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Role of biochar on soil fertility improvement and greenhouse gases sequestration

Abstract

Biochar is mostly porous, stable C rich, formed at high temperature, highly serpent and nutrient rich material. The objective of this work was to understand the role of biochar on soil fertility improvement and greenhouse gases sequestration. Biochar application can improve soil fertility by manipulating soil properties that is soil porosity, soil water holding capacity, soil aggregation soil reaction (pH), soil organic carbon these soil physicochemical properties improved and the soil becomes safe nutrient rich to support plant growth. In addition biochar application increases the activities and population rhizobia species in the soil. Emissions of greenhouse gases were suppressed by application of biochar in agricultural fields. Soil contaminant effectively adsorbed, suppressed biodegradation and leaching of contaminants in to ground water. The efficiency of biochar's depends on feedstock type, pyrolysis temperature. Biochar is the most eco-friendly technology that should be used for soil fertility improvement and reduced the emission of greenhouse gases.

Keywords: Biochar, soil fertility, greenhouse gases emission, remediation

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Introduction

Soil fertility decline and greenhouse gase emission has been perceived as widespread treating challenges in the world.[1] According to Jones et al.[2] crop production shared about 10 to 12% of global greenhouse gases (GHG) emissions and land conversion from forest and pasture to croplands, soil and biomass carbon that accounts an additional 12 to 20% of global GHG emissions and to overcome these bottlenecks, Bichar amendment has been recognized as best method.

International Biochar Initiative (IBI) defined biochar as "a solid material obtained from the thermo-chemical conversion of biomass in an oxygen-limited environment**".**[3] Others also defined it as a carbon-rich and mostly alkaline material produced by thermo-chemical conversion of organic materials such as agricultural residues and municipal wastes in a controlled low-oxygen environment.[4] Following, Paris agreement on climate change mitigation held in December 2015, many countries have been paid attention in biochar application due to different benefits. Even some countries have been forced their people not to burn residual materials in open field. For example, in China, straw burning in open field was strictly forbidden according to the state calls for alternative treatments of waste as raw material for biochar.[5]

Addition of biochar to soil showed increased plant growth and crop yield, improved soil properties,[7] enhanced the bioavailability of nutrients, improved stress tolerance of plants to salinity, drought, heavy metal toxicity and high temperature[8] and also decreased soil nutrients leaching.[9] Biochar has also received increasing attention due to its ability to mitigate climate change[10] due to high carbon sequestration capacity.[11] Basically, amendment of biochar reduced emission of soil nitrous oxide (N_2O), methane (CH_4),[12] and had capable of offsetting about 12% of anthropogenic CO_2-C emission.[13] In addition to this, biochar has been suggested as one of the most eco-friendly and promising approach to reduce environmental contaminants.[14]

Objective

General objective

The general objective of this review was to understand role of biochar on soil fertility improvement and greenhouse gases sequestration

Specific objectives

Based on the general objective mentioned above, the following specific objectives were stated as.

i. To recognize the role of biochar in soil fertility improvement and

ii. To recognize the role of biochar in greenhouse gases sequestration and gaps

Significance of the review

Presence of different research findings about the role of biochar in soil fertility improvement and greenhouse gases sequestration were known at large but most of these findings were scattered. So, this reviewed document will help readers to accesses compiled data.

Scope of the review

As much as possible, the review was focused at findings and reports that have done around the globe about the role of biochar in soil fertility and greenhouse gases sequestration.

Methodology

Published articles (62 article with peer reviewed, 3 article with single author), 1 organizational report, 1 in-press paper, totally 67 references were used. An as much as possible, latest article which contains quantitative data were searched in Google Scholar and purposively selected. Endnote software was used for citation in the text and end reference by using APA style of referencing with synchronization of it with seminar wring guideline of CDAN of Mekelle university.

Review of literature and discussion

Characteristics of biochar

Biochar is carbon-rich,[15] and has high chemical and biological stability.[16] Usually, biochar has high porosity, large specific surface area, adsorption ability, and high cation exchange capacity.[17] The elemental composition of biochar usually includes higher proportion of C.[15] The characteristic of biochar depends by feedstock type and pyrolysis temperature[18] as indicated from the (Table 1) (Figure 1).

