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Role of Biochar Amendments on Soil Microbial Biomass and Nitrogen Dynamics: Review

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Abstract

Biochar is produced in an environmentally friendly manner by recycling plant waste. Due to its stable aromatic forms of organic carbon, biochar is designed to be applied to soil and is relatively stable against microbial breakdown under varied environmental conditions. Biochar is being studied around the world as a way to improve soil fertility, ecosystem services, and carbon sequestration. The use of biochar as a source of soil nitrogen has been the topic of much research. Nitrogen is an important element in crop growth. The objective of this review paper, therefore, is to emphasize both existing knowledge and prospective mechanisms of biochar amendment effects on soil microbial and nitrogen transformation. Biochar addition was found to have significant impacts on the composition and abundance of soil microbial communities. Biochar application improved N_2 fixation in common bean compared to the control treatment. Biochar application to soil has previously been found to increase, reduce, or have no effect on N mineralization. In terms of N immobilization, biochar studies have provided conflicting results. Furthermore, biochar's adsorption and cation exchange capacity for NH_4^+ and NO_3- can effectively minimize nitrate leaching and retain nitrogen. Biochar also aerates the soil and provides a habitat for nitrifying bacteria to convert NH_4^+ to NO_3^-. These modifications, however, may not be wholly helpful, as biochar is not always effective, and alterations to the nitrogen cycle may have unforeseen consequences. Because the features of biochar are strongly impacted by the pyrolytic conditions used to generate biochar and the type of soil it is employed in, more research into the interaction between biochar and soil chemistry is needed.

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Biochar, microbial biomass, nitrogen cycle, pyrolysis, soil amendment.

Introduction

Black carbon is charred plant material that forms in soils as a result of human activities and natural fires along a continuum (Dungait *et al.*, 2012). Biochar's major component, black carbon (BC), is a C-rich, resistant solid material produced by the controlled pyrolysis or thermochemical breakdown of organic material in an oxygen-limited environment (Schmidt *et al.*, 2011). Because of its condensed aromatic structure, biochar relatively resistant to breakdown and degradation (Glaser *et al.*, 2011; Kuzyakov *et al.*, 2009).

Biochar generated from biomass contains a significant amount of organic carbon (5-50%) in some soils, but decomposes at a considerably slower rate than SOM due to its highly condensed aromatic structure (Jeffery *et al.*, 2011; Schmidt *et al.*, 2011). Because biochar has a high proportion of resistant C and thousands of years of stability, it can act as an effective soil C sink (Lehmann, 2015). Consequently, there is a lot of interest in utilizing biochar to mitigate climate change by offsetting C emissions (Woolf, 2010).

Chemical fertilizers, organic inputs, and lime are just a few of the soil amendment technologies available to improve soil qualities. Biochar potential as a soil amendment in agricultural fields has just lately been discovered, and it is still underutilized. Biochar enhances soil quality by influencing important soil processes. Biochar promotes crop yield by increasing water holding capacity, cation exchange capacity (CEC), nutrient adsorption, and creating a favorable environment for soil microorganisms (Glaser *et al.,* 2002; Sohi *et al.,* 2009; Lehmann *et al.,* 2011). Due to its stable aromatic forms of organic carbon, biochar is designed to be applied to soil and is relatively stable against microbial breakdown under varied environmental conditions (Sohi *et al.,* 2010; Bruckman and Klinglmüller, 2014). The chemical structure of cellulose, hemicellulose, and lignin changes at temperatures above 300 °C, giving biochar its high stability. Biochar contained a recalcitrant carbon and is resistant to microbial attack, resulting in less carbon dioxide being emitted into the atmosphere (Shackley *et al.,* 2009).

The availability of key cations and phosphorus, as well as total nitrogen concentrations, have all improved when biochar applied to the soil (Glaser *et al.,* 2002; Lehmann *et al.,* 2003a). Nutrient availability for plant directly associated with the nutrient retention capacity of biochar and its releasing ability to the soil solution (Lehmann, and Joseph, 2009), but it can also be a result of changes in soil microbial dynamics (Lehmann and Joseph, 2009). The very porous structure and enormous surface area of biochar account for many of its benefits. Charges given over a large surface area can increase CEC, which increases a soil's ability to retain and deliver nutrients. Small pore spaces with positively charged surfaces can minimize nutrient loss through leaching, while increased porosity can promote soil water retention (Lehmann and Joseph, 2009; Verheijen *et al.,* 2010).

