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ENHANCING SOIL HEALTH THROUGH BIOCHAR: A COMPREHENSIVE REVIEW

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ABSTRACT

Biochar has a beneficial importance on agricultural prosperity, according to various studies, the key dispute presently is how to maximize that important. It is important to maintain a significant content of organic matter in the soil for maintaining physical, chemical and biological sustainability of the soil and for suitable agricultural productivity. Improving the soil and biomass is estimated at the international level to enhance soil productiveness, fertility and to mitigate climate change. Appropriate use of agricultural waste as biomass by converting it as a useful source of soil organic amendments is one way to manage soil health and fertility. Agro-waste residues are partially utilized or un-utilized due to various constraints. Residue burning traditionally provides a fast way to clear the agricultural field of residual biomass, facilitating further land preparation and planting. However, in addition to loss of valuable biomass and nutrients, Agro-waste biomass burning leads to release of toxic gases including Greenhouse gases. Biochar is attracting a great deal of attention. Its characteristics of chemical, physical and biological properties, containing large surface area, Cation Exchange Capacity, high water-holding capacity, pore size, volume, distribution, and element composition, affect its recognized influences, particularly on microbial communities. Application and utilization of biochar in agricultural scope, forestry production, environmental protection and additional areas, has interested awareness by scientists and investigators inside and outside the country. Use of biochar in agricultural systems is one viable option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality.

Keywords: Review, Significant, Biochar, Soil Health, Enhancing

INTRODUCTION

Biochar is a material generated from the process of pyrolysis, described as the thermal decomposition of organic biomass at different temperatures under restricted or zero oxygen. In general, the use of biochar reduces the pollution potential incurred by the disposal of fresh poultry litter (Cavalcante et al., 2022). Biochar is a promising multifunctional adsorbent for water and wastewater treatment (Barquilha and Braga, 2021) Biochar is a remarkable green and sustainable substitute for numerous forms of carbon materials that otherwise has a non-renewable origin (Rawat et al., 2023). Biochar is a solid product generated during the thermochemical processes of biomass, such as pyrolysis, hydrothermal carbonization, torrefaction, and gasification (Iwuozor et al., 2023).

Biochar is a fine-grained, carbon-rich, porous product remaining after plant biomass has been subjected to thermochemical conversion process (pyrolysis) at low temperatures (350 - 600°C) in an environment with little or no oxygen (Amonette and Joseph, 2009). Biochar is not a pure carbon, but rather mix of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash in different proportions (Masek, 2009). The central quality of biochar and char that makes it attractive as a soil amendment is its highly porous structure, potentially responsible for improved water retention and increased soil surface area. It is important to note that there is a wide variety of char products produced industrially. For applications such as activated carbon, char may be produced at high temperature, under long heating times and with controlled supply of oxygen. In contrast, basic techniques for manufacture of charcoal (such as clay kilns) tend to function at a lower temperature, and reaction does not proceed under tightly controlled conditions. Traditional charcoal production should be more accurately described as 'carbonization', which involves smothering of biomass with soil prior to ignition or combustion of biomass whilst wet. Drying and roasting of biomass at even lower temperatures is known as 'torrefaction' (Arias et al., 2008). Biochar from pyrolysis, and conventional charcoal and char share key characteristics which are related to carbon sequestration (long residence time) and soil fertility (soil conditioning effect). Intensive study of biochar-rich dark earths in the Amazon (terra preta) has led to a wider appreciation of biochar's unique properties as a soil enhancer.

