Bulletin of Environment, Pharmacology and Life Sciences
Bull. Env. Pharmacol. Life Sci., Vol 6 [12] November 2017: 07-14

Online ISSN 2277-1808
Journal's URL:http://www.bepls.com
CODEN: BEPLAD
Global Impact Factor 0.876
Universal Impact Factor 0.9804
NAAS Rating 4.95

REVIEW ARTICLE **OPEN ACCESS**

Application of Biochar in Soil Fertility and Environmental Management: A review

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ABSTRACT

Application of biochar in agriculture increases the soil fertility and crop yields due to the presence of sufficient nutrients and elemental composition. Incorporation of biochar in paddy fields has been noted to influence the soil physico-chemical properties and reduces the green house gases emissions such as methane (CH_4) and nitrous oxide (N_2O). Biochar application in agriculture could be a better option to enhance the C sequestration and to minimize the green house gases emissions. The rice husk biochar, prepared from crop waste materials such as rice husk to agriculture could be a sustainable crop residues management, soil fertility improvement and microbial biomass as well as microbial diversity enhancement including methanotrophs. Thus, long term application of biochar in soil can enhances the soil microbial community composition and biomass of nutrient poor agro-ecosystems and degraded lands.
***Key words**: Biochar, Climate change, Nutrient leaching, Nitrogen mineralization, soil*

Received 01.10.2017 Revised 15.10.2017 Accepted 03.11.2017

INTRODUCTION

Biochar is charred organic product which produced from biologically recalcitrant carbon that is not easily decomposed by the soil microbes due to the highly aromatic nature of carbon so, biochar can persist for long time in soil, which making it a most important tool for carbon sequestration [1; 2]. Therefore, incorporation of biochar in agriculture soil can improve physico-chemical as well as biological properties of the soil. The several studies have been conducted on applications of biochar in agricultural soil which shows that the addition of biochar can improve the soil structure, texture, porosity, particle size distribution, bulk density, soil moisture and water holding capacity of soil as well as enhanced the biological activity [3]. Biochar has internal porous body and its high porosity and surface area of can work as soil microbial habitat for agriculturally beneficial microorganism. According to Xu et al. [4] the application of biochar increased plant growth yield, improved water quality, increased water retention, reduced nutrient leaching and soil acidity as well as fertilizers inputs and balanced the environmental functioning due to their eco-friendly nature. Various studies have shown, that the incorporation of biochar single and with combination can increases the crops yields and soil microbial biomass (SMB) in positive comportment [4; 3]. The presence of SMB in soil is representing the soil fertility index in agro-ecosystem as well as forest-ecosystem and the greater level of SMB in soil indicating the highest soil microbial diversity [5]. The application of biochar in agricultural soil can increase microbial biomass due to the large porosity as well as surface area of biochar, which attracts the beneficial microbial population inside their body therefore the higher microbial population can survive properly without harm of soil predator. The long survival capacity of microbes in soil indicates the large nutrient level of soil while biochar can sustain in soil about more than thousands of years long [1]. Biochar play vital role in carbon sequestration and its nutrient binding capacity in soil is indicated the highest carbon sequestration and carbon negative nature of biochar is reduced the emission of green house gages in the atmosphere including methane, carbon dioxide and nitrous oxide but CH_4 is 30 times more potential than carbon dioxide on the basis of global warming effects but some unique bacterial communities (methanotrophs-methane-oxidizing bacteria) are also reduced the methane emission and oxidized methane in the form of carbon dioxide and used their carbon source [3; 6]. The application of biochar in respect of agricultural production and environmental management can be very effective and economically beneficial technique for the sustainable development. However the complete and clear mechanism of biochar in agro-ecosystem is not understood [7]. Although, number of studies has been done on the application of biochar in soil but the exact mechanisms how biochar influences soil properties is still unknown. It is important to understand the interactions between biochar and soil microbial communities especially involved with nutrient biogeochemical cycles. Relationship between the biochar, soil, microbes and plants, having survey of literature there was not found similar evidence on the mechanism of biochar and soil-plant interaction. But most the studies have been done in positive support of biochar in agricultural and environmental purposes from last two decades in all over the world. [7]. There is the need of systematic and comprehensive studies to understand the clear and complete mechanism of biochar in soil.

