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S. I. BIOCHAR

Biochar for sustainable soil and environment: a comprehensive review

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Abstract
Biochar prepared from organic waste through pyrolysis, thermal combustion in an inert environment, generates a stable form of carbon. The review of established literature reveals that conversion of organic matter into biochar and its addition to soil also reduces the negative effects of carbon aerosols on human health and greenhouse gas effects on environment through carbon sequestration. Physicochemical properties of biochar such as nutrient sorption capacity, pH, pore structure, particle size, surface area, and mineral content play a vital role in determining the soil structure and function. Biochar addition to soil exerts measurable changes in physicochemical soil properties such as bulk density, water-holding capacity, pH and cation exchange capacity, microbial community structure, and their interrelated functions in soil. However, addition of biochar to specific soil improves the soil fertility, and consequently improves the crop yield. It is concluded that optimized pyrolysis of organic waste for biochar production and its use for soils need diversified investigation in diverse environmental conditions.

Keywords Agriculture climate change · Biochar · Soil fertility · Soil microbial community

Introduction

Carbon produced by anthropogenic activities such as burning of fossil fuel and decomposition of organic waste in landfills has been designated a major environmental pollutant. The soot from diesel engines and landfill places is considered a pollution marker (Jansen et al. 2005) as it has longer life time as aerosols. The particulate carbon has higher deposition rate and it is chemically inert in nature (Hedges et al. 2000), and they contribute 5–10% of particulate matter pollution (PMP) (Putaud et al. 2004). The carbon particles have a significant pollutant sorption capacity and are known to bind persistent organic pollutants (POPs) (Mattila and Verta 2008), xenobiotic, and naturally occurring organic pollutants from soils and sediments and reduce their bioavailability (Gustafsson and Gschwend 1997). The particulate carbon in the atmosphere is wet and dry and deposits on water surface and lands. These are carried to water bodies through precipitation, runoff, and sedimentation. Carbon particles emitted to the environment are health concern for humans depending on size and substances sorbed on these particles. Particles with larger size (≥ 4 µm) and below 0.002 µm have a higher tendency to

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deposit in the mouth and throat during inhalation, while ultrafine particles (0.1 < μm) deposit in the alveolar region of the lungs (Chrostowski 1994). Particulate carbon carrying toxic substances on its surface into the lungs may enter into the blood stream through the alveolar epithelium and deposit in extra pulmonary organs such as liver.

The release of particulate and gaseous carbon from combustion processes in the atmosphere has measurable effects on the climate. Airborne carbon particles increase radiative scattering while CO_2 absorbs the light. Deposition of carbon particles on land particularly ice changes the albedo. The CO_2 produced from burning and decomposition of organic mass is considered the second largest global warming contributor. It causes a net positive radiative effect through the absorption, and interception of direct sunlight consequently causes the dimming of surface and reducing the evaporation and rainfall (Ramanathan et al. 2007).

However, the release of carbon to the environment through decomposition and combustion can be reduced by the conversion of organic mass into biochar through pyrolysis. In pyrolysis, various types of organic materials are heated in a partially anaerobic environment converting them to biochar, oil, and gas. The biochar is used as a soil additive for carbon sequestration and fertility (Abbas et al. 2017; El-Naggar et al. 2018; Malik et al. 2018). The biochar has been used to remediate metal-contaminated soil (Rizwan et al. 2016b) as the heavy metals can reduce the crop yield (Rizwan et al. 2016a, c), and thus, their entry in the crops should be chekced for better crop production. The biochar in soils may change the soil pH, microbial community structure, and their related functions (Van Zwieten et al. 2010; Rehman et al. 2016) and improves the nutritional quality of soil by retention of nutrients through adsorption (Liang et al. 2006, 2010; Lal 2018) which depends upon the soil and biochar types (Liang et al. 2006; Grossman et al. 2010; Jin 2010; Younis et al. 2016). The underlying mechanism of changes in soil microbial community due to biochar is not yet clear and needs systematic investigation. Furthermore, addition of biochar to soil is a technique which can be used to minimize climatic change due to its relatively recalcitrant nature against bacterial decomposition, which results in a slower return of terrestrial organic carbon dioxide (CO_2) to the atmosphere (Lehmann 2007). Bacterial groups, decomposing organic matter and their metabolic activities, can determine the stability of biochar in different soils (Fukami et al. 2010). The biochar-amended soils with changed microbial communities and their functions affect nutrient cycling and organic matter decomposition and also the growth of plants in those soils (Kuzyakov et al. 2009; Liang et al. 2010). Conversion of organic mass into biochar and its addition to soils may reduce the greenhouse gas emissions by reducing the release of nitrous oxide (N_2O) and methane (CH_4) from soil to the atmosphere (Spokas and Reicosky 2009; Clough et al. 2010; Singh et al. 2010b; Zhang et al. 2010; Taghizadeh-Toosi 2011). The fast mineralization of indigenous organic mass of soil and greenhouse gas emissions can be reduced by pyrolyzing the biomass prior to addition in the soil (Jin 2010; Liang et al. 2010). In addition, the increased mycorrhizal biomass in biochar-amended soils has been credited to the intrinsic character of biochar (Warnock et al. 2007).

