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The effect of biochar application on plants in sustainable crop production

*Mohamad Hesam Shahrajabian**

Department of Agronomy and Plant Breeding, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan 81551-39998, IRAN

*Corresponding author: e-mail: hesamshahrajabian@gmail.com

Abstract. Biochar is a C-rich material and a solid product which can be obtained from different types of organic feedstock and materials with high carbon content, such as animal manure, sewage sludge, wood and crop residues and other organic waste under high temperatures and in low absence of oxygen. It is also considered as a microporous structure, an alkaline pH, with a high cation exchange capacity, and a notable organic carbon content. Biochar can promote plant growth and improves crop yield as well as various environmental advantages such as sequestering atmospheric carbon, decreasing greenhouse gas emissions, and contrasting global warming. The aim of this literature review is to show the impact of different kinds of biochars on crop yields and quality. Relevant literature has been obtained using the keywords "Biochar", "crop yield" "crop quality" in scientific databases, such as "PubMed", "SciFinder", "Elsevier", and "Web of Science". According to these data, biochar can increase yields and improve the quality of crops, but the study also provides examples of its adverse effects. It emphasizes the need for further research, including on the interactions between biochar, soil, and plants.

Keywords: biochar, organic amendment, crop yield, crop quality

INTRODUCTION

Sustainable agriculture is one that produces abundant food without depleting the world 's resources or polluting its environment. Sustainable agriculture follows basic principles such as sustainable systems for sustainable crop production, with considering social values, provide domestic food security, and considering all concerns of small farmers, environmentalists, agricultural scientists as well as the government policy makers.

The increasing land degradation is a necessary problem that impacts many soils in several countries, and in this aspect, the soil organic matter (SOM) has a vital function, because of its progressive biodegradation parallels to the concomitant emissions of CO_2 to the atmosphere and desertification (Jimenez-Gonzalez et al., 2022). It is considered that soil quality could be a main cause of yield gaps. Soils also has a significant role in the global carbon cycle and are important to the management of climate change (Farooq et al., 2020; Almagro et al., 2021). Soil C content was protected in subsurface and in the more reliable fractions of soil organic matter (Almeida et al., 2021; Sun, Shahrajabian, 2025). Microbial nitrogen immobilization in soil can be improved by boosting carbon bioavailability (Cao et al., 2021; Che et al., 2021). Several techniques to improve both sustainable agricultural intensification and fertilizer utilization will be more successful, if soil fertility is studied comprehensively (Burke et al., 2022).

Biochar is carbonaceous product obtained from the incomplete combustion of numerous organic materials (Mavi et al., 2023; Sun, Shahrajabian, 2023). Generally, biochar application improves soil N accessibility and retention, reduces soil bulk density, boosts water holding capacity, promotes appropriate microorganisms, increases pH and cation exchange capacity, and decreases the bioavailability of heavy metals (Yuan et al., 2022). Application of biochar into soils alone or combined with fertilizer or manure have been reported to have many notable advantages for soil and environmental attributes (Zhang et al., 2017; Bilgili et al., 2019). Biochar benefits soil by increasing their biological, chemical, and physical properties such as pH, electric conductivity, ion exchange capacity, aggregate structural stability, and water-holding capacity (Cao et al., 2021; Liu et al., 2022; Tian et al., 2023; Xiang et al., 2023).

This article aims to study new sources of biochar effect on crop yield and quality in sustainable crop production. The latest relevant literature has been obtained from scientific databases, such as "PubMed", "SciFinder", "Elsevier", and "Web of Science".