BIOCHAR PRODUCTION AND CHARACTERIZATION

Biochar preparation is a burning digestion (pyrolysis) phenomenon of agricultural waste or organic material with using a heap and drum method at 400-500 °C with the residence time of up to 1 hours and different feedstock's have shown in Table 1. These are the traditional method of biochar production to generate economy in various countries of the world as well as India. Heap is a conical or pyramid like shape which is prepared by keeping feedstock inside heap for making biochar [8; 3] to allow the pyrolysied product (biochar) to break away from, the one side and leave for cooling and Ca, Si, Al and K are common elements in biochar but C, N, H and S are also measured by using an elemental analyser (EDX) [9; 10] and electrical conductivity and pH can be measured using a portable pH-EC electronic meter. Biochar can be characterized easily because at present numbers of technique being used in biochar characterization for instance Scanning Electron Microscopy- Energy Dispersive X-Ray Analysis (SEM-EDX) and Fourier Transform Infrared Spectroscopy, (FTIR) both are technique play significant role for the surface and elemental analysis of biochar.

Table 1. Characterization of different feedstock used for biochar production Adapted from Sing et al. [3].

Component	Woodchip [11]	Grass [12; 13]	Poultry litter [14]	Rice Husk [15]	Sugarcane [16]	Wheat straw [17; 18; 19]
Soil C (%)	74.5	- -	71.47	- -	- -	- -
Ash (%)	25.4	14.7	28.53	6.5	11.9-16.4	5.9
pH	7.88	6.1	23.596	6.6	- -	6.76
EC (mS cm^{-1})	0.14	- -	3.0	- -	- -	2770
CEC (c mol kg^{-1})	- -	- -	- -	45-110	- -	- -
C (%)	51.9	42.5	38.6	41	60.4-65.3	43.7
N (%)	0.4	1.9	1.37	1.4	0.8-1.0	0.9
S (%)	- -	5.3	- -	0.1	25.4-15.1	0.283
Ca (ppm)	0.56	4.3 4	1.85	250	- -	0.18
K (ppm)	0.21	64.80	0.99	2604	- -	0.15
Mg (ppm)	0.04	2.3 4	0.19	827	- -	- -
Si mg kg^{-1}	- -	7.44	- -	5.8	- -	0.18
P (ppm)	0.06	2.31	0.35	- -	- -	0.05

APPLICATIONS OF BIOCHAR

Biochar amended soil has a significant advantages in respect to area of environmental management and sustainable agriculture development in nutrient poor soils. The application of biochar in soil can be play significant role in major areas i.e. climate change mitigation, energy production, soil amendment, waste management, carbon sequestration, microbial habitat, eco-friendly fertilizers, Heavy metal reducer, crops yields enhancer, reduced chemical fertilizers input and protect soil microbes from other biota [20].

