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Effects of Biochar Application on Soil Properties, Plant Biomass Production, and Soil Greenhouse Gas Emissions: A Mini-Review

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Abstract

Biochar has been applied extensively as a soil amendment over the past decades. This review summarizes the general findings of the impacts of biochar application on different aspects from soil physical, chemical, and microbial properties, to soil nutrient availabilities, plant growth, biomass production and yield, greenhouse gases (GHG) emissions, and soil carbon sequestration. Due to different biochar pyrolysis conditions, feedstock types, biochar application rates and methods, and potential interactions with other factors such as plant species and soil nutrient conditions, results from those studies are not inclusive. However, most studies reported positive effects of biochar application on soil physical and chemical properties, soil microbial activities, plant biomass and yield, and potential reductions of soil GHG emissions. A framework of biochar impacts is summarized, and possible mechanisms are discussed. Further research of biochar application in agriculture is called to verify the proposed mechanisms involved in biochar-soil-microbial-plant interactions for soil carbon sequestration and crop biomass and yield improvements.

Keywords

Biochar, Soil, Plant, Microbe, Nutrient, Biomass, Yield, Greenhouse Gas Emission, Carbon Sequestration

1. Introduction

Biochar is a charcoal-like material that produced from pyrolysis of biomass at high-temperature with limited or no-supply of oxygen [1] [2] [3] [4] [5]. It can be derived from a wide range of raw materials such as organic waste, feedstock like wood chips, crop residues, animal manure, sewage sludge, and microalgae biomass [6] [7] [8]. Biochar is mainly composed of stable and recalcitrant organic carbon (C) and can be used as a soil amendment [9] [10].

The physical and chemical properties of biochar depend on pyrolysis conditions such as temperature and the feedstock type [11] [12]. Biochar has a high surface area and porous carbonaceous structure [13] [14], thus has a strong affinity to inorganic ions such as nitrate and phosphate [15]. Since it contains highly condensed aromatic structures, biochar is difficult to be decomposed in soil and can sequestrate a portion of the applied C for decades to centuries in soil [16] [17] [18] [19]. Biochar also contains elements of macronutrients (N, P, K, Ca, Mg), micronutrients (Cu, Zn, Fe, Mn), and ashes that accounting for 5% - 60% of the weight [20] [21] [22]. Carbon content mostly increases with increasing pyrolysis temperature, while the nitrogen (N) content decreases [16]. Biochar pH and nutrient contents vary with source materials and pyrolysis conditions: the pH of biochar ranges from 5.6 to 13.0, C from 33.0% to 82.7%, N from 0.1% to 6.0%, and the C:N ratio from 19 to 221 [16].

Due to these physical and chemical properties, biochar application has been advocated as a potential management strategy to improve soil quality, increase crop yield, reduce greenhouse gas emissions, and enhance soil C sequestration [2] [23]-[28]. Over the last decades, biochar has gained increasing attention and has been used in agriculture [1] [4] [5] [18] [23] [29]-[36]. This mini-review summarizes current results of the impacts of biochar application on different aspects from soil physical, chemical, and microbial properties, to nutrient conditions, plant growth and biomass, greenhouse gas emissions, and soil C sequestration. A framework of biochar impacts is summarized and possible mechanisms are discussed. Further research is proposed to verify the mechanisms involved in biochar-soil-microbial-plant interactions for soil enhancement and for crop biomass and yield improvements.

2. Effects of Biochar Application on Soil Physical and Chemical Properties

In the past decades, many studies have extensively investigated the impacts of biochar application on soil properties [13] [22] [37] [38]. In general, biochar application has improved soil physical and chemical properties, including soil pH, nutrient status and cation-exchange capacity (CEC), and soil stoichiometry [1] [9] [39] [40] [41] [42] [43].

Some studies reported that biochar application improves soil physical properties by increasing porosity, decreasing bulk density, and enhancing aggregation and water retention [8] [44]. Biochar reduces soil acidity by 31.9% through liming effect (alkaline pine biochar can lime soils by 1.0 - 1.4 units) [45] [46] [47] [48]. In addition, biochar application has positive impacts on cation exchange capacity and electrical conductivity [49] [50]. It was reported that biochar can increase cation exchange capacity by 20% and soil electrical conductivity by

124.6% [46] [51].