BIOCHAR PRODUCTION AND CHARACTERISTICS

Biochar is a carbon-rich by-product when biomass is degraded under limited oxygen conditions (Huang et al., 2023a,b). Different biochar substrates are natural vegetative growth, organic wastes and residues (floating plant waste, forest residue), farm and crop residues (agricultural crop residue, animal waste), municipal waste (urban solid waste, urban refuse waste), industrial waste such as food processing waste, and plantation producing energy crops such as plant and tree species (Parmar et al., 2014; Kan et al., 2016; Parwar et al., 2019; Diatta et al., 2020; Gabhane et al., 2020; Kapoor et al., 2020). Pyrolysis, a thermochemical process, involves decomposing organic materials at elevated temperatures in the absence of oxygen, and this process produces a variety of products, including bio-oil, biochar, and syngas, whose properties are significantly influenced by several technological parameters, and key parameters include heating rate, temperature, feedstock composition, residence time, and reactor type (Alkharabsheh et al., 2021; Sharma et al., 2022; Bolan et al., 2023; Tan et al., 2023). Biocarbon exhibits varying chemical compositions and physicochemical properties depending on feedstock and production methods, key components include carbon (44% to 95%), oxygen (0% to 45%), and hydrogen (1% to 9%).

The most important physical and chemical properties of biochar are presented in Table 1. The most notable benefits of biochar application are mentioned in Table 2.

THE EFFECT OF BIOCHAR ON CROPS

Biochar has several advantages which predispose it to be used in sustainable agriculture like the potency of sequestering carbon thus inducing to climate change mitigation, improved nutrient retention by soil, sorption or organic contaminants, increase in soil fertility (Shang, Chi, 2023). Biochar can also increase soil microbial activities by providing labile C, mineral nutrients, and habitat as microbes promptly colonizes biochar surface. The addition of biochar as an amendment to soil increases the biological and physicochemical properties of soil, and thereby improves the soil quality (Akhtar et al., 2020; Chen et al., 2023). Due to these properties, biochar may have an impact on crop plants. The scope and direction of the changes it causes were discussed using examples taken from the literature (Table 3).

Studies on the effects of biochar application on different plant species show a mix negative, positive, and neutral responses, commonly influenced by parameters like application rate, biochar type, and plant species, while some studies highlight significant increases in nutrient uptake,

Table 1. Physical and chemical properties of biochar (Yadav et al., 2023).

Characteristics	Key-points
Porosity	The pore size of biochar changes on the basis of the material applied for biochar production and usually ranges from nano (<0.9 nm), micro (<2 nm), meso (2–50 nm) to macropores (>50 nm).
Surface functional groups	Different functional groups (e.g. hydroxyl-OH, amino-NH_2, ketone-OR, ester -(C=O)OR, methyl-CH_3, nitro-NO_2, aldehyde-(C=O)H, carboxyl-(C=O)OH are shaped on biochar surface.
Carbon content	Biochar is greatly stable, consisting of more than 65% carbon. Chemical composition is greatly dependent on feedstock and pyrolysis conditions.
Cation exchange capacity	Low temperature biochars usually have high CEC as they are rich in oxygenated functional categorizes, indicative of high complex formation intensity with metal cations.
Structure	Among elements, C, O, H, and N are the most common elements and usually contribute to the main structures of biochar.
pH	Different alkaline salts, alkali metals (Na, K, Mg, and Ca), and $CaCO_3$ are connected with higher pH of the biochars. Generally, biochar pH is found to be >7.
Surface area	The surface area of biochar boosts with the improvement in pyrolysis temperature. Highly porous structure, large surface area, and high pore volume are assumed favorable.
Non-organic content	The ash constituent is the nonorganic fraction of biochar include elements such as Mg, O, Ca, S, N, K, etc.

Table 2. The most important advantages of biochar application.

Characteristics	Reference
Enhance the soil ·s properties	Oliveira et al., 2017 Tisserant, Cherubini, 2019
Improvement in fertility status by increasing nutrient availability	Karimi et al., 2020
Soil remediation	Wang, Wang, 2019
Induces microbial activity in the soil	Hale et al., 2015
Agronomic importance (crop improvement)	Saudy et al., 2021, 2022
Climate change mitigation	Wang et al., 2022a; Shahrajabian, Sun 2023a,b
Carbon sequestration	Montanarella, Lugato, 2013
Mitigate greenhouse gas emissions	Wang et al., 2023b, Li et al., 2023a

root growth, and biomass, and others indicate potential negative effects on plant health and growth, especially at higher biochar concentrations or with specific biochar types (Xiao et al., 2016).