The role of biochar in soil fertility

Effects of biochar on soil properties

Soil porosity: Hseu et al.[19] reported that amending of rice husk biochar to soil increased the abundance of macro-pores and micro-pores from 4 to 27% and 11 to 54%, respectively. Similarly, Gamage et al.[20] reported that the application of rice husk biochar significantly increased the porosity of clayey textured soils. These increased results could be attributed to soil particle rearrangement due to biochar application.

Soil water holding capacity: Soil moisture content of wood-land increased from 6 to 25% after the application of green waste biochar at the rate of 20 t ha^{-1}.[21] Similarly, Li et al.[22] reported that overall average runoff decreased by 28% after the application of rice straw biochar at a rate of 20 t ha^{-1} over the period of 2 years when compared to that of a control treatment. The reduction in runoff was attributed to the strong water retention effect of biochar. Uzoma et al.[23] found that sandy soils with biochar amendment showed increase in water holding capacity from 0.2 to 56.1%. Dan et al.[24] also confirmed that treatment of soil with biochar significantly increased the water holding capacity of sandy soils.

Soil aggregation: Application of biochar has shown positive effect on soil aggregation.[25] Zhang[26] also reported that addition of biochar in a loamy soil significantly promoted the formation and stabilization of macro-aggregates. Likewise, Lu et al.[25] observed that addition of rice husk biochar increased soil aggregation more than three times that of original pore space (from 8 to 36%) in Vertisol. Similarly, Ouyang et al.[27] revealed that the amending of dairy manure biochar to the soil significantly promoted the formation of aggregates in both silty-clay and sandy-loam textured soils.

Table 1 Characteristics of biochar produced from different feedstock and pyrolysis temperature

Feedstock Type	Pyrolysis T°	pH	C (%)	P.V (cm^3 g^{-1})	S.A (m^2 g^{-1})	CEC (Cmol kg^{-1})	References
Feed lot	350	9.1	53			-	Cantrell et al.[68]
Feed lot	700	10.3	52			-	Cantrell et al.[68]
Soybean	300	7.3	69	-	5.6	-	Ahmad et al.[14]
Soybean	700	11.3	82	0.2	420	-	Ahmad et al.[14]
Turkey litter	350	8	49	-	2.6	-	Cantrell et al.[68]
Turkey litter	700	10	45	-	66	-	Cantrell et al.[68]
Tire rubber	200	-	75	-	-	-	Lian et al.[52]
Tire rubber	400	-	78	0.08	-	-	Lian et al.[52]
Tire rubber	600	-	81	0.12		-	Lian et al.[52]
Tire rubber	800	-	86	0.11		-	Lian et al.[52]
Eucalyptus	700	6	37	-	-	129.75	Eyob and Dereje, in press
Acacia	700	8.1	66	-	-	117.00	Eyob and Dereje, in press
FYM	700	8.2	23	-	-	87.25	Eyob and Dereje, in press
Rice straw	700	6.4	41	-	-	127.50	Eyob and Dereje, in press

Where: PV pore volume and SA surface area

Soil pH: Increased soil pH as a result of biochar application has been extensively investigated in agricultural soils[15] and Rhoades et al.[28] also reported that the combined application of biochar with rate of (20tha^{-1}) and mulch (37 t ha^{-1}) increased soil pH from 5.7 to 6.4 in forest soil.

The observed increase in soil pH may be simply due to the addition of alkaline material[29] or biochar application decreases the exchangeable aluminum content of soils through binding Al^{3+} ion by oxygenated functional groups on its surface, thereby increasing the abundance of soil exchangeable base cations that ultimately resulting in a soil pH increase.[30] So, biochar has been used as an excellent alternative amendment of acidic soil reclamation to increase soil pH.[30] However, some studies have shown no effect of biochar application on pH of forest soils.[31] These contradicting findings among different studies may be attributed due to differences in biochar feedstock, the pyrolysis process, and diverse soil properties.