Soil water holding capacity is an important variable related to soil available water plants can use. Singh *et al.* [5] reported enhanced water retention in soils with biochar application due to the high porosity of biochar. Most studies found that biochar application increases soil water holding capacity and decreases the number of irrigations required [4] [5] [29] [52]. In addition, biochar application alters soil stoichiometry due to the change in organic C inputs of biochar. Studies found that the enhanced soil organic C inputs in some temperate ecosystems greatly immobilize microbial N into biomass [53] and stabilize soil microbial N [49] [54] [55]. The changes in soil dissolved organic C and NO_3^- induced by biochar application are linked to the soil nitrous oxide (N_2O) emission [56].

The changes of soil physical structure and chemical properties with biochar application are attributable to the properties of biochar (**Figure 1**), as the porous structure of biochar increases soil porosity and reduces bulk density [8] [38]. These changes would enable biochar to change soil pH, enhance water holding capacity, and absorb and attach more nutrients in soil [5] [49] [56].

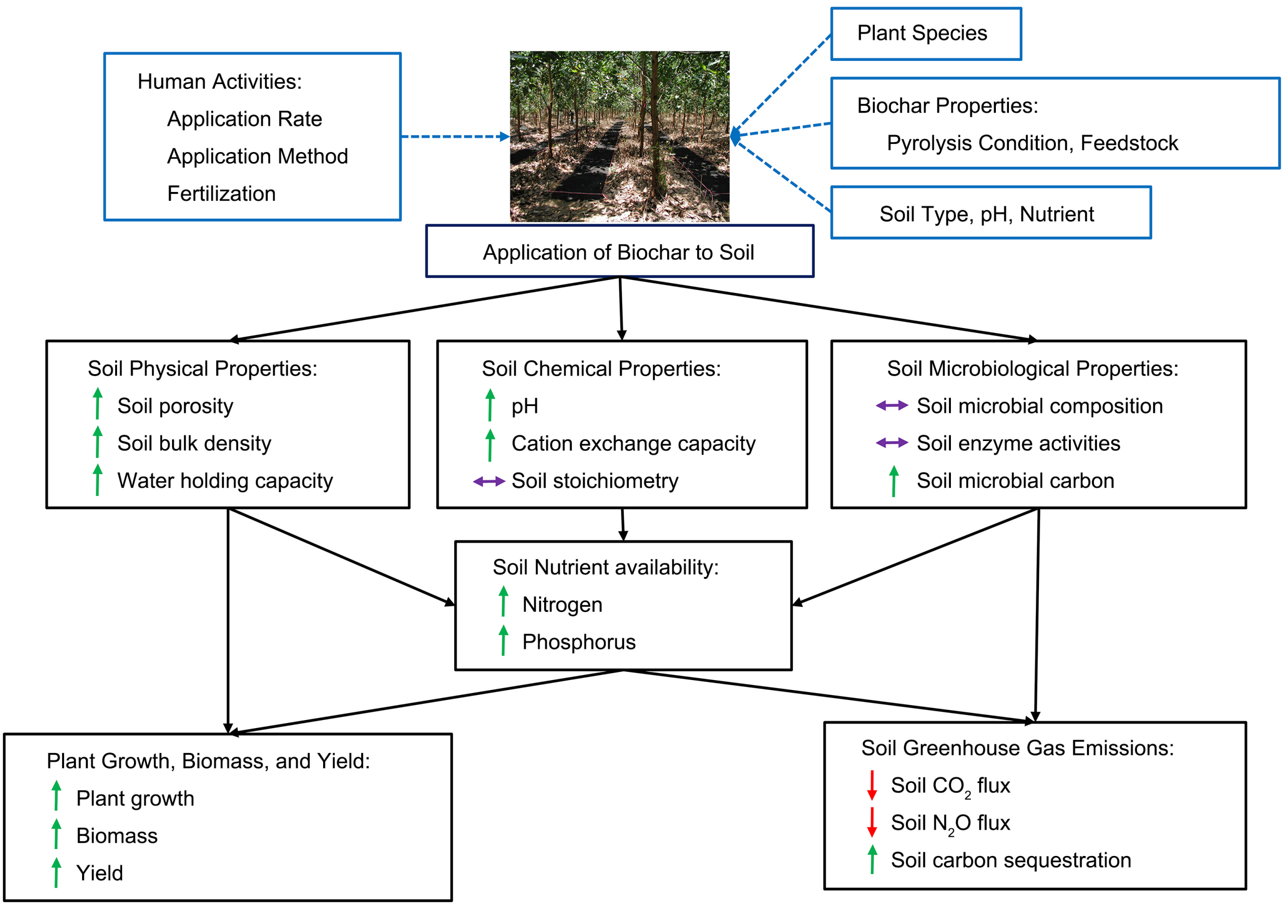

Figure 1. Framework of the impacts of biochar application to soil on soil properties, plant biomass and yield, and greenhouse gas emissions. The blue boxes are factors that may influence the responses to biochar application. Green up arrow indicates major positive effect, red down arrow indicates major negative effects, and purple double arrow indicates multiple impacts by biochar application.

3. Effects of Biochar Addition on Soil Microbial Composition and Activity

Biochar application improves not only soil physical and chemical properties but also soil microbial properties [8]. The large surface area and reactivity of biochar attract ions and organic compounds, and increase potential sites for microbe-substrate interactions [57]. As a result, biochar application has a potential to change soil microbial community composition, influence microbial activity, and affect the soil enzyme activity that influencing various biogeochemical processes [38] [58]. Biochar application often shifts soil microbial populations into soil beneficial fungi and plant growth-promoting rhizobacteria [4] [59]. Fox *et al.