Recent Advances in Biochar Applications in Agricultural Soils: Benefits and Environmental Implications

Biochar, a by-product of biomass pyrolysis, has been suggested as a mean to combat climate change, and at the same time to achieve agricultural and environmental benefits. As one possible source of the components with high aromatic structure in soil humus, biochar is of great importance in increasing soil carbon storage and improving soil nutrient retention and nutrient availability, and in maintaining the balance of soil ecosystem. This paper briefly reviewed and synthesized recent findings and discussions regarding the production and characteristics of biochar, its effects on global climate change and particularly in relation to the environmental effects of biochar in soils. Agronomic benefits of biochar application are critically highlighted because researches show that biochar had varied effects on crop productivity thorough the different bio-physical interactions between the biochar and the soils, which are deserved for further investigations. Potential pitfalls and knowledge gaps were briefly discussed on the environmental behavior and the effects of biochar in agricultural ecosystem.

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1 Introduction

In order to offset the challenges of global climate change, the global warming gases need to be reduced. The burning of plant-derived biomass, whether man-induced or from natural fires, has been suggested as the largest contributor to the anthropogenic greenhouse effect, so a reduction in biomass is a clear priority [1]. In recent years, biochar has been shown as one promising means of reducing the atmospheric CO2 concentration because biochar slows the rate at which photosynthetically fixed carbon (C) is returned to the atmosphere and reduced emissions of some important warming gases [2, 3]. In addition biochar can improve agricultural productivity, particularly in low-fertility and degraded soils where it can be especially useful to the world’s poorest farmers. Biochar application reduced the losses of nutrients, agricultural chemicals in run-off, and improved the environmental quality [4]. After introducing into soils, biochar can improve the soil water-holding capacity and enhance the drought stress in some regions of the world. Finally, biochar is producible from biomass waste [1, 5].

The most attractive quality of biochar as a soil amendment is the highly carbon storage in soil, which will potentially improve the water retention and increase the soil fertility [5]. If we converted biomass into biochar using pyrolysis, the carbon saving can be significantly increased relative to the production of energy only (i.e., combustion). Assumed 15 × 109 ha of cropland over the world, 0.65 GtC yr⁻¹ CO2 will be gained if biochar has been applied to this land area once every 10 years [6]. In this paper, we elaborated upon the properties of biochar, focusing on what they imply for the environment and agriculture.

2 The characteristics of biochar

Biochar is the charred by-product of biomass pyrolysis when the plant-derived materials were heated with the absence of oxygen to capture combustible gases. The production of biochar was originally associated with “slow pyrolysis” (Fig. 1). In this type of pyrolysis, oxygen is absent, duration time ranged from several to 10 h, and peak temperatures were relatively low [7]. However, there are some reports about the biochar produced during “fast pyrolysis” with short duration and higher temperatures and even novel techniques such as microwave conversion. During the process of biochar production, the transformation from energy to heat is relatively low which resulted in high storage of carbon in biochar and significantly low emissions of global warming gases into atmosphere [8].

The quality of biochar and potential application to agricultural soil or carbon sequestration were highly affected by pyrolysis process and process parameters, such as furnace temperature and residence time (Tab. 1). In addition, the feedstock type also influences the nature of the produced biochar [9]. The raw materials mainly include wood chip, plant residues, organic wastes industry, and poultry manure [3].

As is shown in Tab. 2, the elemental composition of biochar included carbon (>60%), nitrogen, hydrogen, and some lower nutrient element (K, Ca, Na, Mg, Si). In general, when pyrolysis temperature increased from 300 to 800 °C, the carbon content increased at the expense of nitrogen, hydrogen content [7]. At the same time, nutrient content also increased. The contained nutrient...
elements were important for plant growth. The bulk composition of biochar is dominated by condensed aromatic rings and a few functional groups, making it resistant to decay. Biochars have a high surface to volume ratio and a strong affinity to inorganic ions (e.g., \( \text{Cu}^{2+}, \text{Zn}^{2+}, \text{Pb}^{2+}, \text{Hg}^{2+}, \text{and NO}_3^-/\text{CO}_3^- \)) and a number of polar or non-polar substances such as polycyclic aromatic hydrocarbons, dioxins, and furans. As a result, biochar has been suggested as a promising adsorbent for pollutant in soil, water, and air [1].

