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Carbon Sequestration by Biochar and other Soil Amendments in Agricultural Soils

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Abstract

The emission of carbon dioxide (CO_2) into the atmosphere on a global scale leading to global warming is a serious environmental issue nowadays. The emission can be restricted by sequestering atmospheric CO_2 in the soils into other carbon pools with longer residence time, thereby mitigating the serious consequence of global warming. Agricultural soils can serve both as a source and sink of CO_2. Among the various types of soil amendments used to sequester carbon in agricultural soils, biochar and activated charcoal are comparatively stable carbon compounds and are recalcitrant in nature whereas crop residues and vermicompost depicts the labile pool of carbon. Application of these soil amendments will cover all the three pools of carbon i.e. active, slow and inert pools and will help us for a better understanding of carbon dynamics. Besides, their application also improves soil quality along with crop growth and productivity. But these amendments when applied to soil cause emission of some GHGs which can offset the beneficial effect of carbon sequestration. There is an increasing concern for carbon sequestration globally and many research works are going on regarding biochar and crop residues as a soil amendment in soil carbon sequestration process. But the role of activated charcoal and vermicomposts as a soil amendment and their role in carbon sequestration are still unclear till date. Further investigations and research work is needed on activated charcoal and vermicomposts to suggest any management strategy in soil carbon sequestration.

Keywords: Carbon sequestration, biochar, charcoal, crop residues, vermicomposts, emission

1. Introduction

Carbon is emitted to the atmosphere as carbon dioxide (CO_2) on a global scale every year due to human activities. This contributes towards greenhouse effect where thermal radiation from planetary surface is absorbed by atmospheric greenhouse gases, and is re-radiated in all directions. As a result, there is a serious risk of increase of overall temperature of the earth's atmosphere due to the increased levels of CO_2. Thus, identifying potential sinks for capturing atmospheric CO_2 is a matter of great concern today, with an objective of sequestering it into other carbon pools with longer residence time, thereby mitigating the serious consequence of global warming.

1.1. Carbon sequestration

Carbon sequestration refers to the capture and secure storage of atmospheric carbon into the soils. Soil organic carbon (SOC) is composed of a complex mixture of partially decomposed substances (i.e. polysaccharides, lignin, aliphatic biopolymers, tannins, lipids, proteins and amino sugars) derived from plant litter as well as faunal and microbial biomass (Stockmann *et. al.*, 2013). Soil organic carbon comprises of several fractions or pools, depending upon their rates of decomposition and stability in soils (Phukan and Ramakrishna, 2014). Depending upon their rate of decomposition in soil, SOC has been classified into three pools i.e. active, slow and inert pools. The active pool, also known as the labile pool, includes microbial biomass carbon, which is readily available for consumption by the microorganisms; the slow pool (humus), contains humified organic matter which is going through different stages of decomposition and resists further breakdown; whereas the inert pool is the stable, resistant or passive pool, where charcoal is the major component, highly resistant to decomposition (Phukan and Ramakrishna, 2014). The labile pools of carbon includes application of crop residues which both declines and restores faster than the non-labile pool, constitute only about 1 to 4 per cent of SOC is the most sensitive indicator of soil carbon dynamics (Rastogi *et. al.*, 2002). Carbon moves amongst these three different SOC pools and the soil amendment which can help build the stable pool proves to be more beneficial in effectively sequestering carbon in soils.

1.2. Carbon sequestration in agricultural soils

Agricultural soils can serve both as a source and sink of CO_2; soils in their natural or undisturbed state contain large pools of SOC depending upon temperature, moisture, soil texture and soil structure whereas it can also serve as a sink or reservoir of CO_2 that have been removed from the atmosphere by the process of carbon sequestration (Lal, 2004). Restoring and sequestering carbon into agricultural soils improves soil quality as well as biomass production and hence enhances crop growth and productivity (Shanthi *et. al.*, 2013; Baronti *et. al.*, 2010). It has been observed that in developing countries, increase in soil organic pool by 1 Mg/ha/yr can increase food grain production by 32 million Mg/yr, thereby reducing poverty, malnutrition, hunger and substandard living of the developing countries (Lal, 2006).