Soil organic carbon: Concentration of soil organic carbon content showed increase after addition of biochar as reported by Laird et al.[32] Wang et al.[33] also reported that addition of biochar at the rate of (5 tha^{-1}) significantly increased soil organic carbon content. Primary reason for these observations could be due to presence of stable carbon in the biochar that is difficult to decompose in soil environments, thus contributing to the soil carbon pool.[34]

Biochar as nutrients source and bio-availability: Biochar application increases nutrients content and bioavailability for plants since biochar itself contains various nutrients.[35] Biochar produced from wood waste materials generally contains high levels of soluble K and variable concentrations of P and Ca.[36]

Sackett et al.[31] observed that bio-available K, Ca and Mg concentrations significantly increased after biochar application at a rate of (5 tha^{-1}). In addition, Gundale et al.[37] reported that biochar addition at a rate of (10 tha^{-1}) increased the soil's net N mineralization

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rate and NH4+ concentration. Other studies also have shown that biochar application increased other nutrient concentrations including silica and boron.[38]

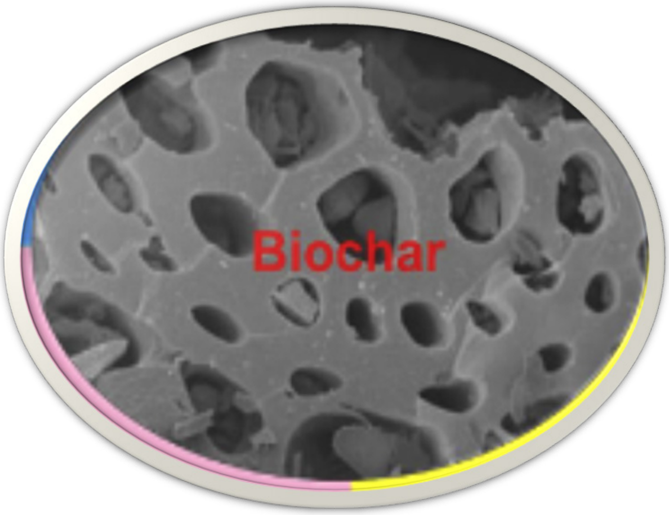

Figure 1 Diagrammatic presentation of porous nature of biochar (source: Li *et al.,* 2017).

Lehmann et al.[39] pointed that the immediate beneficial effects of biochar application on plant growth and yield in tropical soils can be attributed to the increased concentration of Ca, Cu, K, P, and Zn. However, the effect of biochar application on plant growth and yield over the long term was mainly due to modifying nutrient bioavailability rather than via the direct supply of nutrients from biochar (Figure 2).[40]

Biochar based microbs: It has been reported that population of rhizobia associated with chickpea was higher in biochare amended soil due to suitability of biochar as carrier of microbes.[41] Saranya et al.[42] reported that applying biochar with *Azospirillum* significantly increased the rhizosphere population of *Azospirillum* and other diazotrophic microorganisms.

In addition, biochar-based microbes promoted plant growth and nutrient uptake.[43] The biochar-based seed coating with microbes also improved germination, root and shoot growth, chlorophyll content, and phosphorous uptake of plants.[44] Nodule number of lupine plants where seeds were treated with biochar based microbes was increased by up to 146% under drought stress conditions compared to none biochare based.[45] Generally, due to porous nature of biochar, microbes living inside pores may get better protected from external factors such as drought, adverse pH, or toxic substances in soil.[46]

Effects of biochar on greenhouse gases emission

Soil co_2 emission: Most of recent findings reported that soil treated with biochar decreased CO_2 emission or no effect. Sun et al.[47] found that application of biochar with rate of 30tha^{-1} significantly reduced CO_2 emissions by 31.5% in forest soil. But, Sackett et al.[31] and Zhou et al.[48] found that biochar application did not affect the CO_2 emissions as indicated in (Table 2).