* [60] found that biochar application increases abundances of genera of phosphorus (P) mobilizing bacteria. The abundance of living cells of root nodule bacteria is also increased by biochar application [61]. Mitchell *et al.* [62] found that biochar application significantly promotes the ratios of Gram-positive/Gram-negative bacteria and leads to high CO_2 emissions. In addition, biochar application decreases the abundance of mycorrhizal fungi by reducing mycorrhizal symbiosis requirements for nutrients and water, and has direct negative effects on mycorrhiza formation [4] [63] [64]. Ishii and Kadoya [65] reported biochar produces higher rates of root colonization by arbuscular mycorrhizal (AM) fungi. Rillig *et al.* [66] also found positive effects on AM fungal root colonization, as biochar stimulates germination of spores of an AM fungus. Biochar application favors some zoospore-forming pathogens [67].

Biochar can activate soil microorganisms and increase soil microorganism activities [4] [68] [69]. For example, Kolb *et al.* [70] found that biochar application increases soil microbe respiration activity. Similarly, Steiner *et al.* [71] reported that, after biochar application, basal respiration is increased by 30.1%. However, the opposite effect of biochar addition on microbial activity is observed [72]. Biochar reduces the activity of dehydrogenase and esterase by blocking or absorption of substrates [4] [73].

Soil microbial biomass C (MBC) is an important labile C fraction and plays a fundamental role in soil organic C dynamics [49] [54] [74] [75]. Studies have shown that biochar application to acid soils stimulates microbial activity and in turn increases soil MBC content and light fraction organic C [71] [76] [77]. Liang *et al.* [78] reported that biochar increases soil microbial biomass by 43% - 125%. Other studies also found that soil MBC content is higher in the biochar treated soils than in the control [16] [79] [80].

The changes in soil microbial community composition, biomass, and activities with biochar application could also be attributed to physical and chemical properties of biochar as well as biochar-induced changes in soil properties [57] [66] [81] [82]. For example, biochar can provide readily available nutrients for soil microbes and the addition of a small labile component can stimulate microbial activity [13] [83] [84] [85].