Many publications refer directly to the impact of biochar on plant yields. Azeem et al. (2019) indicated that sugarcane-bagasse biochar utilizations in arid soils with low organic carbon may increase crop productivity and N_2-fixation of legumes while decreasing the net ecosystem CO_2 exchange (NEE) of legume-cereal cropping systems. It has been reported that application of straw-derived biochar to amend soil could be the suitable technique for sustaining soil fertility and crop yield in wheat-maize rotation systems in the Loess Plateau of China (Hu et al., 2021). Farhangi-Abriz et al. (2021) reported that biochar increased grain yield of maize (by 14–35%) and wheat (13.5%), and rate of biochar >30 t ha^{-1} did not influence crop yield substantially. Pandit et al. (2018) recommended 15 t ha^{-1} biochar for a maize-mustard field cropping system. For maize yield the effect of biochar depended on the dose (Kim et al., 2016; Jia et al., 2020). Biochar application significantly influence cotton yield and production (Karthik et al., 2019; Li et al., 2023c). Biochar addition boosted crop yield of arugula (*Eruca sativa* L.) (Zhou et al., 2017). In the case of cauliflower plants the highest values of curd size and weight were obtained at the biochar rate of 3% (Losacco et al., 2022). Biochar can be regarded as a potential soil amendment for an increased red onion growth (Peiris et al., 2022). Poultry litter biochar increase onion productivity (Arif et al., 2021). Poultry litter biochar with manure and NP fertilizer increased plant growth and yield of cucumber (Solaiman et al., 2020).

Sometimes biochar application has negative impact on crop plants. Yin et al. (2023) reported that the biochar application reduced the root weights and fresh shoot of corn and rice seedlings, but there was no significant impact on wheat seedlings. Century-old biochar enrichment in soil increased crop canopy, but had an adverse effect on plant greenness over the maturity period of chickory (Dehkordi et al., 2020). Orchard prune residue biochar amendment did not influence biomass yield and decreased germination without nutrient supplement of tomato plants (Beesley et al., 2013). Lai et al. (2013) showed no impact of biochar application on rice and leaf beet yield, pine hardwood biochar had even negative effect on cotton yield (Bohara et al., 2018).

Biochar affects also composition, development, physiological parameters and quality of plants. The combined application of chemical fertilizer and biochar improved crop and essential oil yield of basil plants, but without effect on aroma compounds (Pandy et al., 2016). Biochar from tobacco stems reduced vanillic acid and syringic acid constituents of Chinese ginseng plants (Zhao et al., 2022). Biochar derived from black cherry wood boosted plant height, increased leaf length and width, as well as leaf number of basil, moreover, the chlorophyll content, total sugar, flavonoids were increased significantly (Jabborova et al., 2021). Wood chip biochar increased the photosynthesis and decreased the oxidative stress of ice plant (*Mesembryanthemum crystallinum* L.), (You et al., 2021). Biochar had no effect on cotton fiber quality indices (Li et al., 2023c).

Biochar can also affect phytosanitary status of soil. Biochar combined with *Bacillus subtilis* enchanced growth and plant health of radish (Chen et al., 2023). Poultry litter biochar can suppress Stemphylium leaf blight on onion (Arif et al., 2021). Zhou et al. (2021) concluded that biochar improved the yield of cucumber under continuous cropping system, because of soil microbial community regulation.

Soil biochar application boost the resilience of vineyards to water shortages, and soil biochar addition improves the soil water-holding capacity in vineyards, so it could be an important strategy for climate change adaptation (Baroneti et al., 2022). Biochar application is a factor of improvement of WUE of maize (Faloye et al. (2018) and fenugreek (Bitarafan et al. 2020).

