals, which allows biochar to immobilize organic and inorganic chemicals and prevent their intake into crops (14). Soil benefits from increased oxygen uptake, moisture retention capacity, soil moisture, adsorption surface, density, porosity, and pores from the application of biochar. The following list includes some of the most vital chemical properties that characterize biochar when used in soils: carbon capture, contaminant immobilization, decrease in metal toxicity, decrease in greenhouse gas emission, cationic exchange capacity, soil pH adjustment, changes in elemental composition, H/C and O/C ratios, soil organic carbon, soil EC, soil CEC, nutrient retention, nutrient use efficiency. Besides, it assists in the suppression of weeds while at the same time sustaining a favorable environment for crop growth (15). Biochar, in biological terms, positively affects the occurrence of soil microorganisms in addition to increasing nutrient accessibility in soil, thus improving its quality. Furthermore, it is considered a promising carrier for PGPB due to its capacity for nutrient retention and sustaining a suitable environment for soil microorganisms. All these factors result in better performance and yields of horticultural crops (16). Moreover, the incorporation of biochar into soils allows for agricultural & industrial waste recycling and decreases environmental pressure. Overall, these factors make biochar a viable and sustainable substitute for chemical fertilizers (17).

Tab 1. Main Physical and Chemical Attributes of biochar

Parameter	Unit	Biochar
pH	.....	9.7
EC	ds m-1	7.5
CEC	Cmol+ Kg	21.3
Total N	g Kg-1	9.1
Available N	Mg Kg-1	30
P Total	Mg Kg-1	1221.9
P Available	Mg Kg-1	217
Total C	g Kg-1	778.1
Organic C	g Kg-1	705.6
H	g Kg-1	45.3
H/C	.....	0.76

Literature Review

Biochar Amendment Effects on Horticultural Crop Growth and Development

Many studies have analyzed the effect of biochar incorporation on the growth and productivity of ornamental and horticultural plants, all having positive results in terms of vegetative, reproductive, and qualitative attributes of plant productivity. (18) investigated the impact of two different biochar treatment doses (0% and 100%) on Malus domestica var. Red Fuji and found that the application of the higher dose resulted in better nitrogen uptake by leaves, stems, and roots. Moreover, the quality of the root system in terms of total dry mass, length, number, and surface area of roots was significantly improved in plants under the treatment compared to those without treatment. Similarly, (19) studied the effect of different doses of biochar on banana (Musa spp.) var. Grande Naine over two growing seasons. Results indicated progressive improvements in foliar area, pseudostem dimensions, and macronutrient concentrations with increasing biochar doses. Fruit quality indicators — encompassing finger dimensions, pulp-to-peel ratio, bunch and finger weights, finger count per bunch, total hectare yield, soluble solids, sugar content, and starch levels reached their peak values at the 20 t ha^{-1} rate in both seasons. In a greenhouse-based study, (20) evaluated biochar applications at 0%, 2%, and 5% on potted wheat plants, finding that the 2% rate optimized most growth characteristics such as number of leaves, leaf area, and plant height, shoot & root fresh weights, spike number, spike dimensions, and overall yield per plant. Notably, however, maximum 100-grain weight was recorded at the 5% biochar level.