3 Biochar for environmental implications

3.1 Combating for global climate change

Biochar applications can significantly decrease the emissions of excessive \( \text{CO}_2 \) into the atmosphere by burning fossil fuels or decomposition or open burning of biomass releases \( \text{CO}_2 \) back into the atmosphere. Up to 50% of the feedstock carbon can be stored in stable biochar [3]. What’s more, application of biochars in soil can significantly decrease \( \text{CO}_2 \) emission from soil because the high stability of biochar restrained the organic decomposition. Furthermore, biochar inhibit the release of \( \text{N}_2\text{O} \) and \( \text{CH}_4 \) from soil. Yanai [10] reported that 90–100% of \( \text{N}_2\text{O} \) was suppressed in a wetted Typic Hapludand by applying the municipal bio-waste derived biochar in a short laboratory chamber experiment. Rondon [11] reported that addition of biochar 20 g kg\(^{-1}\) soil reduced emission of \( \text{N}_2\text{O} \) by up to 50% on soybean and by 80% in grass pots. One of the reasons for the observed reduction of \( \text{N}_2\text{O} \) release from the soils may be that biochar promotes the adsorption and retention of ammonium in soils and leads to the amounts of \( \text{N} \) available for denitrification reduced [3, 12]. Globally, 12% of the methane emission is from the agricultural soils, especially paddy rice soils. Methane emissions from biochar-amended soils are mainly related to the soil type, the characteristics of the biochar, and the fertilization and water conditions [13]. In field trials, biochar was amended in soils at 40 t ha\(^{-1}\) and \( \text{CH}_4 \) emissions were by 34 and 41% higher than that without biochar and with or without \( \text{N} \) fertilization, respectively. However, total \( \text{N}_2\text{O} \) emissions were found to decrease by 40–51% and by 21–28%, respectively. There are some field experiments suggested that the fertilizer decreased by 10% after addition of biochar. The fact means more less emissions of global warming gases from soil [6].

3.2 Reduction of environmental hazardous material

Another advantage of biochar is that it had excellent sorptivity to environmental contaminants. Organic contaminants can be
sequestered by biochar and their fate in the environment will also be influenced. Biochar offers a critical binding phase for organic pollutants in the environment due to its high sorption affinity and recalcitrance to microbial decomposition. The biochar contains the carbonized organic matter and the non-carbonized organic matter. Sorption to biochar is determined by the relative carbonized and non-carbonized fractions and their surface and bulk properties [1, 14, 15]. For example, it was reported that the efficiency of sorbing pesticides by the incomplete burning residues of wheat and rice were 400–2500 times than that by soil. Diuron was also found markedly sorbed by soils which were added with red gum derived chars. These researchers also suggested that the charcoal had stronger enhancing capacity when the produced temperature reached higher level (e.g., 850 °C). And they contributed it to the presence of micropores and its higher specific surface area. Zhang evaluated how Pinus radiata derived biochars influenced sorption and desorption of phenanthrene by soil. Cao et al. [16] studied the effect of dairy manure-derived biochar on sorption of heavy metal, Pb, and organic contaminant. Their results suggested that soil sorption of hydrophobic organic compounds was enhanced by biochar application, but the magnitude of enhancement was regulated by the indigenous soil organic carbon levels, the preparation of biochars, and the contact time between soil and biochar [17]. Chen [18] reported that the presence of coexisting heavy metals greatly affects sorption of organic pollutants on BC and thereby their fate and transport. Biochar had shown important adsorptivity for organic contamination (e.g., POPs) because of their high affinity to natural or carbonaceous sorbents such as biochar. For instance, Chen [19] found that added biochar into soil may enhance the sorption of PAHs to soil, thus provide a theoretical reference to apply biochar to mitigating the PAHs-contaminated soils through transferring PAHs from soil to biochar.