Climate change mitigation

Climate change is giant challenge on world level in the perspective of global warning because increasing concentration of green house gases into atmosphere is indicating the future challenges for all living being on earth [6; 21]. Every year earth temperature is going up due to higher concentration of green house gases emissions from various anthropogenic and natural sources but anthropogenic sources is major cause for the emission of green house gases, including agricultural activities and coal mine etc. So there is greater need to developed eco-friendly technique for the agricultural farming all over the world, therefore the application of biochar can play important role in climate change mitigation [22; 3]. The highest carbon sequestration potential of biochar can reduce the emissions of green house gases in to environment. Plants store CO_2 as organic carbon inside their tissue system by photosynthesis and during plant biomass decomposition, releases CO_2 in to the atmosphere which is an important greenhouse gas (GHG) and back into the atmosphere by microbial degradation is showing in Figure 1. Biochar can change the global carbon cycle by pyrolysis of biomass, which is stabilized carbon in form of biochar its long time existence in soil due to the recalcitrant properties against microbial degradation [23; 21]. Besides carbon dioxide, methane (CH_4) and nitrous oxide (N_2O) also two main contributors in emission of green house gases from soil to atmosphere, especially in highly synthetic fertilizers used agriculture soil. Both the pollutants (CH_4 and N_2O) have a 30 and 298 times larger global warming potential than carbon dioxide respectively [24; 25]. Various studies have been exposed, the application of biochar in soils to reduce nitrous oxide emissions [26] while many study results are more indistinct in perspective to green house gases emission [27, 28]. But the well defines mechanisms between biochar and potential greenhouse gases are poorly understood, therefore the need of detail study in this direction.

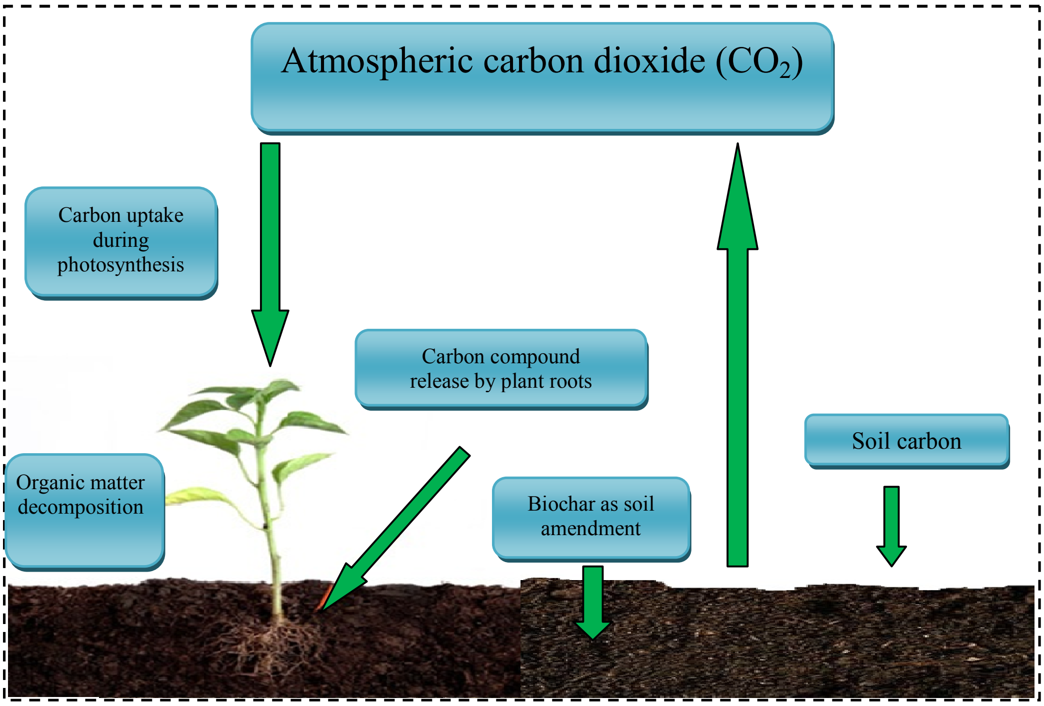

Fig . 1 Biochar application in soil as amendment and carbon mitigation. Sources modified from [29]

Bio-energy production

During the pyrolysis of organic material and biomass is produced three main component of pyrolised biomass i.e. biochar, bio oil and synthesis gas. These all the product of pyrolised biomass are very economically feasible due to commercial uses. Bio oil and synthesis gases can be used as alternative source of energy and electricity respectively [22]. Gasification of any organic material is produced biochar including bio-oil and synthetic gases and the use of bio-oil and synthetic gases as bio-energy. This bio-energy can be used for the transportation of vehicles [30]. When biomass of organic material is pyrolised in limited supply of oxygen produced synthetic gases including carbon monoxide, hydrogen and sometimes carbon dioxide, all these gases are used with combination of various cooking gases. The other bio-energy product is bio-oil can be used as substitute for fuel oil or heating.