Conversely, (21) observed that applying biochar to tomato plants improved plant growth biomass and total yield at a rate of 1 kg m^{-2} in comparison with a lower amount of biochar. These researchers tested the effect of three biochar rates (0, 0.5, and 1 kg m^{-2}), with the highest yielding the best results. (22) stated that biochar applications to sweet pepper plants grown under five different rates at incremental doses of 0, 8, 16, 30, and 40 t ha^{-1} significantly improved total chlorophyll content in leaves, shoot and root fresh and dry matter, and nutrient contents (N, P, & K) in leaves and fruits, and total yield per plant. The greatest impact was achieved by using the highest rate of 16 t ha^{-1}. Root dry weight showed the highest significant result at a dosage of 8 t ha^{-1}, whereas the rest of the variables showed better outcomes at 16 t ha^{-1}. Additionally, according to (23), biochar applications had many benefits for crop performance in the horticulture industry. The objective of this study was to investigate the effect of biochar application on some vegetative & reproductive traits of cherry tomatoes (Solanum lycopersicum var. cerasiforme). Biochar was applied at two rates (0 and 20%) in 9-L pots containing a growing medium composed of peat, silica sand, and bark humus mixed at a ratio of 1:2:1. The study assessed vegetative, root, floral, and fruit growth parameters. The obtained results indicated that an increasing dose of biochar led to considerable improvement in various vegetative growth factors, such as number of leaves, area of each leaf, shoot and root dry weight, root elongation, root surface, proportion of nitrogen in the leaves, and proportion of carbon in the leaves. In addition to vegetative growth improvement, biochar application also contributed to the reproductive process of the plants by increasing reproductive traits, including flowers per plant, fruits per plant, and fruit diameter, dry weight of each fruit, and level of total soluble solids and acid fruit content relative to untreated plants. (24) investigated the impact of varying biochar application rates (0, 3, 6, 9, and 12 t ha^{-1}) in potted lettuce (*Lactuca sativa* L.) cv. Vera and observed a considerable increase in total leaf chlorophyll content, fresh biomass and dry biomass of leaves and roots & average root length. Among all applied biochar doses, the highest rate of 12 t ha^{-1} proved to be superior in producing the greatest impact on the growth of the crop, especially when planted in two distinct soils: Andosol

(originating from a coffee farm) and Embrisol (obtained from a greenhouse). Furthermore, (25) proved that application of biochar at 1.6 kg tree^{-1} in two subsequent years for peach trees (*Prunus persica* L.) cv. Meredith resulted in significant improvements in individual leaf area, fresh weight of leaves, stem diameter, fresh weight of each fruit, fruit count, and cumulative yield per plant in comparison with the control trees without biochar.

(26) observed remarkable benefits in terms of performance of common beans (*Phaseolus vulgaris* L.) upon inclusion of biochar in the growth substrate, with remarkable increases achieved in the total amount of chlorophyll in foliage, growth and yield attributes such as number of leaves per plant, plant height, flowering period, pod number, pod size, and pod weight, number of seeds per pod, and ultimately yield per hectare. From among the different levels assessed, it is clear that 6 t ha^{-1} performed better than 3 t ha^{-1} and the controls (untreated).

Concurrently, (27) revealed that tomato plants (Solanum lycopersicum L.), which were grown under greenhouse conditions for two successive years (2021-2022), benefited from biochar amendment at a level of 30 t ha^{-1}, resulting in significant increases in photosynthetic pigment content, leaf area, and plant development height, stem diameter, total plant biomass, fruit diameter, and number of fruits per plant compared to controls. Fruit-related quality attributes were equally responsive, with fruit number, per-plant total yield, soluble solids content, total sugar levels, and ascorbic acid concentration in harvested fruits all reaching their highest recorded values at the 30 t ha^{-1} biochar rate relative to the control treatment.

(28) evaluated the effect of biochar application at two rates of 0% and 5% on the vegetative growth of three strawberry varieties (Fragaria × ananassa Duch.), namely Paros, Camarosa, and San Andreas, under a hydroponic production system. Their findings show that each variety responds differently to biochar addition. For instance, cv. Paros was able to obtain considerable increases in leaf total chlorophyll content, fruit mass, fruit number, and productivity at 5% biochar application rate. Meanwhile, cv. San Andreas demonstrated remarkable improvement in fruit firmness, soluble solid content, total acidity, vitamin C level, and fruit zinc content at 5%. Meanwhile, cv. Camarosa demonstrated a distinct response, with fruit iron concentration registering a significant maximum increase at the 5% biochar treatment compared to control plants across all three cultivars.

(29) demonstrated that biochar treatment of 'Red Fuji' apple trees (Malus domestica Borkh.) at seven rates (0, 2, 4, 6, 8, 10, and 12 kg plant^{-1}), established at a spacing of 4 × 4 m, resulted in significant increases in fruit longitudinal and transverse diameters, total yield per tree, and total sugar percentage at a biochar rate of 6 kg plant^{-1}. Furthermore, fruit color intensity and fruit weight were maximized at 8 kg plant^{-1}, whereas the highest significant improvements in fruit firmness, marketable fruit percentage, total soluble solids content, and fruit acidity were recorded at 12 kg plant^{-1} compared with the other treatments. (30) stated that biochar applied at a rate of 2% to two-month-old Malus robusta seedlings significantly enhanced total photosynthetic pigment content, stem girth, and plant stature, biomass production (fresh & dry), and root system traits such as length, surface area, and volume & root number compared with the control. Additionally, biochar treatment markedly increased the activities of antioxidant enzymes, including the antioxidant enzymes superoxide dismutase (SOD), catalase (CAT), & peroxidase (POD), in both leaves and roots. A study also revealed a significant increase in beneficial soil bacterial and fungal populations, as well as an improved bacteria-to-fungi ratio in rhizosphere soil. (31) found that biochar application to okra plants (Abelmoschus esculentus L.) under four treatments (control without biochar, rice husk–derived biochar, biochar derived from plant stems) significantly