Nitrogen is universally one of the most deficient and important elements for plant growth and development. The majority of nitrogen in soil is in complex organic forms that must be ammonified to NH_4^+ and then nitrified to NO_3^- before it can be absorbed by plants (Stevenson and Cole, 1999).As a result, the nitrogen cycle will inevitably remove a large portion of the soil's nitrogen before the plant can use it, either by the release of gaseous nitrogen dioxide or through the leaching of nitrates by water runoff. Biochar has the ability to modify the rates of N cycling in soil systems in different ways, according to current studies.(i) increasing the population of nitrifying soil bacteria for biological nitrogen retention; (ii) reducing the emission of N_2O and losses of nitrogen leaching; (iii) increasing the soil content of NH_4^+ and NO_3^- through direct adsorption by the biochar; (iv) reducing the emission of N_2O and losses of nitrogen leaching (Clough, and Condron, 2012). Biochar is being studied around the world as a way to improve soil fertility, ecosystem services, and carbon sequestration. The objective of this review paper, therefore, is to emphasize both existing knowledge and prospective mechanisms of biochar amendment effects on soil microbial and nitrogen transformation.

Effects of biochar addition on soil microbial biomass, communities and their activities

Biochar has been shown a stronger potential for causing changes in microbial abundance, community structure, and activity (Gul, 2015; Jaafar, 2015). Different types and amounts of biochar, on the one hand, have a significant impact on soil microbial diversity and population size. Soil microbes, on the other hand, have the ability to alter the amount and qualities of biochar in the soil.Soil microbial biomass improved through biochar amendment that is due to the presence of labile C components and non-pyrolysis feedstock, according to several previous research findings (Bruun *et al.,* 2011; Zimmerman *et al.,* 2011; Luo *et al.,* 2013).

Similarly, Kolb *et al.,* (2009) and Lehmann *et al.,* (2011) found that incorporating biochar into soils has a beneficial effect on soil microbial populations, signifying soil microbial populations grew up as biochar rates increased.

In previous studies (O'Neill *et al.,* 2009; Liang *et al.,* 2010; Grossman *et al.,* 2010), biochar addition was found to have a significant impact on the composition and abundance of soil microbial communities. By influencing microbial structure (Rillig and Mummey, 2006) and nutrient cycling, these changes have an indirect impact on plant development (Steiner *et al.,* 2008; Warnock *et al.,* 2007).

However, Lehmann *et al.,* (2011) and Dempster *et al.,* (2012a) discovered that the amount of biochar applied to the soil had a negative impact on soil microbial biomass, implying that biochar additions reduced soil microbial biomass due to a toxicity effect caused by biochar.

Because of the presence of recalcitrance carbon, previous research reports have concluded that biochar has no effect on soil microbial biomass (Castaldi *et al.*, 2011; Kuzyakov *et al.*, 2009).

Biochar amendments also have impacts on soil microbial composition and activities. With the addition of biochar, the composition and quantity of soil microbial communities change as well (Liang *et al.*, 2010; Grossman *et al.*, 2010). Furthermore, some study has suggested that biochar may cause changes in soil microbial community composition, as seen in Amazonian Dark Earths (Terra Preta). Pore areas inside biochar structures may provide a suitable habitat for soil microorganisms (bacteria, fungus, protozoa) and hence increase their activity (Gul, 2015). Microbial growth is fueled by nutrients and dissolved organic carbon (DOC) desorbed from biochar surfaces, which leads to changes in nutrient cycling and consequently nutrient retention (Deenik, 2010). According to Anderson *et al.*, (2011)'s biochar pot experiment on soil bacterial community structure, biochar could potentially enhance the growth of organisms that create NH_4^+-N from NO_3^-N that can subsequently be adsorbed to biochar. However, more research into direct proof of the effect on microbial processes is required.