1.3. Types of soil amendments used for sequestering carbon in agricultural soils

Among the various types of soil amendments used to sequester carbon in agricultural soils, biochar and activated charcoal are comparatively stable carbon compounds and are recalcitrant in nature (Harvey *et. al.*, 2012; Glaser *et. al.*, 2002) whereas crop residues and vermicompost depict the labile pool of carbon (Aira *et. al.*, 2007; Blanco-Canqui and Lal, 2007). Thus, application of these soil amendments will cover all the three pools of carbon and will help us for a better understanding of carbon dynamics. Moreover, the resources required for the preparation of these amendments are also cheap and easily available to the small scale farmers as discussed below.

1.3.1. Biochar

Biochar is a fine-grained and stable carbon compound, produced when biomass is heated to temperatures between 350 to 600ºC in absence of oxygen (Whitman and Lehmann, 2009). The char produced by pyrolysis, containing about 70 to 80% carbon, is sterile and therefore several steps are required to make it a catalyst for the soil Rhizosphere-Plant continuum and its economic feasibility is dependent on the costs of feedstock production, pyrolysis and the value of carbon offsets (Robert *et. al.*, 2010). Phukan and Ramakrishna (2014) recommended inoculation of char with bacteria, as the microbes would play a buffering role by colonizing the nano pores of biochar and thereby helps in nutrient cycling. Further investigations are needed for improving the methods of extraction of biochar from dried and partially pyrolyzed materials and for further understanding the chemistry of biochar.

Biochar, when added to soil, improves soil quality and sequesters carbon in the soil, thereby reducing the emission of greenhouse gases into the atmosphere (Shanthi *et. al.*, 2013; Chan *et. al.*, 2007). Biochar being a stable carbon compound is recalcitrant in nature and has long-term effect on the soil environment compared to other amendments (Spokas *et. al.*, 2011; Harvey *et. al.*, 2012). The interaction between biochar and soil will increase soil carbon storage via the processes of organic matter sorption to biochar and physical protection owing to its large surface area (Zimmerman *et. al.*, 2011). Relatively small rates of biochar application leads to enhanced crop yield by reducing the loss of nutrients in the rooting zone by leaching and is also accompanied by carbon sequestration (Baronti *et. al.*, 2010).

But recent studies on biochar have yielded contrary results on soil quality and yield improvements, where it was observed that the yield improvements were on a short-term basis (Spokas *et. al.*, 2011; Quilliam *et. al.*, 2012). Jones *et. al.* (2012) studied the changes influenced by biochar in soil quality and plant growth in a 3 year field trial, where it was concluded that addition of biochar causes small and potentially transient changes in a temperate agroecosystem functioning. Also, the short-term effects of biochar with respect to yield improvements and carbon cycling, reported from laboratory studies were not observed in the field. This emphasizes the requirement of long-term field trials of biochar to suggest any agronomic management strategy.

1.3.2. Activated charcoal

There are two different methods for the preparation of activated carbons; one is the physical activation and the other is the chemical activation. The physical activation involves the carbonization of a carbonaceous precursor, followed by gasification of the resulting char; whereas in chemical activation the precursor is impregnated with a chemical agent and then it is pyrolyzed (Lozano-Castello *et. al.*, 2001). The chemical activation is more advantageous than the physical activation since it takes place at a lower temperature and within a shorter span of time than physical activation. The process of charcoal production is a well-known technique and is similar to that of biochar production, but biochar distinguishes itself from charcoal by the fact that biochar is porous and is always produced with an intent to be applied as a soil amendment (Phukan and Ramakrishna, 2014), whereas activated charcoal is widely used as adsorbents in technologies related to pollution abatement owing to its highly porous structure and large adsorption capacity (Lozano-Castello *et. al.*, 2001).