influenced growth and yield attributes, indicating the potential role of biochar feedstock type in determining its effectiveness on crop performance.… cassava- and wood shavings–derived biochar applied to okra plants grown in pots caused a significant differences in plant height, foliar traits (*leaf number and area*), and fruit characteristics (*length, diameter, weight, and number per plant*) The greatest improvement was recorded with biochar prepared from rice husk feedstock in relation to other treatments especially during the tenth week after planting. The data were obtained at two, four, six, eight, and ten weeks after planting.

(32) determined the outcomes of applying biochar to the soil on the fruit qualities of tomatoes using different temperatures during the pyrolysis process of biochar (0, 300, 400, and 500 °C), all added to plants at a constant rate of 5 g per plant. They found that there was substantial variation in the fruit qualities based on treatment for TSS, TA, and the TSS/TA ratio, where biochar pyrolyzed at 300 °C exhibited the best results compared to the other temperatures. Using pots, (33) conducted an experiment to determine the response of strawberries to different types of biochar (control, unmodified biochar, CO_2-activated biochar). Each type was applied in the pots in concentrations of 0, 2, and 15 g L^{-1}. Differences in the responses were found in plant and reproductive performance, such as greater plant height for unmodified biochar at 2 g L^{-1}, more flowers for the control, and a significantly higher number of fruits per plant when using the unmodified biochar at 15 g L^{-1}. (34) also evaluated the effect of incorporation of biochar at 0, 2, and 4% on potted strawberry of the cultivar 'Charlotte'. Incorporation of 4% biochar led to significant increases in total leaf chlorophyll status, per-plant leaf area, plant height, and fresh weight of above-ground tissues (leaves and stems), leaf dry matter percentage, and several reproduction-related traits including flower number, floral bud number, and inflorescence number. Crown diameter, root length, and root fresh biomass reached their peak levels at the medium level of 2%, suggesting that the optimal dose depends on the trait under investigation. (35) studied the tomato plant response to biochar addition under application levels of 0, 4, and 12 t ha^{-1} and demonstrated a dose-dependent increase in vegetative growth. Leaf area, plant height, and stem diameter all exhibited a positive correlation with biochar dose, with their highest values obtained at 12 t ha^{-1}. In the research conducted by (36), impacts of biochar treatment on blueberry yields in different farming practices were evaluated. Biochar was added at three concentrations: 0%, 5%, and 10%. The highest stem diameter and yield of fruits per plant were observed in plants treated with 10% biochar. The fruit quality indices of TSS, titratable acidity, TSS/TA ratio, total phenolic content, and anthocyanin content also demonstrated statistically significant differences between the three groups. Thus, the results obtained validate the potential use of biochar as a means of improving blueberry soil. In turn, in the investigation of (37), the influence of biochar was analyzed on orange tree seedlings (Citrus sinensis) at five concentrations of biochar addition: 0%, 5%, 10%, 20%, and 40%. Positive changes in leaf number, stem diameter, shoot height, and dry biomass of shoots and roots were achieved, & the highest growth rate was achieved at 5%. Finally, the effects of different concentrations of biochar on fig trees (Ficus carica cv. Aswad Diyala) were investigated in the work of (38). All biochar treatments significantly elevated leaf chlorophyll content and the contents of macronutrients (N, P, K, Mg, Ca) and trace elements (Zn, Fe, Mn), while branch carbohydrate accumulation was highest at the 4% rate.