The impact of biochar on the main soil biogeochemical processes demonstrates a frontier in soil and environmental science research with several un-investigated phenomena. In this review, we first examined published literatures about the properties of biochar. In the second part, effects of biochar on the environment were identified and summarized. The third section focuses on the literature related to the conversion of organic waste into biochar and addition to soils with particular attention to carbon sequestration and soil quality.

Physicochemical nature of biochar

General properties

Biochar comprises varying labile and stable carbon fractions and ash contents. Biochar is mostly generated at a temperature of 250–500 °C by partial combustion of feedstocks under limited oxygen supply (Baldock and Smernik 2002; Rizwan et al. 2016b). Spectroscopic studies revealed that in the pyrolysis process, O-alkyl and di-O-alkyl molecules can convert into aromatic rings of carbon such as phenol, methyl, and alkyl substituents of the aromatic carbon (Schmidt et al. 2002). At pyrolysis temperatures exceeding 1000 °C, graphite-like carbon forms were reported (Haumaier and Zech 1995). The major chemical difference among biochar and other organic materials is the greater ratio of aromatic to aliphatic carbons, especially the presence of fused aromatic rings in contrast to other aromatic structures (Schmidt and Noack 2000). These fused aromatic rings are present in varying forms, such as amorphous carbon containing higher quantities of aromatic rings at lower pyrolysis temperatures and turbostratic carbon at higher temperatures (Keiluweit et al. 2010; Nguyen et al. 2010). Since the majority of biochars contains more condensed aromatic rings with few functional groups, which make the biochar resistant to decomposition (Dai et al. 2005), the degree of biochar polymerization, macromolecular structure (graphitic vs. diamond) and the presence of surface functional groups is mainly affected by the feedstock types, pyrolysis time, and temperature and post-pyrolysis aging or weathering.

Chemical properties of biochar

Chemical properties of biochar are significantly influenced by feedstock and pyrolysis conditions. Biochar produced from different feedstocks such as *Eucalyptus saligna*, paper mill sludge, poultry litter, oak wood, corn stover, and cow manure biochar at 400–550 °C (Singh et al. 2010b; Lehmann et al. 2011) contain variable quantities and types of elements (Table 1). The paper mill sludge biochar contains higher calcium, $CaCO_3$, copper, and CEC and lower potassium content (Table 1). In majority of biochars, the aromatic hydrocarbons and heavy metal contents are below the detection limit (Singh et al. 2010a; Abbas et al. 2017; Rehman et al. 2017). The FTIR spectrum revealed that biochars have almost similar strong, sharp, and medium peaks with their corresponding functional groups. Positional changes in peaks were found in biochar of the same feedstocks pyrolyzed at higher temperatures. This corresponds to the shifting of bonds from predominantly aliphatic to aromatic carbonyl groups (Sharma et al. 2004). Moreover, the shifting of peak positions at higher temperature is due to the removal of thermo-labile functional groups and formation of thermally stable compounds like aromatic rings. This indicates the degradation of straight carbon chains and formation of complex carbon structures (Kaal et al. 2012). Strong and broad absorbance peaks in subjected biochars were recorded between 3300 and 3500 cm^{-1} and have been corresponded to O–H groups representing the phenols, ester, and alcohols (Cantrell et al. 2012), while mostly strong and sharp peaks in selected biochar have been recorded between 1500 and 1700 cm^{-1} and designated to C–C, C=C aromatics, and N–H primary amines and alkyl halides in the range of 400–800 cm^{-1} accordingly (Cantrell et al. 2012).