Charcoal is a chemically stable aromatic compound of soil organic matter (SOM) and its turnover time is much lower than that of plant litter and hence can reduce the emission of CO_2 into the atmosphere, leading to higher carbon sequestration in the soil in comparison to the application of equal amounts of non-charred organic matter. (Glaser et. al., 2002). Also, the resilience of SOM in charcoal amended soils (4 to 8% soil C loss) indicates the recalcitrant nature of charcoal compared to other amendments like chicken manure (27% soil C loss), composts (27% soil C loss) and control experiment (25% soil C loss) (Steiner *et. al.*, 2007). Moreover, bamboo charcoal, a kind of manufactured biocharcoal and also a residual byproduct of bamboo processing industry, is an ideal amendment for nitrogen retention and heavy metal stabilization due to its excellent absorption capacity (Hua *et. al.*, 2009).

Although many researchers are of the opinion that charcoal improves soil quality and increases SOC pool (Lal, Solow Background Thematic Report - TR04A) but the use of charcoal as a soil amendment is not a well recognized technology (Glaser *et. al.*, 2002). Further investigations are needed to suggest management strategies for carbon sequestration involving charcoal.

1.3.3. Vermicompost

Vermicomposting is a biotechnological process of composting, in which certain species of earthworms are used to enhance the process of waste conversion and produce a better end product. It is a mesophilic process, utilizing microorganisms and earthworms that are active at 10-32ºC and it differs from composting by the fact that it is faster, since the material passes through the earthworm gut and the earthworm castings are rich in microbial activity and plant growth regulators (Nagavallemma et. al., 2004). The raw materials used for vermicomposting are dry organic wastes, dung slurry, rock phosphate, earthworms and water, which are cheap and easily available resources and thus its preparation is considerably cheaper compared to that of chemical fertilizers.

Vermicompost influences the quality and quantity of soil organic matter and increases the population of fungi (Aira *et. al.*, 2007). There is a close positive correlation between the abundance of arbuscular mycorrhizal fungal hyphae, soil aggregation and carbon sequestration in the soils (Wilson *et. al.*, 2009). Also the microbial growth efficiency and chemical recalcitrance of fungi is greater than that of bacteria and hence greater amount of carbon is sequestered in fungi dominated soils (Ngo *et. al.*, 2012; Six *et. al.*, 2006). It has also been observed that application of vermicompost increases crop yields to a great extent (Alam *et. al.*, 2007; Ngo *et. al.*, 2012). Besides, it is also expected that carbon sequestration would increase due to the application of the earthworms since earthworm casts are rich in stable soluble and particulate organic carbon compounds that can migrate to deeper layers of the soil and can get associated into organo-mineral microaggregates (Luth *et. al.*, 2011).

1.3.4. Crop residues

Crop residues refer to any biomass left after the harvest of grains in the field. Incorporation of crop residues like straw, stubble, husk, and tree leaves etc. is the principal source of biomass in cropland soils and the effectiveness of soil carbon sequestration in mitigating the emission of greenhouse gases into the atmosphere depends on the quantity and quality of biomass returned to the soil by the incorporation of crop residues (Blanco-Canqui and Lal, 2007; Lal, 2005). Residue retention is especially useful for the poor and small scale farmers in developing countries, who cannot afford chemical fertilizers.

Witt *et. al.* (2000) studied the effects of crop rotation and residue management on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems, where more carbon sequestration was observed with the early incorporation of crop residues (i.e. 63 days before transplanting) than with the late incorporation of crop residues (i.e. 14 days before transplanting). Liu *et. al.* (2014) also observed that straw return increased SOC concentration by 12.8 ± 0.4% on average, with a 27.4 ± 1.4% to 56.6 ± 1.8% increase in soil active C fraction. Similar findings were observed by Duiker and Lal (1999), where application of crop residues along with conservation tillage practices increased organic carbon content in the soils.