MATERIALS AND METHODS

Production of Biochar

Biochar can be produced using a wide variety of feedstock, processed at different pyrolysis temperatures, applied at different particle sizes and rates, and time of application relative to stages of crop growth and development (Lakitan et al., 2018). An irreversible thermochemical conversion of agro-waste biomass be it plant, or animal sources heated at very high temperature under a limited oxygen has resulted to a product of biochar (Solaiman et al., 2020). The physical and chemical properties of biochar which include pH, specific surface area, pore volume, cation exchange capacity (CEC), other nutrients, volatile matter, ash, and carbon content are largely dependent on the origin and nature of feedstock used for its production, temperature, and activation treatments for pyrolysis (Tomczyk et al., 2020; Solaiman et al., 2020). Researchers have reported different effects. For instance, biochar produced at different temperatures varied in their effect on N uptake by Eruca sativa (Zhou et al., 2017) and on growth of lettuce (Hunter et al., 2017) (Lakitan et al., 2018). The adopting interest in using biochar for many applications has result to increased conversion of biomass to biochar (Yaashikaa et al., 2020). Thermochemical conversion is a common technique for biochar production. Thermochemical conversion method includes pyrolysis, hydrothermal carbonization, gasification and torrefaction (Lin et al., 2016). Pyrolysis is one of the most effective and efficient processes to get energy in the form of char from biomass. Other than charcoal pyrolysis also produces different bio-oil and other value-added products. Pyrolysis is a thermochemical process in which biomass is thermally degraded in its chemical constituents under inert or very low stoichiometric oxygen atmosphere. Along with the efficiency pyrolysis also offers less pollution as compared to combustion (Tripathi et al., 2016).

Method of Biochar Application in Soil

Biochar is most incorporated into the soil. First, evenly spread the desired amount onto the soil, then till it in with machinery or by hand. In some cases, such as fruit orchards and other perennial crops where tilling is not an option, biochar can be (1) applied to the soil surface and, preferably, covered with other organic materials (2) applied mixed with compost or mulch (3) applied as a liquid slurry if finely ground (on a large scale, this could be done with a hydro-mulcher). When planting trees or other potted plants, biochar can be mixed with the backfill material. Deep banding can also be used under appropriate conditions. Biochar as a component of compost can have synergistic benefits. Biochar can increase microbial activity and reduce nutrient losses during composting (Dias et al., 2010). In the process, the biochar becomes “charged” with nutrients, covered with microbes, and pH-balanced, and its mobile matter content is decomposed into plant nutrients. Regardless of the application method, it is important to be cautious when handling dry biochar, which is very dusty and should not be spread in windy conditions. This can be easily remedied by wetting the biochar before application. Respiratory protection (e.g., dust mask) should be worn when handling the dry material. Furthermore, higher heating time renders biochar more macro- and micro-pores which is a desired trait for land application (Antonangelo et al., 2021). Different temperature used in pyrolysis produces biochar that can be used for different applications (Enaime et al., 2020). Pyrolysis with temperature above 500 ◦C produces biochar with high hydrophobicity, surface area and micro-pore volume, which are suitable to adsorb organic pollutants (Antonangelo et al., 2021).

Preparation of Biochar

For as long as human history has been recorded, heating or carbonizing wood for the purpose of manufacturing biochar has been practiced (Emrich, 1985). Carbonization is as old as civilization itself (Brown, 1917). There are different ways to make biochar, but all of them involve heating biomass with little or no oxygen to drive off volatile gasses, leaving carbon behind. This simple process is called thermal decomposition usually achieved from pyrolysis or gasification. Pyrolysis is the temperature driven chemical decomposition of biomass without combustion (Demirbas, 2004). In commercial biochar pyrolysis systems, the process occurs in three steps: first, moisture and some volatiles are lost; second, unreacted residues are converted to volatiles, gasses and biochar, and third, there is a slow chemical rearrangement of the biochar (Demirbas, 2004). At the instant of burning, the biomass carbon exposed to fire has three possible fates. The first, and least possible fate of biomass exposed to fire is that it remains un-burnt. The other two possible fates are that it is either volatized to carbon dioxide or numerous other minor gas species, or it is pyrolyzed to biochar (Graetz and Skjemstad, 2003). These methods can produce clean energy in the form of gas or oil along with biochar. This energy may be recoverable for another use, or it may simply be burned and released as heat. It is one of the few technologies that are relatively inexpensive, widely applicable and quickly scalable. To differentiate between the different pyrolysis reactors, nomenclature recommended by Emrich (1985) is given below.