Table 2 Effect of biochar application the green house gases emission in forest soils

Soil type	Biochar type	Biochar rate	Time (duration)	CO_2 emission	CH_4 uptake	N_2O emission	References
Cambisols	Corn silage (500 °C)	1 *w/w*	105 days	Not significant	Not significant	Decreased	Malghani et al.[56]
Ferralsols	Chicken manure (540 °C)	10%, *w/w*	84 days	-	Significantly Increased	-	Yyu.
Brunisol	Sugar maple wood (500 °C)	5, 10, & 20 t ha^{-1}	24 days	Significantly increased	-	-	Mitchell et al.[49]
Humo-ferric Podzols	Douglas-fir (420 °C)	1%,w/w	25 days	Significantly increased	Significantly decreased	Not significant	Hawthorne et al.[58]
Humo-ferric Podzols	Douglas-fir (420 °C)	10%, *w*/w	25 days	Significantly increased	Significantly decreased	Increased by 191%	Hawthorne et al.[58]
Lixisol	Wheat straw (450 °C)	30 t ha^{-1}	1 year	Decreased by 31.5%	-	D Decreased by 25.5%	SSun et al.[25]
Ferralsols	Bamboo leaf (500 °C)	5 t ha^{-1}	1 year	Not significant	-	-	Wang et al.[33]
Humo-ferric Podzols	Mixed maple & spruce sawdust (350–450 °C)	5 t ha^{-1}	1 year	Not significant	Not significant	Not significant	Sackett et al.[31]

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Table Continued

Soil type	Biochar type	Biochar rate	Time (duration)	CO_2 emission	CH_4 uptake	N_2O emission	References
Ferralsols	Bamboo leaf (500 °C)	5t ha^{-1}	1 year	-	-	Decreased by 20.5	Xiao et al.[54]
Humo-ferric Podzols	Douglas-fir slash (420 °C)	20 t ha^{-1}	3 months	Increased by 6.6%	Decreased by 8.4	-	Johnson et al.[50]
Ultisol	Chicken manure (400 °C)	24 t ha^{-1}	1 year	-	Not significant	Not significant	Lin et al.[22]
Ferralsols	Bamboo (800 °C)	10 and 30 t ha^{-1}	16 months	Not significant	-	-	Zhou et al.[48]
Ferralsols	Bamboo (800 °C)	10 and 30 t ha^{-1}	16 months	Not significant	-	-	Zhou et al.[48]