However, contradictory results were also observed by Liu *et. al.* (2014), where carbon dioxide emission increased in both upland (27.8 ± 2.0%) and paddy systems (51.0 ± 2.0%), while methane emission increased by 110.7 ± 1.2% only in rice paddies by the incorporation of straw residues. Similar findings were observed by Lu *et. al.*, (2010), where incorporation of straw residues to rice paddies would sequester 10.48 Tg x a(-1) of C, and the contribution to the global warming mitigation was 38.43 Tg CO_2-eqv x a(-1); also methane emission from our rice paddies increased from 5.796 Tg x a(-1) to 9.114 Tg x a(-1), and the increased 3.318 Tg x a(-1) of CH_4 emission would lead to a global warming potential of 82.95 Tg CO_2 -eqv x a(-1), which was 2.158 times of the mitigation from carbon sequestration in rice paddies. Thus, incorporation of crop residues have a dual effect on agricultural soils; it can enhance carbon sequestration as well as carbon emission from the fields and hence it needs further investigation involving long-term experiments on a wide range of soils and environment to suggest any management strategy involving crop residues.

2. Improvement of soil quality and crop production due to application of soil amendments

Application of the soil amendments, biochar, activated charcoal, vermicompost and crop residues improves the physical, chemical and biological properties of the soil.

2.1. Improvement in physical property

Application of biochar, activated charcoal and crop residues not only improves soil structure but also enhances soil water retention and soil aggregate formation owing to their porous nature and improvement in the saturated hydraulic conductivity of the topsoil (Shanthi *et. al.*, 2013; Glaser *et. al.*, 2002; Blanco-Canqui and Lal, 2007; Asai *et. al.*, 2009). It has also been reported that soils amended with vermicomposts had greater bulk density owing to the increase in porosity, attributed to the increased number of pores in between 30-50 ìm and 50-500 size ranges and a decrease in the number of pores greater than 500µm, resulting in improved air-water relationship in the soil, thereby enhancing plant growth (Nagavallemma *et. al.*, 2004; Atiyeh *et. al.*, 2001; Azarmi *et. al.*, 2008).

2.2. Improvement in chemical property

Application of both biochar and activated charcoal increases the soil pH (by one pH unit), cation exchange capacity (by about 40%) and improves the nutrient availability, both due to direct addition and greater nutrient retention by the soils (Shanthi *et. al.*, 2013; Chan *et. al.*, 2007; Topoliantz et. *al.,* 2010). Incorporation of crop residues also improves nutrient cycling of the soil (Blanco-Canqui and Lal, 2007). Long-term benefits of nutrient availability include greater stabilization of organic matter, slower nutrient release as well as greater retention of cations owing to its higher CEC; the higher CEC of biochar and charcoal amended soils is the result of their greater surface area and higher charge density per unit surface area. Previous literature have also revealed that application of vermicompost not only favourably affects soil pH but also reduces the proportion of water-soluble chemical species, which cause possible environmental contamination (Nagavallemma et. *al*.,2004). Besides, large amounts of total carbon and nitrogen in sheep manure vermicomposts provide a larger source of nitrogen for mineralization; also soils amended with vermicomposts contain more phosphorus in the form of orthophosphates owing to the slow release of phosphorus from vermicomposts and activity of soil microorganisms which is responsible for decreasing the soil pH (Arancon et. *al.*, 2006; Azarmi et*. al.,* 2008). Application of vermicomposts also increases the amount of available potassium in soils, since the increase in organic matter decreases potassium fixation in the soils; also the selective feeding of earthworms on organically rich substances along with enzymatic influence on finer particles of soil increases the proportion of different forms of potassium in the soils (Azarmi *et. al.*, 2008).