Kiln

Kilns are used in traditional biochar making, solely to produce biochar.

Retorts and Converters**:** industrial reactors that can recover and refining not only the biochar but also products from volatile fractions (liquid condensates and syn-gases) are referred to as retorts or converters.

Retort

The term retort refers to a reactor that can pyrolyze pile-wood, or wood log over 30 cm long and over 18 cm in diameter (Emrich, 1985).

Converters

Produce biochar by carbonizing small particles of biomass such as chipped or pelletized wood.

Slow pyrolysis

Refers to a process in which large biomass particles are heated slowly in the absence of oxygen to produce biochar.

Fast pyrolysis

Refers to reactors designed to maximise the yields of bio-oil and typically use powdery biomass as feedstock.

The major criteria to consider are the targeted final products: (1) biochar and heat, (2) biochar, bio-oil and gases, (3) biochar, carbon black, and syngas (gas mixtures that contain varying amounts of CO and H), and (4) syngas (Pelez-Samaniego et al., 2008). Depending upon the requirement, suitable procedure is followed for production of biochar alone or combination with other useful coproducts. But biochar production technology is more than just the equipment needed to produce biochar. It necessarily includes entire integrated systems that can contain various components that may or may not be part of any system. Brazil is by far the largest biochar producer in the world producing 9.9 million tons/year. Other important biochar producing countries are Thailand (3.9 million tons/year), Ethiopia (3.2 million tons/year), Tanzania (2.5 million tons/year), India (1.7 million tons/year) and Democratic Republic of Congo (1.7 million tons/year). Biochar can be produced at scales ranging from large industrial facilities down to the individual farm (Lehmann and Joseph, 2009), and even at the domestic level (Whitman and Lehmann, 2009), making it applicable to a variety of socioeconomic situations. Various pyrolysis technologies are commercially available that yield different proportions of biochar and bio-energy products, such as bio-oil and syngas. The gaseous bio-energy products are typically used to generate electricity; the bio-oil may be used directly for low-grade heating applications and, potentially, as a diesel substitute after suitable treatment (Elliott, 2007). To make biochar technology popular among the farmers, it is imperative to develop low-cost biochar kiln at community level or low-cost biochar stove at individual farmer's family level.

RESULTS AND DISCUSSION

Importance of Biochar

Biochar, a stable organic material prepared under limited oxygen supply, has been recognized as an amendment used for the improvement of soil fertility and reduction of abiotic and biotic stresses such as heavy metals and drought stress (Rizwan et al., 2018). Biochar has been shown to enhance soil water holding capacity and plant production under limited water supply (Zong and Lu, 2016). Interestingly, after the addition to soils, it may improve soil physical properties, water-holding capacities, and mitigate greenhouse gases through enhanced carbon sequestration (Duan et al., 2024). Recent studies have revealed several environmental and agricultural benefits of applying biochar, including carbon sequestration for reducing carbon emission into the atmosphere, phytoremediation of soil contaminants, adjusting soil physicochemical and biochemical properties for agriculture, creating soil health by inducing growth of beneficial and suppressing pathogenic organisms and improving crop growth and yield (Lakitan et al., 2018). It plays a potential role in rainfed agriculture for improvement of soil physical properties, improved retention of nutrients and soil moisture, consequently enhanced crop yields. Every biochar has its own characteristic which ultimately influences the crop growth after field application (Nataraja et al., 2021). Biochar's as organic amendments have recently become famous for enhancing crop productivity in salt-affected soils including nano-biochar, is a carbon-rich organic material prepared through pyrolysis of organic waste materials (Duan et al., 2024). The use of chicken litter biochar to mitigate N losses was recently explored and results demonstrated that this organic amendment does not only mitigate N losses, but it also improves soil physico-chemical properties which in turn increases N use efficiency. This is because chicken litter biochar reduces the detrimental effects of Al and Fe on plant roots. Also, this reaction enhances N uptake. Additionally, biochars are rich in carboxylic and phenolic functional groups that have high affinity for ammonium ions to prevent these ions from being leached or volatilized. (Maikol et al., 2021). Biochar as compared to other carbon-based materials yield the best in term of economic effectiveness due to its ability to be generated from agro-waste biomass (Wang et al., 2021). Apart from high surface area, considerable porosity, abundant existence of functional groups and excellent electron transferring ability were also the key important of biochar, in relation with other materials, in promoting anaerobic methane production (Kumar et al., 2021).