Impact of biochar on soil properties

Physico-chemical properties of biochar-amended soils

Biochar changes the physico-chemical properties of soil (Ali et al. 2017; Dai et al. 2017; El-Naggar et al. 2018). These changes depend on biochar production conditions, the feedstock used (Downie et al. 2009) but also the soil itself (El-Naggar et al. 2018; Malik et al. 2018). The physico-chemical changes in biochar-amended soils on spatial scales in different climates and soils have not been fully investigated. However, biochar with less tensile strength can minimize, overall, tensile strength of soil upon addition (Chan et al. 2008; Chen et al. 2008; Malik et al. 2018). Mechanical impedance is one of the major factors in soil, determining the root proliferation and elongation (Bengough and Mullins 1990). Reduced tensile strength of soil due to biochar enhances the contact of root with mycorrhizal nutrient mining and promotes seed germination. It also helps the progress of invertebrates in soil and favors the root growth; however, it has not yet been studied in details (Harding and Hilton 1992). Biochar changes the soil density (Table 1) which affects soil water retention, rooting

Table 1 Physicochemical properties of biochars produced from different feed stocks at different temperatures. Source (Lehmann et al. 2011; Singh et al. 2010a)

Features	Oak wood			Corn stover			Poultry litter			*E. saligna*		*E. salinga* leaves		Paper sludge		Cow manure	
Temperature °C	60	350	600	60	350	600	60	350	600	400	550	400	550	400	550	400	550
pH (H_2O)	3.73	4.80	6.38	6.70	9.39	9.42	7.53	9.65	10.33	7.67	9.49	9.17	10.0	–	9.22	9.03	8.94
CEC	182.1	294.2	75.5	269.4	419.3	252.1	363.0	121.3	58.7	47.3	39.0	77.7	57.4	–	212.1	208.8	127.3
SAe (m^2/g)	–	450	642	–	293	527	–	47	94	–	–	–	–	–		–	–
Ash%	0.3	1.1	1.3	8.8	11.4	16.7	36.4	51.2	55.8	4.2	4.6	9.9	11.7	–	65.4	703	762
volatiles%	88.6	60.8	27.5	85.2	48.8	23.5	60.5	47.2	44.1	–	–	–	–	–	–	–	–
C%	47.1	74.9	87.5	42.6	60.4	70.6	24.6	29.3	23.6	69.4	79.2	66.3	71.98	–	31.59	17.5	16.53
C/N ratio	444	455	489	83	51	66	13	15	25	–	–	–	–	–	–	–	–
Total P (mg/kg)	5.0	12	29	526	1889	2114	16.7	21.3	23.6	127	160	2077	2673	–	378	4359	4927
Fixed C%	11.1	38.1	71.2	6.0	39.8	59.8	3.1	1.6	0.1	–	–	–		–	–	–	–
H/C ratio	1.48	0.55	0.33	1.56	0.75	0.39	1.51	0.57	0.18	–	–	–	–	–	–	–	–
O/C	0.72	0.20	0.07	0.74	0.29	0.10	1.03	0.41	0.62	–	–	–	–	–	–	–	–
Aromatic C (% of total)	–	82.8	86.6	2.0	76.9	88.2	–	–	–	–	–	–	–	–	–	–	–
Aromatic cluster	–	18	37	–	293	527	–	–	–	–	–	–	–	–	–	–	–
EC	–	–	–	–	–	–	–	–	–	0.13	0.17	1.44	2.27	–	0.44	9.18	9.64
N (g/kg)	–	–	–	–	–	–	–	–	–	0.21	0.23	6.4	17	–	0.21	13.5	11.4
K (mg/kg)	–	–	–	–	–	–	–	–	–	1756	1907	12,816	14,923	–	520	26,429	23,075
S (g/kg)	–	–	–	–	–	–	–	–	–	127	165	910	992	–	1591	4526	3737
Ca (mg/kg)	–	–	–	–	–	–	–	–	–	1.8	1.8	17.14	20.52	–	179.5	17,518	18,810
Mg (mg/kg)	–	–	–	–	–	–	–	–	–	911	927	4657	5420	–	2825	10,699	11,823