2.3. Improvement in biological property

Large surface area as well as large surface hydrophobicity of both biochar and microorganisms increases their biological activity in the soils (Zimmerman *et. al.*, 2011) since adhesion of microorganisms to biochar increases with higher hydrophobicity and stimulates shifts in microbial population towards plant growth promoting rhizobacteria and fungi (Graber *et. al.*, 2010). However, biochar is quite recalcitrant to microbial attack, but it is expected to be broken down due to mineralization and the decomposition rate may be very rapid as well as slow. Similarly, activated carbon also sorbs microorganisms strongly owing to their higher hydrophobicity. Application of both vermicomposts and charcoal favourably enhances microbial biomass and activity, especially when supplied with nutrients by the fertilizers (Nagavallemma *et. al.*, 2004). The leaching of the nutrients is reduced due to microbial nutrient immobilization, since the microorganisms sequester nutrients for using them for their metabolic activities (Arancon et. *al.*, 2006). Crop residues are the source of biomass in the soil and it provides habitat for the soil microorganisms for their enrichment and flourishment (Blanco-Canqui and Lal, 2007). Similarly, biochar can also act as a habitat for extraradical fungal hyphae that sporulate in their micropores owing to their lower competition from saprophytes, thereby acting as an inoculum for arbuscular mycorrhizal fungi.

2.4. Improvement in agronomic production

Studies revealed that application of biochar, activated charcoal, vermicomposts and crop residues increased plant growth and crop productivity (Shamthi *et. al.*, 2013; Chan *et. al.*, 2007; Baronti *et. al.*, 2010; Glaser et. *al*., 2002; Alam et. *al*., 2007; Ngo *et. al.*, 2012; Blanco-Canqui and Lal, 2007). Hossain *et. al.*, (2000) observed improvement in the production of cherry tomatoes by 64% above the controlled soil condition due to the combined effect of increased nutrient availability (P and N) and improved soil chemical conditions upon biochar application. Charcoal application reduces the loss of nitrogen by leaching and therefore increases crop yield (Steiner *et. al.*, 2008; Hua *et. al.,* 2009). Several studies have also reported that application of charcoal increases seed germination, plant growths and crop yields. Charcoal application increased biomass production of rice crop by 17% compared to a control on a Xanthic Ferralsol owing to the effect of improved P, K and Cu nutrition (Glaser et. *al*., 2002). Alam *et. al.* (2007) suggested that 100% inorganic fertilizers with 5-10 t/ha of vermicompost enhances the production of potato. Similar findings with vermicomposts were observed by Ngo *et. al.* (2012) for the production of tomato and maize. Blanco-Canqui and Lal (2007) reported that removal of 50 % to 75 % stover reduced grain yield by 1.95 Mg/ha, while complete removal of stover reduced it by 3.32 Mg/ha. However, in some cases crop yields may decline due to decrease in nitrogen availability through immobilization by microbial biomass at high C:N ratios owing to the incorporation of C-inputs.

5. Conclusion and recommendations for future research

Out of 2344 Gt of organic carbon contained in the soil, 8.7 Gt is emitted to the atmosphere globally, which is contributing towards greenhouse effect. To mitigate this effect, identifying potential sinks for capturing carbon from the atmosphere is necessary. Sequestration of carbon in soil can be achieved by the application of various amendments like biochar, activated charcoal, vermicomposts and crop residues. Biochar and activated charcoal being a stable carbon compound is recalcitrant in nature and therefore have a long-term effect on soil carbon sequestration. On the other hand crop residues and the resources needed for preparing vermicomposts are cheap and easily available to the local small scale farmers. Moreover, vermicomposts enhances soil microbial activity and the crop residues are principal source of biomass in the fields, which increases the effectiveness of soil carbon sequestration. Capturing and storing carbon in the fields will improve soil quality, increase plant growth and crop productivity, thereby ensuring food security for a vast population globally as well as will help to mitigate the process of global warming by reducing the emission of greenhouse gases into the atmosphere.

Although there is an increasing concern for carbon sequestration globally and many research work is going on regarding biochar and crop residues as a soil amendment in soil carbon sequestration process, but the role of activated charcoal and vermicomposts as a soil amendment and their role in carbon sequestration is still unclear till date. Further investigations and research work is needed on activated charcoal and vermicomposts to suggest any management strategy in soil carbon sequestration.

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