More recently, as a soil conditioner in agriculture, supplementation of biochar substances was attempted, and their positive impacts on saline soil structure and plant growth and yield were reported. In these reports, it has been concluded that application of biochar in proper concentrations can overcome the adverse effects of water deficit and soil salinity, improve fertility and the structure of the soil, and enhance plant and root growth and plant productivity under normal or soil salinity stress conditions. (Abd El-Mageed et al., 2021). Biochar application to soils has been proposed as one of the best techniques for climate change mitigation via C sequestration in soil. A few recent studies have shown that biochar can reduce nitrous oxide (N_2O) and methane (CH_4) emissions from soil via both biotic and abiotic mechanisms (Tomczyk et al., 2020).

The nutrient content in poultry litter biochar is high. As such, it can be applied as soil amendment for organic fertilizer (Solaiman et al., 2020; Sikder and Joardar, 2019). Although, application in high rate to the soil and its direct use may have resulted in many environmental effects, which include ammonia volatilization, water contamination, mineralization of nitrogen, and the emission of greenhouse gases (KA and Benson, 2014). Thus, poultry litter biochar production as an organic amendment has a high chance of use in improving of soil fertility (Sikder and Joardar, 2019), therefore improving seed germination, pH, water-holding capacity, and the soil nutrient content when applied at a low rate (Revell et al., 2012).

Soil Quality and Fertility Improvement

Biochar is a high carbon containing material (more than 50%) produced by heating of biomass in absence of oxygen. Biochar application to soil leads to several interactions mainly with soil matrix, soil microbes, and plant roots (Lehmann and Joseph, 2009). The types and rates of interactions depend on different factors like composition of biomass as well as biochar, methods of biochar preparation, physical aspect of biochar and soil environmental condition mainly soil temperature and moisture. Biochar can act as a soil conditioner by improving the physical and biological properties of soils such as water holding capacity and soil nutrients retention, and enhancing plant growth (Sohi et al., 2010). The application of biochar in soils is based on its properties such as: (i) agricultural value from enhanced soils nutrient retention and water holding capacity, (ii) permanent carbon sequestration, and (iii) reduced GHG emissions, particularly nitrous oxide (N2O) and methane (CH4) release (Bracmort, 2010; Brown, 2009; Glaser et al., 2002; Kammen and Lew, 2005; Lehmann et al., 2006; Steiner, 2010; Steiner et al., 2008). Farmers will be motivated to apply biochar on their farms if these benefits can be demonstrated explicitly. At the local scale, soil organic carbon levels shape agro-ecosystem function and influence soil fertility and physical properties, such as aggregate stability, water holding capacity and cation exchange capacity (CEC) (Milne et al., 2007). The ability of soils to retain nutrients in cation form that are available to plants can be increased using biochar.

The addition of biochar to agricultural soils is receiving considerable interest due to the agronomic benefits it may provide (Quayle, 2010). Several authors have reported that biochar has the potential to: (i) increase soil pH, (ii) decrease aluminium toxicity, (iii) decrease soil tensile strength, (iv) improve soil conditions for earthworm populations, and (v) improve fertilizer use efficiency. Black carbon may significantly affect nutrient retention and play a key role in a wide range of biogeochemical processes in the soil, especially for nutrient cycling. Chan et al. (2007) studied the influence of rate and type of biochar produced from poultry litter under different conditions on soil quality parameters.