Soil amendment

The incorporation of biochar in agricultural soil produces a considerable enrichment in organic matter content and hence significantly enhances the physico-chemical properties and resulting the high fertility and crop productivity. Biochar is introduced as carbon rich by-product which increases the soil organic carbon, which is essential to the plant metabolism for huger crops yield. [22; 31] and can augment the cation exchange capacity (CEC) and pH level of soil [15]. This makes the nutrients more usable for the plant growth and subsequently obtained nutrient rich higher crops yields. Application of biochar to soils contributes to carbon pool but at the same time act as eco-friendly fertilizers [32; 33]. The treatment of biochar increases the total C, organic C, total N, available P, and exchangeable cation like Ca, Mg, Na, and increase K, and decreases Al in soil [34; 35] so plants are used these nutrients and various studies have carried out on biochar application in agricultural soils and produced variable results [35]. According to Major et al. [35] the nutrient uptake capacity of plants was increased in biochar treated soil (Table 2. is showing the physico-chemical properties of soil after amendment of biochar) with increase plant productivity with higher availability of Ca and Mg in soil. Biochar increases the ability of soils to keep hold of nutrients and plant available water and reduces nutrient leaching in agricultural soil [36] and it is reduced the density of soil due to their low density nature ([36] and in that way enhances water infiltration, plant root penetration, and better soil aeration, increase soil aggregate strength etc. [32]. Biochar application to soils is a considerable tool to transfer more easily decomposable organic matter in soil for plant utilisation [37].

Table 2. Physico-chemical properties of soil after amendment of biochar adapted from [38]

Parameter	Unit	Control	Biochar
pH ($CaCl_2$)		7.5	7.4
$CaCO_3$	%	15.8	15.2
Humus	%	2.4	18.1
Total N	%	0.148	0.203
P (CAL)	mg kg $^{-1}$	49	84
P_{tot} (acid digest)	g kg $^{-1}$	5.46	5.54
Sand	%	18.3	Not determined
Silt	%	57.2	Not determined
Clay	%	24.5	Not determined
CEC	cmol kg $^{-1}$	22.5	20.8
Ca (CEC)	cmol kg $^{-1}$	20.7	18.2
Mg (CEC)	cmol kg $^{-1}$	1.46	1.53
K (CEC)	cmol kg $^{-1}$	0.36	0.99
Na (CEC)	cmol kg $^{-1}$	<0.04	<0.04
Al (CEC)	cmol kg $^{-1}$	<0.06	<0.06
Fe (CEC)	cmol kg $^{-1}$	<0.01	<0.01
Mn (CEC)	cmol kg $^{-1}$	<0.01	<0.01
H (CEC)	cmol kg $^{-1}$	0.002	0.002
Fe (EDTA)	mg kg $^{-1}$	40	67
Mn (EDTA)	mg kg21	107	128
Cu (EDTA)	mg kg $^{-1}$	7.2	7.1
Zn (EDTA)	mg kg $^{-1}$	2.3	7.5

Waste management

The focusing on management of waste materials are produced from different sources including domestic, agriculture and industries is serious concern in respect of environmental safety. The huge amount of waste material is produced from agricultural fields all over the world but due to inadequacy of awareness most of the farmers are burned this agricultural waste in the fields and caused the different type's perilous exertion. The accumulation of waste in the environment that leads to surface and ground water pollution but according to newly generated technology (pyrolysis) can convert the large amount of biodegradable waste in the precious form of biochar and used in agricultural field as soil conditioner. [22]. The nutrient concentration of the inorganic matter in biochar is increased due to the pyrolysis process above 350 °C, biochar production from waste material and application in soil is a carbon negative process. Biochar has highly aerometric and recalcitrant nature against microbial decomposition and hundreds to thousands of years can exist in environment. Conversion of agricultural biomass in the form of biochar is a considerable method of carbon negative environment and waste management. Many studies have been suggested that biochar can sequester approximately 50–80% of the carbon which is presented within the biomass feedstock and created pollution free environment [39].