Impacts of biochar on soil nitrogen transformation

Biochar, a product of organic material pyrolysis, has gotten a lot of attention as a way to improve soil fertility and agricultural productivity, absorb pollutants in the soil, and sequester carbon to combat climate change.

The low uptake efficiency of nitrogen fertilizer by crops (an international average of 33%) is a global environmental issue. Unabsorbed nitrogen fertilizer is washed into lakes and rivers, causing eutrophication, or is turned to gaseous nitrous oxide by soil microorganisms, causing acid rain (Raun and Johnson, 1999).

Biochar, on the one hand, cannot directly deliver nitrogen to crops like most conventional fertilizers since it is largely made up of refractory aromatics rather than accessible amines (Novak *et al.*, 2009).

On the other hand, biochar inhibits the leaching of nitrogen compounds and affects the availability of nitrates and ammonia in the soil. Various studies indicated that nitrogen transformation process including BNF, mineralization, immobilization, gaseous N_2 emissions through denitrification and ammonia volatilization significantly influenced due to biochar application.

Biological nitrogen fixation as affected by biochar addition

Biological nitrogen fixation (BNF) is the primary natural source of nitrogen for terrestrial ecosystems and is vital to agricultural nitrogen cycles (Vitousek, 2002). Leguminous crops are thought to account for around half of the global symbiotic BNF, or 21.5 106 tons (Herridge *et al.*, 2008). Biological N fixation (BNF) is a key ecosystem service for global agriculture, so it's crucial to comprehend the implications of biochar use. Soils with free ammonium (NH_4^+) or nitrate (NO_3-) can impede N_2 fixation, which is a microbially mediated process (Giller, 2001; Herridge and Betts, 1988). According to Rondon *et al.*, (2007) biochar application improved N2 fixation in common bean (*Phaseolus vulgaris* L.) compared to the control treatment. This could be due to the increased availability of boron (B) and molybdenum (M) after the addition of biochar. Biochar treatment improved nodulation in white clover (Rillig *et al.*, 2010), soybean (Ogawa and Okimori, 2010; Tagoe *et al.*, 2008), and alfalfa (Tagoe *et al.*, 2008). (George *et al.*, 2012).

Biochar application improved N_2 fixation in common bean (*Phaseolus vulgaris* L.) compared to the control treatment, according to Rondon *et al.*, (2007). This could be due to the increased availability of boron (B) and Mo following biochar addition. Improved nodulation was observed, due to biochar application, in white clover (Rillig *et al.*, 2010), soybean (Ogawa and Okimori, 2010; Tagoe *et al.*, 2008) and alfalfa (George *et al.*, 2012). Several agronomic research has found that biochar has a significant impact on BNF (Quilliam, 2013; Mia, 2014; Güerea, 2015; Rose, 2016; Mollinedo, 2016). The good outcomes could be linked to biochar's increased availability of trace elements like Mo, which is a component of the Mo-Fe protein nitrogenase, which can drive nodulation. In addition to trace elements, increased BNF is likely linked to increased macro- or micronutrient availability, such as K (Mia, 2014), P (Güerea, 2013), Ca (Güerea, 2013), and Fe and Mn (Mia, 2014). (Hass, 2012).

Biochar additions can reduce mineral N concentrations through a variety of methods (Cayuela *et al.*, 2014; Clough *et al.*, 2013), and this decrease in free soil NO_3^- and NH_4^+ may help legumes fix more N_2. A more recent glasshouse study by Guerna *et al.*, (2015) found that biochar amendment enhanced biological N_2 fixation as a result of increased plant P absorption, which was linked to a 360 percent increase in mycorrhizal colonization. Mia *et al.,* (2014), on the other hand, suggested that enhanced K nutrition in moderately acid soil resulted in improved biological N_2 fixation in red clover (*Trifolium pratense* L.) following biochar amendment. Biochar application improved N2 fixation in acid soils, according to Rondon *et al.,* (2007) and Guerna *et al.,* (2015), and maybe a viable choice for low-input farming systems by using locally available feedstock's properties (Cowie *et al.,* 2012).