Effect of Biochar on Different Soil Properties

Biochar application to soil is proved to have the possible to raises soil fertility and consequently agricultural productivity (Solaiman et al., 2020; Chan et al., 2008) and increase nutrient, nutrient use efficiency and water holding capacities of the soil. Also, hydraulic property of the soil is increased (Paymaneh et al., 2018) and the emissions of greenhouse gasses is decreased (Solaiman et al., 2020). Biochar has the increases the cation exchange capacity of soil by about 50% (Glaser et al., 2002). Gaunt and Cowie, 2009 reported that about 10-30% increase in fertilizer use efficiency when biochar was added to the soil. It can also be used as liming up 1 point pH increase (Lehman and Rondon, 2006). The soil moisture retention can also be increase by up to 18% (Tryon, 1948). There is also an increase in crop productivity because of biochar application by 20-120% (Lehman and Rondon, 2006). Application of biochar to the soil has the potential of 100% decrease in methane emissions (Rondon et al., 2005) and 50% decrease in nitrous oxide emissions (Yanai et al., 2007). Bulky density of the soil can also be improved (Laird, 2008). Biochar can improve mycorrhizal fungi up to 40% increase (Warnock et al., 2007) and about 50-72% increase in biological nitrogen fixation (Lehman and Rondon, 2006).

The different effects of the two biochars (one produced at 450°C and the other at 550°C) could be related to their different characteristics. Significantly different changes in soil biology in terms of microbial biomass and earthworm preference properties were observed between the two biochar. Similarly, Asai et al. (2009) studied the effect of biochar application on soil physical properties and grain yield of upland rice (*O. sativa* L.) in northern Laos. Biochar application improved the saturated hydraulic conductivity of the topsoil and xylem sap flow of the rice plant. Mankasingh et al. (2011) conducted a plot-scale evaluation of biochar application to agricultural soils in Tirunelveli, Tamil Nadu, India, to investigate the potential of biochar to improve soil fertility and moisture content. Several locally available feedstocks (rice husk, cassia stems, palm leaves and sawdust) were analysed as proposed soil amendments so that no single biomass material is depleted.

The biochar from different biomass feedstock contained >20% C and were high in macro- and micronutrients. The results suggest that an application rate of 6.6 metric tons cassia biochar/ha was enough to initiate C-accumulation, which is reflected in an increase in organic matter and a net reduction in soil bulk density. Significant changes in soil quality, including increase in pH, organic carbon and exchangeable cations as well as reduction in tensile strength were observed at higher rates of biochar application, i.e. > 50 t/ha. Reduction in tensile strength and increase in field capacity of hard-setting soil were the most significant findings (Chan et al., 2007). Biochar can potentially increase the cation exchange capacity (CEC) of soils especially for highly weathered, nutrient-poor sandy soils; however, this is dependent on biochar properties and aging of applied biochar in the soil. The published data suggest that biochar from woody materials tend to provide low CEC values, while non-woody plant materials such as sugarcane trash (leaf) or tree bark tend to have higher CEC values (Yamamoto et al., 2006; Chan et al., 2007; Major et al., 2009; Singh and Gu, 2010; Van Zwieten et al., 2010).