Carbon sequestration

The application of Biochar amendment to the soil not only works like soil fertility enhancers, but also stores the soil carbon in the form of highly aromatic and recalcitrant carbon. Which is not decomposed by soil microorganism? The conversion of organic material and agricultural waste in the form of biochar is considered as the most valuable and eco-friendly idea for the sequestration of carbon from different plant residue in soil (Mathews 2008). Carbon sequestration is a phenomenon in which storing soil carbon with soil organic matter and thus reducing CO_2, CH_4 and N_2O from atmosphere [40; 3]. Soils are large reservoirs of carbon, which store three times more carbon than exists in the atmosphere, hence carbon cycle is a very interesting biological phenomenon in the environment. Plants absorb atmospheric carbon during photosynthesis and carbon go back to soil as plant residue and contributing to soil carbon. Hereby this carbon eventually returns to the atmosphere as soil microbial-mediated decomposing carbon based plant biomass and release carbon dioxide, [29]. Biochar mediated carbon sequestration potential in soil is based on climate change mitigation agricultural practice. The carbon amount based majority in biochar is (70-80%), it can strongly contribute much more carbon then plant residue (40% carbon) in similar amount.

Microbial habitat

The application of biochar in soil is increased the physico-chemical and as well as biological properties soil. Biochar can work as ecological niche for the growth of various microorganisms in biochar amended soil and provide nutritional demand of microorganism. Earlier studies have been shown that the porous structure of biochar has greater internal surface area and potential to immobilize the organic and inorganic nutrients and declared as a cheering shelter for microorganisms which play important role to improving productivity in nutrient deprive soil ([41; 3]. According to Liu *et al.* [42] reported that biochar application in agricultural soils enhanced soil microbial biomass (SMB) due to the macropores (> 200 nm) of biochar could serve as habitats for agriculturally beneficial microorganism such bacteria, fungi and actinomycetes and also protect them from soil predator i.e. protozoon's, nematodes etc. ([43; 44] and Rillig *et al*. [45] also reported that biochar porosity absorbed moisture content from soils and attract largest microbial population and stimulate the spore's germination of fungi. Therefore the long term recalcitrant nature of biochar in soil against microbial degradation is increased the soil microbial biomass and diversity.

Heavy metal reducer

Soil has very complex composition including humus, organic and inorganic matter as well as soil biota and contains pore spaces filled with water or air. [3] Organic matter serves as a binder for mineral particles, contributing to good soil structure and tilth, which refers to the nature and texture of soil under cultivation but due to excess use of various pesticides and synthetic fertilizers for the higher production of crop yields is being disturbed the natural composition of soil and increasing toxicity level but the application of biochar in heavy metal contaminated soil can be reduced the toxicity of various heavy metals from contaminated soil [46; 47]. Biochar may attract various heavy metals which are present in soil including cadmium (II), lead (II), copper (II), and zinc (II) etc. and previous studies have shown that biochar can adsorbed various toxic compounds from contaminated soils and the largest adsorption efficiency of heavy metal ions [cadmium(II), lead(II), copper(II), and zinc(II)] on biochar surface was found. So biochar has been evaluated as a potential adsorbent of heavy metal ions in metal-contaminated soils. [48].