Effects of biochar application on denitrification processes

In anaerobic environments, microorganisms such as Pseudomonas and Clostridium perform the denitrification process (Smil, 2000). Denitrifying bacteria use nitrates instead of oxygen as an electron acceptor during respiration, resulting in nitrogen gas that is inert and unavailable to plants. Because nitrate is a less efficient electron acceptor than oxygen, most denitrifies only do so when oxygen is lacking. Denitrification is a main target for greenhouse gas abatement since nitrogen (N) cycling in agriculture accounts for about 45% of total terrestrial N_2O emissions (Montzka, 2011; Reay, 2012).

Biochar has been found in a number of experiments to reduce N2O emissions (Cayuela, 2014). Only a few studies have found that using biochar increases N2O emissions (Clough, 2010). In near-saturated, fertilized soils, biochar can reduce cumulative soil N2O production by 91 percent (Case SDCC, 2015).

Ameloot (2016) found a 50-90 percent reduction in N2O emissions seven months after applying biochar to a loam, showing that biochar exerts an indirect physical control over soil denitrification. Harter *et al.,* (2013) illustrated that biochar addition to soil enhanced microbial nitrous oxide reduction. Biochar application to soils reduced soil N_2O emissions by 54 percent in laboratory and field tests, according to a meta-analysis by Cayuela *et al.,* (2014), which looked at 30 papers and 261 experimental treatments from 2007 to 2013. Yanai *et al.,* (2007) and Van Zwieten *et al.,* (2009) suggested several explanations and mechanisms to clarify the decreased N_2O emissions caused by biochar application: (a) alteration of soil properties such as pH, aggregation, and CEC due to biochar application; (b) inducing catalytic reduction of N_2O to N_2 following oxidation and subsequent reactions of biochar with soil minerals; and (c) influencing microbial community structures, and microbial enzymes.

Effects of biochar application on mineralization and immobilization

The process of converting organic nitrogen to inorganic forms (mainly NH_4^+-N and NO_3^-—N) is known as nitrogen mineralization. Bacteria degrade organic nitrogen from manure, organic debris, and crop residues into a bioavailable form of nitrogen, which is a soluble form that plants and microbes may take up again. This conversion is carried out by microbes and other soil organisms that release or mineralize nutrients as a by-product of their detritus consumption. Ammonification is the process of converting organic-N to NH_4^+-N. In the past, ammonium was thought to be the initial product of mineralization, and mineralization was commonly referred to as ammonification in older literature (Schimel and Bennett, 2004).

Biochar application to soil has previously been found to increase, reduce, or have no effect on N mineralization. In a soil column investigation, Xu *et al.,* (2016) reported an increase in net N mineralization after biochar application. In a field research, Pereira *et al.,* (2015) discovered a nearly two-fold increase in N mineralization after biochar addition in an organically maintained lettuce farm compared to the control. They also discovered that the gross N mineralization rate was inversely proportional to the biochar H/C ratio, implying that less recalcitrant biochar with high H/C ratios boosted mineralization rates because they are more likely to degrade and release N into the mineral pool. Gundale *et al.,* (2015) found enhanced net soil N mineralization rates and soil NH_4^+-N concentrations two growing seasons after wood biochar application to soil in northern Sweden regardless of the soil mixing treatment. Prommer *et al.,* (2014) and Ulyett *et al.,* (2014), on the other hand, showed no significant change in N mineralization when low N feedstock biochar was used. In conclusion, these investigations show that the biochar feedstock, biochar formation circumstances, time since application, biochar capacity to adsorb NH_4^+, and soil type are all aspects to consider when evaluating soil N mineralization response to biochar.

The conversion of inorganic nitrogen into organic nitrogen by microbial uptake and the synthesis of amino acid N is known as nitrogen immobilization. It is the reversal of mineralization, in which soil organisms take up inorganic forms of nitrogen (nitrate and ammonium) and convert them to organic nitrogen, which is unavailable to plants. When microorganisms die, however, the organic nitrogen in their cells is transformed to bioavailable nitrogen through mineralization and nitrification processes. Immobilization reduces the amount of plant-available nitrogen in the soil, whereas mineralization increases the amount of bioavailable nitrogen (Robertson and Groffman, 2015).