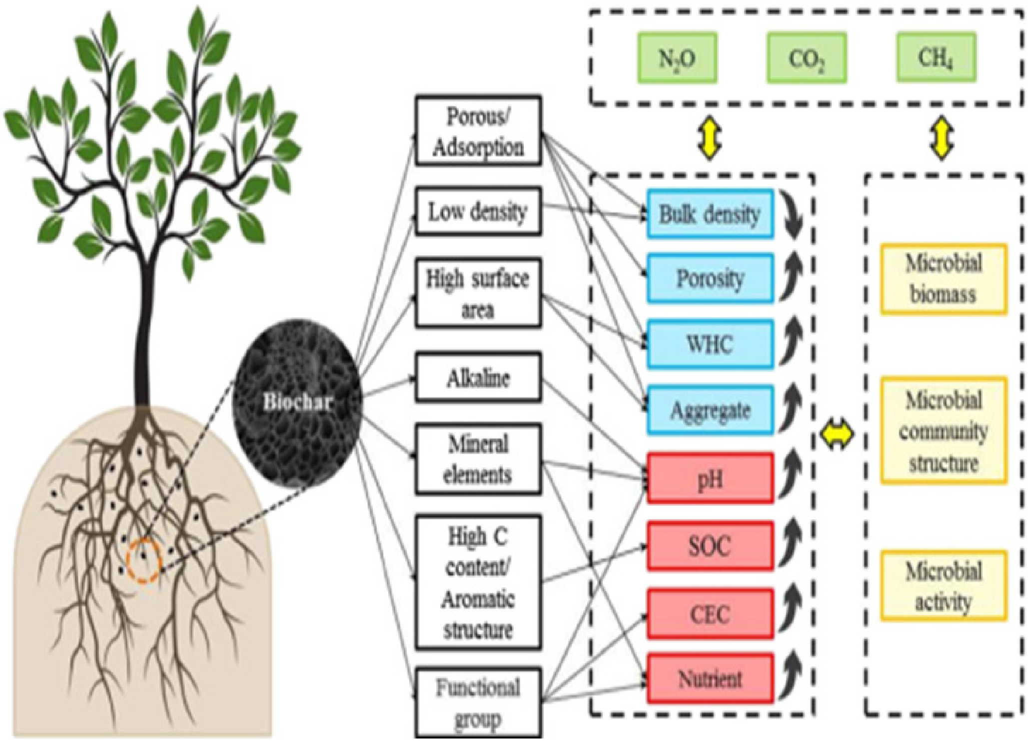

Figure 2 Conceptual framework for effects of biochar application on soil properties and green house gases emission.

On other hand, Mitchell et al.[49] reported that the application of sugar maple biochar with rate of (5, 10, and 20 t ha^{-1}) significantly increased soil CO_2 emissions in a temperate forest soil. Similarly, Johnson et al.[50] also reported increased CO_2 emissions from a biochar-amended soil compared to that of emissions from the untreated control soil (Table 2).

The variability of effects of biochar application on soil CO_2 flux in the above studies might be due to differences in the type and rate of biochar applied, vegetation and soil types, in addition to the time period between CO_2 measurement and biochar application.[51]

Soil CH_4 emission: Addition of biochar suppressed CH_4 emission especially from waterlogged rice paddy soil as reported by Liu et al.[52] and also application of chicken manure biochar significantly decreased CH_4 emission in forest soil.[53] Biochar amendment significantly decreased soil CH_4 emission in an intensively managed plantation regardless of the application rate.[54] Amendment of biochar decreased soil bulk density and increased soil porosity which favors CH_4 oxidation and uptake activity by soil bacteria.[55]

However, some studies has been indicated that application of biochar did not affect soil CH_4 emissions,[31] had no significant effect on the CH_4 emissions from a deciduous forest soil,[56,57] no significant difference in CH_4 flux between biochar-treated and control soils in a temperate hardwood forest,[31] and application of it with rate of (24 tha^{-1}) did not affect CH_4 emission in a sub-tropic acidic forest soil[22] (Table 2).

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Contrary to these findings, Mitchell et al.[49] reported that the application of sugar maple biochar (5, 10, and 20 t ha^{-1}) significantly increased soil CO_2 emissions in a temperate forest soil. Johnson et al.[50] also reported increased CO_2 emissions from a biochar-amended soil compared to the emissions from the untreated control soil. Hawthorne et al.[58] also reported significantly higher CO_2 fluxes (increased by 191%) from soil treated with 10% biochar compared to the emissions from the same soil treated with 1% biochar. According to Yongfu et al.[59] mechanisms underlying CH_4 flux from soils after biochar application and especially concerning with microbial metabolism were complicated.

Soil N_2O emission: Evidence concerning the potential for reduced N_2O emissions as a result of biochar application in dry land soils has been confirmed in many farmland soils.[60] Sun et al.[47] found that the application of biochar with the rate of 30 tha^{-1} significantly decreased cumulative N_2O emission in forest soil by 25.5%. Likewise, Xiao et al.[54] reported that biochar application with rate of 5 t ha^{-1} in the forest soil reduced annual average flux and annual cumulative total soil N_2O emissions by 27.4 and 20.5%, respectively when compared to that of the untreated. Rondon et al.[61] also reported that 50% and 80% reduction of N_2O emissions under soybean and grass systems, respectively due to biochar addition.