4 Application of biochar in agricultural soils

The addition of biochar can dramatically enhance organic matter content in soils and thereby improve soil fertility, which is apparent in the terra preta. The terra preta of the Brazilian Amazon displayed three times faster of crops growth than the adjacent soils. There are number of studies which show that the incorporation of biochar in soils influences soil structure, texture, porosity, particle size distribution, and density. Because of highly porous structure and large surface area, biochar can provide refuge for beneficial soil microorganisms such as mycorrhizae and bacteria, and influences the binding of important nutritive cations and anions. Evidence shows that biochar application increased plant growth yield, improved water quality, reduced leaching of nutrients, reduced soil acidity, increased water retention, and reduced irrigation and fertilizer requirements. The plant uptake of key nutrients and growth yield significantly increased in response to biochar application, particularly when in the presence of added nutrients [20].

4.1 Improvements of nutrient availability and nutrient loss

The incorporation of biochars in soils has shown to influence soil structure, texture, porosity, particle size distribution, and density. Addition of biochar can reduce soil acidity and increase soil electrical conductivity and cation exchange capacity (CEC) and subsequent nutrient availability [21]. The increase of soil pH induced by biochar application is a well-documented mechanism for improving nutrient availability, especially P and K [22]. In a laboratory incubation of soil with biochar, Nelson found that biochar application at 20 g kg\(^{-1}\) increased soil NH\(_4\)N concentrations by 1.1 to 4.8 mg kg\(^{-1}\) and consistently decreased NO\(_2\)N recovery by 5–10 mg kg\(^{-1}\). However, biochar decreased Mehlich-3 P concentrations in soil by 0.9 mg kg\(^{-1}\) in the absence of P additions and increased Mehlich-3 P concentrations by 3.3 mg kg\(^{-1}\) when added with a P source [23]. The results indicated a combination reaction occurred between biochar and input fertilizer. In a soil column experiment, soil available Ca, K, Mn, and organic carbon increased while soil available S and Zn decreased after biochar addition. The biochar application also significantly decreased levels of Ca, P, Mn, and Zn increased K and Na concentrations in leachate solutions [24]. Oxidation on the particle surfaces of biochar is always reported when biochar is applied to soils. It was suggested the oxidation of the aromatic C and formation of carboxyl groups to be the main reason for the observed high CEC [25]. The enhanced CEC increased soil fertility through greater nutrient availability as nutrients are retained in the soil against leaching. In addition, the adsorption of highly oxidized organic matter onto the biochar surface may create negative surface charges. As a result, the positive exchange sites on biochar surfaces decline and negative charge sites develop with the biochar ages [26].

Biochar application can also affect soil physical properties such as water retention and aggregation which are important for plant growth. Major et al. [27] report the surface soils of oxisols amended with char at 20 Mg ha\(^{-1}\) contained more water by volume and the water was held more tightly than un-amended soil. Moisture release curves from a Tifton loamy sand indicated moisture holding capacity may be increased at very high rates of char addition (88 t ha\(^{-1}\)). However, low rates of char addition do not appear to increase the water holding capacity of the loamy sand Tifton soil [28]. Tryon reported increases in available moisture with the addition of charcoal to sands soil. However, the results suggested that improvements of soil water retention by charcoal additions may only be expected in coarse-textured soils or soils with large amounts of macropores [29].