Incorporation of organic materials with a high carbon to nitrogen ratio (usually more than 25:1) may boost biological activity and increase N demand, resulting in N immobilization (Robertson, 2007). Previous research has found that limited accessible N is reported at high biochar rates, since N availability reduces due to microbial biomass immobilization at high C: N ratios, but other growth-limiting factors may also be at play (Lehmann *et al.*, 2003; Sigua *et al.*, 2016). Due to the addition of biochar, the microbial mediated N immobilization process was reduced to some extent, as it is N restricted and has a high C: N ratio. In terms of N immobilization, biochar studies have provided conflicting results. According to Bruun *et al.*, (2012), incompletely pyrolyzed biomass (rapid pyrolysis at low temperature) may promote soil N immobilization. Similarly, Nelissen *et al.*, (2012) and Budai (2016) found that biochar made at low temperatures has a lot of labile carbon that is bioavailable C or more surface functional groups. This carbon can be used as a microbial substrate, resulting in an increase in microbial demand for inorganic nitrogen, which is then immobilized by biotic processes (Nelissen *et al.*, 2012 and 2014; Zheng *et al.*, 2013). Sigua *et al.*, (2016) conducted a field study using switch grass biochar, found that biochar additions to soil increased N immobilization, and decreased in total inorganic N in soils due to the wide C/N ratio of switch grass.

Impacts of biochar addition on gaseous nitrogen emissions

Leaching, denitrification, volatilization, crop removal, soil erosion, and runoff all contribute to nitrogen losses in the soil ecosystem. Ammonia volatilization is a physicochemical process that converts ammonium N to ammonia gas, which is then discharged into the atmosphere. There are two types of ammoniums: free or unionized form (NH_3) and ionized form (NH_4^+). Unionized ammonia is volatile and quickly removed from soil, whereas ionized ammonium is soluble in water. Another method of gaseous N loss to the atmosphere is ammonium volatilization. Ammonium volatilization occurs when ammonium ions are present in an alkaline medium and is dissociated into gaseous ammonia, which then is released into the atmosphere (Abrol *et al.*, 2007). This reaction is pH dependent with alkaline pH favoring the presence of aqueous forms of NH_3 in solution, while at acidic or neutral pH the ammonium N is predominantly in the ionic form. It is generally known that soils with a higher pH>6 might increase NH_3 volatilization.

Previous finding indicated that NH_3 volatilization was significantly reduced with the addition of Douglas-fir chip produced biochar, mostly due to the NH_3 adsorption at oxygen-containing surface functional group or biochar micro pores (Dougherty *et al.*, 2016). Taghizadeh-Toosi *et al.*, (2012) discovered a 45 percent reduction in NH3 volatilization after adding wood-derived biochar, and Doydora *et al.*, (2011) discovered a 53 percent reduction in NH3 loss after applying chicken litter biochar. Biochar addition has also been shown to lower the propensity for NH3 volatilization in studies (Mandal, 2016; Steiner, 2010). Biochar addition, according to Hua *et al.*, (2009), can reduce NH3 volatilization by 64%.

Impacts of biochar application on nitrate leaching and ammonium adsorption

Nutrient leaching from soils can deplete soil fertility, hasten soil acidification, raise fertilizer costs for farmers, diminish agricultural yields, and, most importantly, endanger environmental health (Lehmann *et al.*, 2003; Major *et al.*, 2009). In agricultural contexts, biochar has been shown to prevent nutrient leaching. By combining electrostatic, complexation, and capillary forces on their surfaces and in their pores, biochar can absorb ions from soil solutions (Major *et al.*, 2009; Moreno-Castilla, 2004). These features of biochar have the potential to reduce nutrient leakage from soil and ion accessibility to soil microbes (Lehmann *et al.*, 2003). The use of biochar has been shown to considerably minimize nitrate, ammonium, and phosphate leaching (Haider *et al.*, 2017; Yao *et al.*, 2012). Biochar helps to prevent nitrogen leaching into groundwater while also reducing the need for fertilizers, which are sources of excess nitrogen (Glaser *et al.*, 2015; Zhang *et al.*, 2016). One technique for improving N retention and reducing N leaching could be the use of charcoal (BC) (Lehmann, 2007).