Reduced chemical fertilizers input

Poor agricultural practice and human activities have disturbed the natural cycles of Carbon, Nitrogen and Phosphorus in soil. [49]. But the application of biochar being used to enhancing economical and ecological benefits, including soil fertility improvements, higher yields, grain quality, better soil structure and water retention etc. its use in soil is better than other soil conditioner. The quality or nutrients level of biochar depends on the nature of feedstock and pyrolysis temperature. Therefore, the biochar production and application strategies must be well designed. The low nutrient based feedstock-mediated biochar have inadequate potential to provide satisfactory and economical nutrient supply for reduction of synthetic fertilizers use in agriculture soil [49]. Therefore the nutrient level of biochar is important reservoir in soil for influencing soil fertility and crop yields due to various beneficial properties of biochar in agriculture hence farmers attracting toward the application of biochar for the improvement of barren soil [49].

Soil microbial biomass C and nitrogen mineralization

The long term application of biochar in soil can enhance the soil microbial biomass carbon (SMB-C) as well as nitrogen (N). [50; 31]. But biochar application rates soil type and feedstock nature also affects the soil microbial biomass [51; 5]). Soil microbial biomass increased due to enhancement of available soil nutrients in biochar amended soil such as dissolved organic matter, P, Ca and K etc. biochar can adsorb soil toxic metal and improved microbial activity, soil water holding capacity and pH level etc. Microbial biomass could be increased due to higher microbial diversity in biochar amended soil. Lehmann *et al.* [51], greater surface area and porosity of biochar can be most important survival niche to soil microorganism and protect them to grazing from others soil predators, which are present in soil and store C substrates and mineral nutrients for their growth [52; 50] Zhang et al [50] was analysed soil microbial biomass carbon (SMB-C) and nitrogen (SMB-N) in a field experiment during a winter wheat growing season after four consecutive years cycle with the application of different treatment Results indicated that biochar amendment increased SMB-C significantly compared to the others treatment, and that the effect size increased with biochar application rate [50] and it's has been observed that the effect of Treatment of biochar on soil SMB-N was less strong than SMB-C. However the treatment of biochar significantly increased the C/N ratio [50].

Nitrogen is one of the most essential nutrients for plat growth therefore organic and inorganic nitrogen play significant role in nutrient cycle. Nitrogen deficiencies in soil influence the crop yields. The transformation of organic nitrogen in to the plant usable form (inorganic nitrogen) by microorganism affects by the application of various types synthetic fertilizers [3; 31]. While biochar is increased the microbial population therefore the rate of microbes-mediated nitrogen transformation become high and reduced the NH_4^+ and NO_3^- ions leaching [53; 54; 55]. The rate of soil N transformations could be increased due to the adsorption of organic nitrogen on the surface of biochar. Thus microbes-mediated nitrogen mineralisation could be occurred in biochar amended soil [56].

CONCLUSION

Based on the above discussion it may be concluded that application of biochar in agriculture is safe and viable option for soil and environmental management. Its application to agriculture soil has great potential to improve the soils fertility, plant growth promotion and increasing soil microbial biomass. The quality of biochar depends on the nature of feedstock and pyrolysis temperature. The best proposed temperature for making high quality biochar is 500-600 ^{0}C. Biochar quality affects the physico-chemical properties of soil. Because biochar can improve the soil physico-chemical properties due to their nutrient rich properties and at the same time due to large surface area and internal pore structure it may increase the soil water holding capacity and microbial abundance. Exchangeable cations and nutrient elements could increase the cation exchange capacity and availability of soil nutrients. The pH level may be increased due to the highest hydrogen ion concentration in biochar. So, improvements of soil physical, chemical and biological properties promote the productivity of plant after increasing the amount of nutrient accessibility and reducing nutrient leaching. Biochar is not only soil fertility enhancer for the nutrients deprive soil but also play significant role in environmental management and agricultural economic benefits. So, biochar application in soil can mitigate the emissions of green house gases, by increasing the C sequestration process and consequently sustainable environmental management.

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Citation of this Article
C Singh, S Tiwari, and J S Singh. Application of Biochar in Soil Fertility and Environmental Management: A review. Bull. Env. Pharmacol. Life Sci., Vol 6 [12] November : 07-14