4. Effects of Biochar Addition on Soil Nutrients

Biochar addition alters nutrient cycles by directly adding nutrients (N, P, K, Ca, Mg) in biochar to the soil [86] and by indirectly influencing the exchange of nutrients due to increased reactive surfaces [87] [88]. The effects of biochar application on N dynamics and N-cycling enzymes remains ambiguous [89], as soil N mineralization has been found to decrease [90], increase [74], and remain unchanged [91] after biochar application [49]. Biochar addition mostly modifies N fluxes in soil and reduces gaseous N emissions [92]. Studies found that biochar increases nitrification activity in forest soils, but not in grassland soils, and enhances cation exchange capacity [4] [93]. Biochar changes soil nitrogenase dynamics and accelerates N dynamics [94]. Mia *et al.* [95] also showed that biochar application influences nodules formation and N fixation.

Biochar of different origins has different impacts on soil nutrients, as raw biomass materials vary in nutrient contents [14] [29] [50] [96]. For example, biochar made from Miscanthus can be used as a slow release silicon fertilizer [97] and animal bone biochar is a good P fertilizer [98] [99]. On the one hand, biochar can lower P bioavailability due to adsorption of orthophosphate and organic P compounds to its surface [51]. On the other hand, biochar decreases nutrient leaching [4] [100], as a result, there are more available P for plants in biochar-enriched soils [101] [102].

Several mechanisms have been proposed for the increase of soil nutrient availability including 1) the initial addition of soluble nutrients from biochar [29] and the mineralization of the labile fraction of biochar [13]; 2) reduction of nutrient leaching due to biochar's physicochemical properties [79]; and 3) reduced N losses by ammonia volatilization and N_2O from denitrification [8] [55].

5. Effects of Biochar Addition on Plant Growth, Biomass Production, Yield, and Resource Use Efficiencies

While the effects of biochar vary with experimental conditions such as crop species, soil types and environments, biochar properties, and biochar application rates, methods, and frequencies [103], benefits of biochar application for plant biomass production and crop yields have been well documented in the literature [16] [39] [83] [104]. Biomass of crops is often enhanced by biochar application. For example, Novak *et al.* [105] reported an 81% increase in above- and below-ground biomass of winter wheat treated with biochar compared to the untreated control [5]. Above-ground biomass is enhanced by 25% with biochar application [16] [32]. The average biomass increase of agricultural crops with biochar application is 10% - 30% [16] [32] [39] [103]. Some studies found that higher growth responses generally occurred in legume than non-legume crops [3] [103]. Biochar addition also increases the biomass of the roots of maize [106] and barley [107], and *Satsuma mandarin* trees [65]. Due to a higher P content of biochar-enriched soil, biochar addition may inhibit the development of root hairs [107].

Biochar has greater impacts on plants grown in nutrient-rich soils compared to in poor soils [108]. Positive growth responses with biochar application are more common, particularly in coarse-textured or acidic soils [83]. Strong positive plant responses to biochar are also reported in acidic infertile tropical soils, due to soluble P from biochar and P retention by biochar [109], sorption of salts [110] [111], and soil liming effects [112].

Crop yields are often improved by biochar application, particularly on highly weathered soils or sandy soils and moderately acidic soils [39] [103] [113] [114] [115]. Lehman *et al.* (2006) reported a higher increase of 20% - 120% in crop productivity with biochar addition. Maize grain yield can be significantly increased by 98% - 150% after the application of biochar [18] [116]. Zhang *et al.* [117] reported 8.8% - 14% increase in rice yields. Harvest index of double rice production is significantly increased [118]. However, decreases in crop productivity have also been reported for specific combinations of biochar and soil [45] [119]. Grain yields are decreased by 10% - 23.3% with biochar application [120]. Spokas *et al.* [83] reviewed the biochar literature and found that 30% of the studies reported no significant differences, and 20% reported negative yield or growth effects [83] [105].

The increases in crop production and yields are mostly attributed to that biochar application improves soil physical and chemical properties, nutrient supply or fertilizer use efficiencies [5] [83] [121]. Wheat yield and fertilizer use efficiency are increased with biochar application in dryland Australia [122]. High fertilizer use efficiencies are also reported in biochar amended low fertility soils [5] [123] [124]. The decreased crop yield may be attributed to toxic and harmful substances in biochar, which can reduce nutrient uptake and inhibit plant growth.