Because of the presence of acidic functional groups and CEC sites on biochar, it has the capacity to adsorb ammonium-N (NH_4^+) (Asada *et al.*, 2002; Cheng *et al.*, 2006; Kastner *et al.*, 2009). Mukherjee *et al.*, (2011) discovered that the surface chemistry of biochar has a significant impact on the chemisorption of adsorbates. Furthermore, surface functional groups have been found to have an important role in nitrogen chemisorption (Padhye *et al.*, 2011; Huang *et al.*, 2013). The adsorbed nitrogen can then be used by plants (Taghizadeh-Toosi *et al.*, 2012). Biochar has been proven to absorb NH_4^+ and water-soluble ammonium ions (NH_4^+), with ammonia (NH_3) concentrations in emissions dropping by up to 52% when composted with biochar (Steiner *et al.*, 2010). Studies have shown that biochar in soil can reduce NH_4^+ and NO_3^- leaching (Knowles *et al.*, 2011; Singh *et al.*, 2010).

Biochar incorporation has been shown in previous research investigations to reduce inorganic N leaching and increase N retention in the soil (Sun *et al.*, 2017; Yao *et al.*, 2012). The mechanisms underlying biochar's effects on soil N retention are unknown, although some possible explanations have been proposed: a). Biochar has a high cation exchange capacity (CEC) and affects the pH of the soil (Novak *et al.*, 2009), allowing NH_4^+ and NO_3^- to be directly absorbed. Biochar can improve the soil's water-holding capacity (WHC), lowering the overall volume of leachate (Zheng *et al.*, 2013).

One explanation for this is because biochar has a high porosity and surface area, which allows it to physically absorb NH_4^+ N and NO_3^-N. In addition, biochar-treated soils have higher overall porosity and water retention, both of which are important variables in nitrogen retention (Chen, *et al.*, 2014). According to Lehmann, the soil's high surface area and porosity: (i) give sites for electrostatic adsorption; and (ii) have the potential to hold water and dissolved nutrients (Lehmann, *et al.*, 2003). Furthermore, according to Lehmann *et al.*, (2006), biochar treatment has the ability to reduce contaminant leaching from agricultural soils. Increased NH_4^+ adsorption, enhanced soil aeration status, and the presence of volatile organic matter affecting N nitrification and denitrification are postulated mechanisms for the impacts of biochar amendments on soil N transformations (Deenik *et al.*, 2010; Kammann *et al.*, 2012; Zhang *et al.*, 2012). Previous research has demonstrated that biochar can adsorb ammonium ions through its functional acid groups (Asada *et al.*, 2002) or its high CEC (Asada *et al.*, 2002).

Biochar is a relatively new soil amendment method that is gaining attention among scientists. Biochar is produced in an environmentally friendly manner by recycling plant waste into fertilizer. The use of biochar as a source of soil nitrogen has been the topic of much research. Nitrogen is an important element in crop growth. Because biochar contains more carbon than nitrogen, it is ineffective as a nitrogenous fertilizer when applied directly. Because biochar's nitrogen is not bioavailable, it improves the nitrogen content of the soil by altering the nitrogen cycle. Instead, biochar's porosity and vast surface area are good at retaining nitrogen compounds and preventing runoff from leaching them. Furthermore, biochar's adsorption and cation exchange capacity for NH_4^+ and NO_3- can effectively minimize nitrate leaching and retain nitrogen. Biochar also aerates the soil and provides a habitat for nitrifying bacteria to convert NH_4^+ to NO_3^-. These modifications, however, may not be wholly helpful, as biochar is not always effective, and alterations to the nitrogen cycle may have unforeseen consequences. Because the features of biochar are strongly impacted by the pyrolytic conditions used to generate biochar and the type of soil it is employed in, more research into the interaction between biochar and soil chemistry is needed.

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