The effect of biochar on plants under different stress conditions was also studied. Biochar has the capability to boost crop yields on degraded, tropical soils (Elias et al., 2020; Tan et al., 2023). Sunflower stem biochar improved millet yield in saline and sodic soil (Taheri et al., 2022). Rice straw biochar stimulated crop performance of cotton and wheat under saline water irrigation (Singh et al., 2021).

P-rich biochar limits Pb accumulation in rice on Pb-contaminated soils (Yang et al., 2023). The application of biochar and modified biochars with H_2O_2, KOH, and H_3PO_4 could increase mint growth and productivity under fluoride and cadmium toxicities (Ghassemi-Golezani, Farhangi-Abriz, 2023). Zeeshan et al. (2020) concluded that the lower size biochar particles were notably more effective for potential agronomic and soil

Table 3. The impacts of different kinds of biochar on growth and final yield of crops.

Plant	Treatment	Key points	Reference
1	*2*	*3*	*4*
Basil (*Ocimum basilicum* L.)	Biochar (BC) and Chemical fertilizer	• The combined application of chemical fertilizer and biochar improved crop and essential oil yield. • Higher concentration of biochar improves the overall microorganism population.	Pandy et al., 2016
	Biochar derived from black cherry wood (1, 2, and 3%)	• Biochar concentrations of 2% and 3% significantly boosted plant height by 38% and 48%, leaf length by 15 and 24%, leaf number by 15% and 27%, and leaf width by 36% and 50%, respectively. • The chlorophyll content, total sugar, flavonoids and soil enzymes activities were increased significantly with 2 and 3% biochar treatments. • The biochar treatment of 3% significantly increased root surface area by 47%, root diameter by 37%, and root volume by 45% over the control.	Jabborova et al., 2021
Cauliflower (*Brassica oleracea* L.)	Nitrogen compounds (nitrate, ammonium) from biochar-amended soil in comparison to untreated (Control)	• Biochar enhanced nutrient availability in the soil by boosting its chemical and physical characteristics. • The highest values of curd size and weight were obtained at the biochar rate of 3%.	Losacco et al., 2022
Chicory (*Cichorium intybus* L.)	Century-old biochar	• Century-old biochar enrichment in soil boosts crop canopy cover. • Biochar has an adverse effect on plant greenness over the maturity period.	Dehkordi et al., 2020
Chinese cabbage (*Brassica rapa*)	The biochar was prepared by charring rice hull from Purnnature (Suncheon, Korea) and Yoogi Lnd (Gonchang, Korea)	• The impacts of biochar amendment on soil physico-chemical properties, changes soil nutrition dynamic including nitrogen and have agronomic advantages.	Chun et al., 2022
Chinese ginseng (*Panax notoginseng*)	Biochar from tobacco stems at the rates of 9.0, 12, 15, and 18 t ha^{-1}	• Biochar increased soil pH, available K, and P but reduced NH_4^+-N content. • Biochar boosted soil microbial diversity and reduced vanillic acid and syringic acid constituents.	Zhao et al., 2022
Cotton (*Gossypium hirsutum* L.)	Biochar application rate (BCAR) at 10 t ha^{-1}	• Neither cotton fiber quality indices (length, Micronaire, strength or uniformity index) were meaningfully influenced by biochar applications.	Li et al., 2023c
	Biochar application rate (BCAR) at 4.0 t ha^{-1}	• Biochar application rate (BCAR) at 4.0 t ha^{-1} significantly increased soil physical-chemical characteristic of a cotton field.	Karthik et al., 2019
Millet (*Panicum miliaceum* L.)	Sunflower stem biochar (15 t ha^{-1} biochar)	• Application of biochar in saline and sodic soil improved millet yield by improving the soil·s chemical and biological properties.	Taheri et al., 2022
Mint (*Mentha crispa* L.)	The application rate of biochar and modified biochars with H_2O_2, KOH, and H_3PO_4 was 25 g kg^{-1} soil	• The chemically engineered biochars are the appropriate treatments to increase mint growth and productivity under fluoride and cadmium toxicities.	Ghassemi-Golezani, Farhangi-Abriz, 2023
Radish (*Raphanus sativus* L.)	Microbial biochar formulations (BCMs) and *Bacillus subtilis* SL-44	• The combination of biochar and *B. subtilis* SL-44 increased soil texture, reduced *Fusarium* wilt, and stimulated radish growth. • BCMs treatments showed a significant boost in the abundance of bacterial genera in the rhizosphere soil of radish.	Chen et al., 2023
Red onion (*Allium cepa* L.)	Different biochar (BC) ratios (2% and 5% w/w)	• The tea waste biochar (TWBC) can be regarded as a potential soil amendment for an increased red onion growth.	Peiris et al., 2022