Biochar can be used by farmers to control the pH of soil and to reduce lime applications (Rodriguez et al., 2002). Rodriguez et al. (2009) used biochar produced from sugarcane bagasse to increase the pH of soil from 4.0-4.5 to 6.0-6.5 in a maize trial in Colombia. The pH increase in sandy and loamy soils has been reported to be larger than in clayey soils (De Gryze et al., 2010). In a study on the effects of charcoal production on soil physical and hydrological properties in Ghana, Oguntunde et al. (2008) reported that the saturated hydraulic conductivity of soils under charcoal kilns increased significantly. When mixed with organic matter, biochar can result in enhanced retention of soil water because of its pore structure which contributes to nutrient retention because of its ability to trap nutrient rich water within the pores (Oguntunde et al., 2008; Major et al., 2009; De Gryze et al., 2010). Biochar has an even greater ability than other soil organic matter to adsorb cations per unit carbon (Sombroek et al., 1993), due to its greater surface area, greater negative surface charge, and greater charge density (Liang et al., 2006). In contrast to other organic matter in soil, biochar also appears to be able to strongly adsorb phosphate, even though it is an anion, although the mechanism for this process is not fully understood. After reviewing the experimental evidence for symbiotic association between biochar and mycorrhizal association, Warnock et al. (2007) critically examined the hypotheses pertaining to four mechanisms by which biochar could influence mycorrhizal abundance and/or functioning. These are (in decreasing order of currently available evidence supporting them): (i) alteration of soil physicochemical properties; (ii) indirect effects on mycorrhizae through effects on other soil microbes; (iii) plant–fungus signalling interference, and (iv) detoxification of allele-chemicals on biochar. Purakayastha et al. (2012) also reported that microbial activities measured in terms of dehydrogenase activity and microbial biomass carbon were enhanced due to biochar application in soils; rice biochar showed greater microbial activities than other biochar because of its higher lability than the others. Rondon et al. (2007) studied the potential, magnitude and causes of enhanced biological N2 fixation (BNF) by common beans (*Phaseolus vulgaris* L.) through biochar additions. Biochar was added at 0, 30, 60, and 90 g/kg soil, and BNF was determined using the isotope dilution method after adding 15N-enriched ammonium sulphate to a Typic Haplustox cropped to a potentially nodulating bean variety in comparison to its non-nodulating isoline, both inoculated with effective *Rhizobium* strains. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g/kg biochar added. Although total N derived from the atmosphere (NdfA) was significantly increased by 49% and 78% with 30 and 60 g/kg biochar added to soil respectively, NdfA decreased to 30% above the control with 90 g/kg due to low total biomass production and N uptake. It was reported that the higher BNF with biochar additions was due to greater B and Mo availability. Increase in K, Ca and P availability, as well as higher pH and lower N availability and Al saturation, might also have contributed to a lesser extent. Enhanced mycorrhizal infections of roots did not contribute to better nutrient uptake and BNF. Bean yield increased by 46% and biomass production by 39% over the control at 30 and 60 g/kg biochar respectively. However, biomass production and total N uptake decreased when the biochar applications were increased to 90 g/kg. Results demonstrate the potential of biochar applications to improve N input into agroecosystems while pointing out the need for long-term field studies to better understand the effects of biochar on BNF. Plant available nutrients in the soil and offering the possibility of improving crop yields while decreasing environmental pollution by nutrients. Thus, biochar application could provide a new technology for both soil fertility and crop productivity improvement, with potential positive and quantifiable environmental benefits, such as carbon trading (Bracmort, 2010 and Yeboah et al., 2009).

Global Status of Biochar Production

Production of biochar is extensively developing globally like America and Europe. In the Asian continent India and China are the major biochar producing countries (Anon, 2021). Development of new technologies has help in increasing biochar production (Hadiya et al., 2022). According to the information worldwide for biochar production and estimated compound annual growth rate of biochar production for the period of 2021-2031 showed North American accounted for 36%, Europe 24%, Asia 20%, Middle East and Africa 12% and Latin America 8% (Hadiya et al., 2022).

CONCLUSION

The use of biochar in agricultural systems is one important option that can enhance natural rates of carbon sequestration in the soil, reduce farm waste and improve the soil quality. Further, several studies across the world have established that biochar application increases conventional agricultural productivity and mitigate GHG emissions from agricultural soils. This has led to renewed interest of agricultural researchers particularly in the world to produce biochar and its use as a soil amendment. However, to promote the application of biochar as a soil organic amendment and as a climate change abatement option, research, development and demonstration on biochar production and application is very vital. It is necessary to develop low-cost biochar kilns to make the technology affordable to small and marginal farmers. Further, inter-disciplinary and location-specific research must be taken up for studying the long-term impact of biochar application on soil physical properties, nutrient availability, soil microbial activities, carbon sequestration potential, crop productivity and greenhouse gas mitigation.

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