Discussion

The role of biochar in horticultural crops and soils can be clearly observed, as it is considered an effective soil amendment that contributes to supporting improved growth and yield performance

of horticultural crops under both non-stress and abiotic stress conditions such as drought, salinity, heavy metal contamination, and heat stress. (39). Biochar application to horticultural crops produced a modest increase in the permanent wilting point, which represents a physiological condition at which both plants and soil reach low moisture content, accompanied by an increase in soil water content at field capacity. This, in turn, contributed to increasing the amount of water available to horticultural crops. This effect is attributed to soil improvement in terms of water-holding capability, which positively reflects on vegetative growth through an increase in leaf area and photosynthetic efficiency, and consequently enhances flowering and fruit development. In addition, biochar application improved the growth of horticultural crops, increased germination, and enhanced grain yield associated with reducing the severity of water stress (40, 41). Biochar added to soil improved water interactions between horticultural crops, soil, and the surrounding environment, under both drought and irrigation conditions (42). This improvement led to enhanced vegetative and floral growth, increased flower number and fruit set percentage, and consequently improved fruit development and total yield. Furthermore, it has been revealed that the use of biochar has increased horticultural crop production when water scarcity was observed due to improvement in the efficiency of water usage by plants. Concerning the problem of salinity stress, Evidence suggests that increasing amounts of biochar application help reduce salinity-induced stress effects in horticultural plants. (43). The mechanism that explains the positive impact of biochar on horticultural plant development lies in improving ionic balance in the organism due to neutralization of negative influences of sodium ions and potassium ion accumulation, which helps improve vegetative growth, regular flowering, better fruit setting, and higher productivity (44).

Moreover, biochar addition to soils contributed to the physiological development of horticultural plants and the improvement of grain quality and its characteristics, as well as the development of tolerance to osmotic stress, nutrition, and soil characteristics. This is due to the induction of the plant antioxidant system via the stimulating activity of the peroxidase enzyme, ascorbate peroxidase enzyme, and catalase enzymes. Finally, several Recent studies support the idea that biochar is vital in protecting horticultural plants from different biotic stresses, such as powdery mildew and wheat rust (45). An extensive analysis conducted on 13 cropping systems suggested that 85% of the research found reductions in plant disease severity upon biochar application, while only 3% reported negative effects, and 12% showed no difference (46). As a result, biochar addition had a positive effect on disease incidence within horticultural crops, hence affecting their vegetative growth, increasing flowering, and fruiting. Further, biochar application led to increased biomass accumulation within horticultural plants, reduced diseases caused by nematode infections, and increased the resistance of crops against diseases and abiotic stress through the activation of defense-related genes, such as Pathogenesis-Related protein-1b (PR-1b) and Jasmonate Ethylene Response Factor 3 (JERF3). Consequently, biochar application promoted the improvement of fruit quality traits and productivity (47). Moreover, the incorporation of biochar was associated with elevated seedling length and leaf area, hence improving overall growth performance of horticultural crops. Furthermore, biochar possesses the unique property of carbon sequestration in soils due to the pyrolysis of organic material, transforming carbon into its stable form, which persists in soils for several hundred and even thousands of years. It helps reduce greenhouse gases in the air, improves soil physical and chemical conditions, increases biological activity, and reduces environmental stresses (48). Thus, biochar has several impacts on rhizosphere processes by

enhancing the decomposition of organic substances into mineral elements, nutrient absorption, and reduction in heavy metal toxicity. These factors enhance plant disease resistance, improve vegetative, floral, and fruit growth, improve fruit quality, and promote better tolerance of horticultural plants facing biotic and abiotic stressors (41). These results correspond to those observed by other researchers, supported by multiple studies, e.g., (18, 22, 30, 28, 31, 32, 37)

Conclusion

Clearly, the results obtained prove that biochar is an essential component in improving crop performance, due to the capacity of biochar to enhance crop development, productivity, and quality characteristics. on soil properties & plant physiological functions. First of all, the introduction states that soil moisture-holding capacity can be increased through biochar amendment. content, nutrient supply, and root activity, leading to better growth and development of vegetative parts, flowers, and fruits. Additionally, biochar is useful for coping with negative effects of abiotic stresses, like water scarcity, salt accumulation, heavy metal toxicity, and excessive temperature, as well as biotic stresses, like diseases and nematodes, owing to improved ionic balance, enhanced action of antioxidant systems, and regulation of gene expression involved in stress responses. Besides agro-beneficial effects, biochar acts as an important carbon sink, contributing to improving fertility in the long term and preserving the environment from anthropogenic changes.

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