Table 3 continuation

1	*2*	*3*	*4*
Onion (*Allium cepa* L.)	Three pyrolyzed biochars cotton sticks, wheat straw and poultry litter	• Poultry litter biochar can be successfully applied to suppress SLB in onion and productivity of the crop.	Arif et al., 2021
Rice (*Oryza sativa* L.)	Biochar manures were applied at a rate of 12 Mg ha^{-1} (dry weight) in a rice paddy	• Compost and biochar significantly reduced net global warming potential (GWP) within rice cropping boundary. • Composting and pyrolysis emitted huge amount of greenhouse gas (GHCs) within industrial process boundary.	Canatoy et al., 2022
	Combining 20 t ha^{-1} of biochar with 25% inorganic fertilizer application rate	• Biochar improves the cost of production in the first cropping season. • Residual biochar decreases cost of production in the second cropping season. • The greater the quantity of biochar used, the higher the cost of production.	Danso et al., 2023
	Fe-modified and P-rich biochars	• They could remediate paddy soils contaminated with As, and increase the yield and quality of rice.	Yang et al., 2023
	P-rich biochar	• Application of pristine P-rich biochar could also be a promising technique to remediate the Pb-contaminated paddy soils and limit Pb accumulation in rice.	Yang et al., 2023
	Fresh and aged holm oak biochar (BH)	• The application of BH as organic amendment may be an effectual tool to greatly decrease water contamination by clomazone in rice fields under conventional tillage and flooding irrigation, but also under sprinkler irrigation.	Lopez-Pineiro et al., 2022
	Biochar addition rate at 20 t ha^{-1}	• Biochar addition significantly reduced YSGE in paddy rice field. Biochar stimulated biodiversity and abundance of methanotrophic microbes. • Biochar increased soil pH and aeration by reducing soil bulk density.	Qin et al., 2016
Soybean (*Glycine max* L.)	The application of 2% peanut straw biochar (PSB) in polluted soil	• The application of 2%% PSB in polluted soil resulted in significant increases in soybean height (58%), biomass production, root length (44%), shoot length (52%), chlorophyll contents (92%), soybean functional leaves (62%), total soluble sugars (TSS) (71%), and base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+})	Kamran et al., 2022
Sunflower (*Helianthus annuus* L.)	The optimum biochar concentration at both CO_2 levels (420 ppm and 740 ppm) was found to be 15%	• An elevated atmospheric CO_2 concentration (740 ppm) suppresses sunflower plant reproductive part growth. • Biochar decreases the heavy metal accumulation in sunflower roots and seeds. • Seeds of sunflower plants grown with safety compliant biochar meet with food safety regulations.	Wang et al., 2023c
	Four biochars namely, B1) fast pyrolysis from pine wood, B2) paper-sludge, B3) sewage sludge, B4) derived from grapevine wood.	• Addition of 1.5 t ha^{-1} biochar did not significantly alter the pH of the soil, its electrical conductivity (EC) or its war holding capacity (WHC). • Increasing the amount of biochar to 15 t ha^{-1} changed those parameters.	Paneque et al., 2016
Wheat (*Triticum aestivum* L.)	2% (w/w) bamboo biochar (BB), coconut shell biochar (CB), and maize straw biochar (MSB)	• Biochar could reduce dietary risk of polycyclic aromatic hydrocarbons (PAHs) in wheat grains particularly by improving the abundance of bacteria related to PAHs degradation, promoting the biodegradation of PAHs in the rhizosphere soil, and consequently decreasing PAHs uptake in wheat.	Wang et al., 2023a
	10 t ha^{-1} and 20 t ha^{-1} biochar	• Biochar addition significantly altered the composition and diversity of the rhizosphere bacterial community and increased the growth traits of winter wheat.	Li et al. 2023b