However, application of biochar with rate of (5 tha^{-1}) in a temperate hardwood forest did not change soil N_2O emission.[31] On other hand, Clough et al.[62] reported that N_2O emissions increased after the application of biochar to the soil. Similarly, Hawthorne et al.[58] reported that amending of 10% biochar in a forest soil significantly increased N_2O emissions. Thus, why and how biochar addition on soil increased N_2O emission processes was quite complicated.[59]

Soil contamination: According to Jones et al.[63] application of biochar with rate of (25 tha^{-1}) was the most effective for soil contaminant adsorption, suppressed biodegradation and leaching of contaminants into groundwater. Yu et al.[64] also reported that biochar produced from woodchips and cotton straw which pyrolyzed at 850ºC resulted a remarkable decrease in the uptake of pesticides by the plants grown in contaminated soils. In general, the biochar produced at higher temperatures exhibit higher sorption efficiency for organic contaminant remediation in soil.

Unlike organic contaminants, heavy metals are non-biodegradable and their bioavailability makes them highly toxic to living organisms.[26] But, biochar has been mostly amended to synchronize those toxic heavy metals in contaminated soil[65] as indicated in (Figure 3) and (Table 3).[66–70]

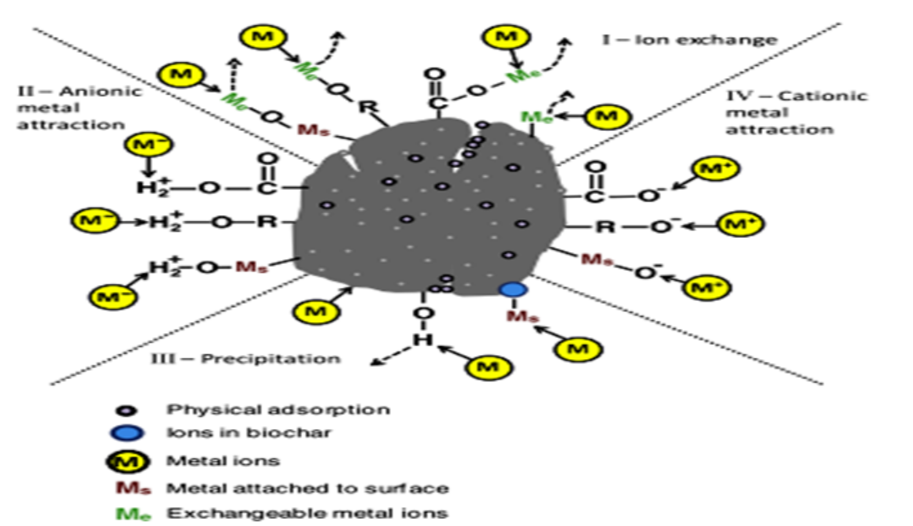

Figure 3 Mechanisms of biochar interaction with inorganic contaminants. Circles in the biochar particle show physical adsorption, I-ion exchange between target metal and exchangeable metal in the biochar, II-electrostatic attraction of an ionic metal, III- precipitation of target metals and IV-electrostatic attraction of cationic metal (Source: Ahmed et al., 2014).

Table 3 Effect of biochar application in contaminated soil

Contaminants	Biochar type	Matrix	Effect
Chloropyrfos & carbofuran	Woodchips (450 & 850)	soil	Adsorption due to high surface area and nano-porosity
Pentachlorophenol	Bamboo (600 °C)	soil	Reduced leaching due to diffusion and partition
Pentachlorophenol	Rice straw	soil	Adsorption due to high surface area and micro-porosity
Simazine	Hardwood (450 and 600 °C)	soil	Sorption due to abundance of micro-pores
Arsenic	Hard wood (400°C)	soil	Mobilization due to enhanced pH
Cadmium and zinc	Hard wood	soil	Immobilization due to enhanced pH
Lead	Oak wood (400 °C)	soil	Immobilization by rise in soil pH and adsorption onto biochar

Source cited in Ahmad et al.[66]

Conclusion and way forwards

Biochar is most eco-friendly technology that should be used for soil fertility improvement and climate change mitigation. But:

a. The effects of biochar addition on soil N_2O emission processes and the mechanisms involved require further investigations

b. CH_4 flux from soils after biochar application especially concerning microbial metabolism require further investigations

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None.

Conflicts of interests

Authors declare no conflict of interest exists.

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