6. Effects of Biochar Addition on Soil Greenhouse Gas Emissions and Carbon Sequestration

Biochar application may mitigate climate change by reducing greenhouse gases (GHG) emissions and increasing soil C sequestration [1] [27] [125] [126], but the precise effects of biochar application on soil GHG emissions remain controversial and vary among different studies [127] [128]. Soil CO_2, CH_4, and N_2O fluxes increase significantly in some studies [129] [130] [131], but substantially decrease or remain unchanged in others [132] [133] [134] [135]. For example, biochar application to paddy soils induces a 12% increase in CO_2 emissions, but a 41.8% decrease in N_2O emissions [136]. Another field experiment showed no significant effects of biochar application on soil CO_2 and N_2O emissions in a pasture ecosystem [137]. Thus, the impacts of biochar application are still uncertain due to these variable effects on soil GHG emissions.

Increases in soil CO_2 fluxes with biochar application have been reported in several studies but with large uncertainties [27] [130] [136] [138]. Reduced soil CO_2 fluxes or no effect of biochar amendment were found in some studies (e.g.,

[139] [140] [141] [142]. The change in soil CO_2 emission rate could be related to several factors such as soil temperature, soil type and disturbance intensity, biochar pyrolysis temperature, and biochar application rates [143] [144]. This increase in soil CO_2 emission after biochar application may result from a number of processes: 1) biotic use of biochar and biochar decomposition [145] [146], 2) release of biochar-C such as carbonates [37] [147] [148]; 3) priming of native soil organic C pools due to interactions between biochar and native soil organic matter [37] [146]. In addition, [62] found that biochar addition significantly promotes the ratios of Gram-positive/Gram-negative bacteria, and potentially leads to increased CO_2 fluxes from soil organic C decomposition. The changes could also be a direct addition of relatively labile C of biochar [79] [145] [148].

Effects of biochar application on CH_4 emissions from soils have been reported to vary remarkably in the literature, with results from reduced CH_4 emissions to no changes, and to elevated emissions [149] [150] [151] [152] [153]. It appears that responses of CH_4 emissions to biochar depend on the soil type, biochar properties, and the agricultural practices (e.g., fertilization and water management). Most studies reported biochar addition significantly reduces CH_4 emissions [141] [153] [154] [155] [156]. For example, Rondon *et al.* [157] [158] found suppressions of CH_4 emissions from soils treated with biochar in a grass stand, a soybean cropland, and a tropical soil. Qin *et al.* [118] reported that biochar amendment significantly decreased CH_4 [118] [157] [158]. The reduction in CH_4 emission is primarily ascribed to an increase in soil pH, enhanced adsorption by soil particles, and the stimulated biodiversity and abundance of methanotrophic [118] [133] [159] [160] [161]. In contrast, other studies reported increased CH_4 emissions or no significant effect of biochar addition. For example, Knoblauch *et al.* (2008) reported no significant change in CH_4 production from a calcareous Fluvisol in both field and laboratory experiments [154]. Jia *et al.* [162] also reported no changes in CH_4 in a vegetable production system. But Zhang *et al.* [153] found that total soil CH_4 emissions are increased by 34% with N fertilization and 41% without N fertilization. The increased CH_4 production with biochar addition is attributed to the input of labile organic substrates reduced soil redox potential [163] [164] [165], and an improved favorable environment for microbial activity [13] [166].

While studies have reported inconsistent findings on the effects of biochar application on soil N_2O emission, most studies found that biochar contributes to the reduction in N_2O emissions from soil [4] [131] [158]. For example, biochar application reduces soil N_2O emission by 50% in soybean plots on acidic soils, by 61% - 72% in Tenosol soil, and 17% - 23% in Ferrosol soil [56]. Responses of N_2O emission is related to soil moisture content as demonstrated in a laboratory study [131]. When comparing biochar effects, pot and field experiments need to be separated, as soil N_2O emission reductions are 50% less under field versus laboratory conditions [167] [168]. Jia *et al.* [162] also reported significant decreases in soil N_2O emission with biochar addition in a vegetable production system.