Table 3 continuation

1	2	3	4
Wheat (*Triticum aestivum* L.)		• Biochar application had contrasting impacts on wheat yield in the two soils. • The abundance and diversity of keystone species close correlated with wheat yield.	Qiu et al., 2022
		• Biochar rates to soil improve grain yield and shoot biomass tropical wheat. • The highest biochar rate boosted the number of tillers and heads in wheat plants.	Abburuzzini et al., 2019

fertility advantages of tomato crops of biochar under heavy metal contaminated soil conditions. Biochar decreases the heavy metal accumulation in roots and seeds of sunflower (Wang et al., 2023c). Biochar application can ameliorate rice yield and reducing the accumulation of As in rice grain (Sun et al., 2024a,b). Peanut straw biochar used on arsenic polluted soils increased size and weight of soybean plant, as well as chlorophyll and soluble sugars content (Kamran et al., 2022).

The application of biochar with swine manure and sawdust mixture increase the content of nutrients and reduce the level of phytotoxicity in vegetable crops such as carrot (*Daucus carota*), radish (*Raphanus sativus*), tomato (*Lycopersicon esculentum*), cabbage (*Brassica oleraceae*), and napa cabbage (*Brassica rapa*) (Milon et al., 2022). Erdem (2021) reported that corn cob and rice husk biochar reduced Cd uptake of tobacco plants, and the effect of corn cob biochar was better because of its higher specific surface area. Biochar amendment reduce phytotoxicity of herbicide sulfentrazone on wheat seedlings (Wang et al., 2022b).

CONCLUSIONS

Biochar is the solid, carbon-rich product of the pyrolysis of biomass. It is potentially valuable and important soil amendment with tremendous agricultural benefits. Pyrolysis conditions like reactor shape and type, feedstock particle size, biomass type, heating rate, chemical activation, residence time, etc., influence the physical parameters of biochar. The benefits of biochar are increasing soil nutrients and soil organic matter content, improving soil chemical, physical and biological properties. It can reduce pollution by binding heavy metals and other contaminants. Biochar application is an effective management practices to reduce the negative impacts of climate change, which is a great challenge for human society and a pressing global issue. The interaction between plants, soil, and biochar is multifaceted, involving chemical physical, and biological processes. Biochar can positively influence both crop yield and quality. The examples from the latest literature on the subject given in the study confirm the beneficial effect of biochar application on wheat, rice, millet, soybean as well as radish, onion, cucumber, basil, mint, but they also show the possibility of negative impact on crop plants.

According to the results, future researches are important to study the mechanisms containing the microbiological and chemical nature of the synergistic and antagonistic interactions between organics and biochar so that efficient guidelines can be progressed to assure trustworthy performance of biochar treatments on crop productivity in various agricultural methods. Researches are needed to analysis and evaluate the applications of biochars with considering both its advantages and disadvantages in both plant health and soil quality.

Future studies and researches should consider long-term effects of biochar application on both plants and soil, optimizing biochar for specific goals, and improving new strategies for biochar quantification and characterization, and considering the importance of effectiveness of biochars in arid and semi-arid regions.

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Author	ORCID
Mohamad Hesam Shahrajabian	0000-0002-8638-1312

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