4.2 Increase crop production with biochar amendments

In response to increased soil fertility of biochar application, the seed germination, plant growth, and crop yield had significantly increased compared to control (Tab. 3). Chan reported that a significant increase in dry matter of radish in the presence of N fertilizer and biochar compared to control. However, a significant biochar and nitrogen interaction was observed because radish yield did not increase even at the highest rate of 100 t ha\(^{-1}\) in the absence of N fertilizer application of biochar to the soil [30]. Uzoma [31] found that maize grain yield significantly increased by 150 and 98% as compared with the control after applying of biochar at 15 and 20 t ha\(^{-1}\) mixing rates, respectively. The authors attributed the higher yield in 15 t ha\(^{-1}\) compared with 20 t ha\(^{-1}\) to lower P availability in 20 ha\(^{-1}\) rate soil because higher biochar applications rate favored P fixation by calcium. Similar observations were made in a rice paddy soil from Tai Lake plain, China where the biochar amendments of 10 and 40 t ha\(^{-1}\) increased rice yields by 12 and 14% in unfertilized soils, and by 8.8 and 12.1% in soils with N fertilization, respectively [32].
A 4 years of biochar application was conducted in a Colombian savanna oxisol, the results show that maize grain yield did not significantly increase in the first year, but increases in the 20 t ha\(^{-1}\) plots over the control were 28, 30, and 140% for second, third, and fourth year, respectively. The authors indicated that a single biochar application may provide benefits over several cropping seasons, although longer-term studies are still lacking and needed to determine when a steady state is reached or if and when a decline starts to occur [33]. On the other hand, there are some reports addressed that application of biochar may also have detrimental effects on crop growth. For instance, Asai [34] found that biochar application without additional N fertilizer application could reduce grain yields in soils with a low indigenous N supply. Gundale and Deluca [35] observed that laboratory produced charcoal from Ponderosa Pine (Pinus ponderosa) and Douglas-fir had a negative effect on plant growth whereas the same charcoal created from wildfires showed a positive effect on plant growth. Deenik [36] found that high volatile matter (VM) biochar inhibited plant growth and reduced N uptake and increased soil respiration which means that biochar with high VM content may not be a suitable soil amendment in the short-term. In general, the decreased plant growth due to biochar application can be attributed to temporary levels of pH, VM, and/or nutrient imbalances associated with fresh biochar [37]. Biochar often can have an initially high alkaline pH, which is desirable when used with acidic, degraded soils; however, if soil pH becomes too alkaline, plants may suffer nutrient deficiencies. Mobile matter (such as tars, resins) on the biochar surface can inhibit plant growth [32].

5 Research prospects and knowledge gaps in the application of biochar in soils

There are a number of studies which show that biochar offers the chance to turn bio-energy into a carbon-negative industry. The applications of biochar present an ideal method to combat the challenges of global climate change and to supply more food in agriculture with increasing world populations. However, some fundamental mechanisms and the utilization of biochar in agro-ecosystem are poorly understood.

(1) It is important to understand the interactions between biochar with soil microbial communities especially involved with nutrient biogeochemical cycles. The resolution may be critically important for CH\(_4\) and N\(_2\)O release from soil.

(2) Understanding the dynamic mechanisms of biochar addition to soil. The biochar, as a soil amendment, on the one hand proposed a new method for the use of agricultural biomass. On the other hand, addition of biochar significantly increased the fertilizer use efficiency and reduced the loss of non-point pollution from agricultural land to adjacent water bodies. Interactions between biochar, soil, microbes, and plant roots after application to the soil are far from understood [7]. The extent, rates, and implications of these interactions are very important to the soil nutrient retention, nutrient availability, and crops yield because there some positive effects of biochars application on crop productivity and some studies reporting adverse effects. The difference may depend on the interactions and processes that occur after biochar is applied to soil, which are not yet fully understood.

(3) The decomposition rate of biochars in soil is still poorly understood. Biochar is more recalcitrant to microbial decomposition because of the aromatic structure. As we all known that the changes of biochar content are too small for any relevant experimental period. As a result, direct estimations of biochars decomposition rates are almost impossible. Meanwhile, studies on the basis of CO\(_2\) efflux are also unsuitable because the contribution of biochar to CO\(_2\) is neglectable compared to other sources. An incubation study, which was conducted for evaluating the decomposition pattern of \(^{14}\)C-labeled biochars, suggested that the mean residence time of biochar was about 2000 years and half-life was about 1400 years.

(4) Biochars have demonstrated high and nonlinear sorption of organic compounds and toxic metals. However, quantitative prediction of sorption capacity remains to be a challenge for biochar synthesized from different biomass sources, pyrolysis conditions, and pre- and post-treatments. Another issue needs to be considered related to the toxic compounds or leachable metals in the biochar. This kind of compounds may limit the safe application of biochar into the soil. Unfortunately, there is little information on contaminants present in different biochar, and their availability to plants and potential leaching to the environment.

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References