Mechanisms such as increased soil aeration, NO_3^- and NH_4^+-N sorption, increased soil pH, and enhanced N_2O reductase activity have been identified [55] [162] [169]. A toxic effect induced by biochar organic compounds on nitrifier and denitrifier communities may cause a reduction in soil N_2O emission [127] [170] [171] [172]. In contrast, increases in soil N_2O emissions may be ascribed to biochar-induced increases in soil water content, which favors denitrification, the release of biochar embodied-N, and dissolved organic C content [138] [173].

Intense investigations have been conducted on the effects of biochar on C sequestration in agricultural and forest ecosystems [25] [62] [145] [174] [175] [176]. Biochar may increase, decrease or have no effect on soil organic C mineralization rates [27] [140] [143] [176]. Most studies reported positive effects for C sequestration, soil fertility, and contaminant immobilization [5] [29] [38] [177] [178], as biochar is highly recalcitrant in soil [23] [103] [179]. Biochar application increases not only soil organic matter and mineral contents but also the stability of aggregate C fractions, as biochar can form cationic bridges with soil minerals [57] [180] [181]. Carboxylic and phenolic functional groups in biochar bind minerals and soil organic matter [76] [182], and contribute to soil aggregation [57]. Maestrini *et al.* [183] showed that labile C fractions induce a short-term positive priming effect on native SOC, but over long-term, the priming effect may become weak due to sorption of dissolved organic C by biochar.

7. Conclusions and Future Research

Biochar application has great impacts on soil physical, chemical, and biological properties, plant growth, and crop yield. It directly affects soil bulk density, pH, water holding capacity, and nutrients contents. Due to the vast differences in biochar, its application methods and rates, the responses of soils and plants to biochar application vary dramatically among different experimental studies [184]. While some studies reported negative effects of biochar on soil nutrient availability and plant growth, a majority of studies found that biochar application improves soil fertility, increases soil water holding capacity, enhances crop yields, reduces GHG emissions, and increases soil C storage (**Figure 1**).

The positive responses to biochar application have been attributed to several mechanisms [4] [127] including 1) improved nutrient availabilities and soil water retention to enhance plant biomass and crop yield [52] [87] [107] [185]; 2) stimulated soil microbial processes by absorbing/detoxifying inhibitory compounds [67] [186] [187] [188]; 3) reduced enzymatic activity and the precipitation of CO_2 onto the biochar surface to reduce soil CO_2 emission [134]; and 4) decreased N_2O emissions due to improved soil aeration and soil pH, and reduced activities of nitrifier and denitrifier [170] [171] [172].

Despite great interests of using biochar to manage soils are increasing and many studies have been conducted with biochar application, large uncertainties of biochar effects still exist [8]. Future research is needed with focuses on these several aspects: 1) to create a linkage and association among biochar properties, soil properties and processes, plant species, and sources of variation to biochar application; 2) understand the mechanisms of biochar responses with regard to the newly found electron transfer and free radical activation functions of biochar [9] [189] [190]; 3) detect the interactions of biochar with climatic factors such as global warming, precipitation changes and agricultural practices like no-tillage and N application; and 4) conduct systematic studies of soil and plant responses to biochar in field experiments across a larger spatial scale and over a long term.

Understanding these complex plant-soil-microbial interactions is important for developing soil management and conservation practices to improve soil properties and agricultural productivity. To accurately quantify the effects of biochar application on soil properties, crop biomass production and yield, GHG emissions, and soil C sequestration, a coordinated large-scale biochar field study may be needed. It is critical that the new experiments are designed with the same protocols and include different crop systems, soil types, biochar types and application rates, and fertilization status so that the sources of variation could be distinguished, and the mechanisms could be uncovered [191]. The experiments should be run at least 3 - 5 years with biochar application in the field, using the same protocols for field measurements. As such studies will help us understand the role of environmental factors in controlling biochar-induced changes in soil chemical and biological properties. More model simulations of biochar effects on soil and plant considering different application approaches and rates are also needed.

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Author's Contributions

Conceptualization, D.H.; writing—original draft preparation, D.H.; writing—review and editing, D.H.

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Conflicts of Interest

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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