patterns, and soil biota due to its low density, mineral contents, and porous structures (Downie et al. 2009). Biochar density is greater than its feedstock (Brewer et al. 2009). Bulk densities of biochars are between 0.09 and 0.5 g cm^{-3} (Spokas et al. 2012). Biochar amendment to the hard setting soils considerably increases the physical and chemical properties such as C, N, pH, and available P while reducing soil strength (Chan et al. 2008). Biochar increases minerals and organic matter such as soils with lesser bulk density, usually related to the elevated soil organic matter. The bulk density presents a rough sign for how organic matter changes soil composition and pore size (Sohi et al. 2010; Hafeez et al. 2018). Studies conducted on outcome of biochar regarding crop yield demonstrated water-holding capacity of soil as a key factor influenced by biochar. The water-holding capacity of sandy soils increased with biochar addition. For instance, the water-holding capacity in terra preta soil is 18% higher than the nearby soils where charcoal is lower or deficient and a mutual effect is expected between the higher biochar content and higher levels of organic matter that appears to be associated with charcoal in these soils. Biochar is generally chemically stable in soil with potential to provide a direct and long-term change to soil water-holding capacity through its macro porous structure compared to its feedstocks (Sohi et al. 2010). The particle volume in biochar-supplemented soils possibly has a direct effect on soil fertility at macro scale, but is short-term in nature since biochar are split into micro particles gradually (Brodowski et al. 2007). This shows that biochar applications can positively increase the water-holding capacity of sandy soils, which is normally dominated by larger pores. Moisture release curves for loamy sand field soil having 88 ton ha^{-1} biochar (Harris et al. 2007) and soils with 22 ton ha^{-1} biochar showed no significant difference. Other studies revealed that higher biochar contained twice the higher water content compared to soils without biochar. Soil warmth, evaporation, and evapo-transpiration have an effect on soil water availability, so comparison of volumetric water content among biochar altered and direct soils in field experiments might be confounded by indirect effects (Sohi et al. 2010).

Biochar reduces the nutrient leaching from soils. Studies reported the increased yield from biochar-amended soils which are due to increased nutrient cycling. On the other hand, the fundamental principles have not been established, and no experimental or mechanistic explanations have been developed. It is generally accepted that mineral and organic matter contributes to cation exchange capacity (CEC) of the soils. The CEC mostly controls the flush of positively charged ions following fertilizer application. The soils containing large amounts of biochar have a greater CEC than soils supplemented with biochar (Rizwan et al. 2016b; Ali et al. 2017), compared to the un-amended soils. This may contribute higher CEC for long duration in tropical as experienced in soil containing high temperatures. The higher CEC has been designated to greater surface area and higher charge density (per unit surface area) of biochar. In addition, the low molecular adsorption of organic matter has been proposed from cation adsorption, which can be increased by coating of biochar from extracts of manure (Lehmann et al. 2006).

However, biochar additions to soils improve the soil quality by rapid nutrient cycling in soil organic matter, microbial biomass, and better colonization of *Arbuscular mycorrhiza* of roots. It increases the availability of nutrients for crop through retention of nutrients in highly weathered humid tropical soils, which have lower CEC values and better supply of fixed P to the plants.

The determination of mechanisms involved in degradation of biochar by microorganism is difficult due to its long shelf-life and its recalcitrant nature (Schmidt and Noack 2000). The mineralization rates are not yet clear and available literature showed that biochar generated at low temperature decompose rapidly (Bird et al. 1999), compared to those at higher temperatures (Shindo 1991), and decomposition rate also depends on feedstock types. However, large part of biochar is decomposed over a short timescale, and a minor part remains in stable form (highly aromatic) displaying greater 14 °C age than the old soil organic matter fractions (Pessenda et al. 2001).

Increase of soil nitrogen and plant productivity

Now, it has been accepted that biochar can largely influence the mineralization and immobilization of soil nitrogen. Fresh and fast pyrolysis biochar immobilize 43% of nitrogen in soil. The slow pyrolysis biochar mineralize the 7% nitrogen in amended soil. In fast pyrolysis biochar, carbon loss is high and strongly influencing the microbial communities in soils (Bruun et al. 2012). Biochar amendments to soil affect microbial populations, diversity, activity, and plant-microbe interactions by nutrient cycling and by modification of habitat. *Rhizobia* spp. has a symbiotic relationship with legume species and converting atmospheric nitrogen to organic nitrogen through a cascade of enzymatic actions called nitrogen fixation (Giller 2001). This biological nitrogen fixation (BNF) is an important opportunity to fulfill the nitrogen deficiency in cropping systems throughout the globe. The BNF decreases when the high concentrations of nitrates and low available concentrations of calcium, phosphorus, and micronutrient are present in soils (Giller 2001). Soils containing significant concentrations of biochar showed reversed conditions as reported from Amazonian Dark Earths usually containing low nitrate concentrations, while calcium, phosphorus, and micronutrient were at a higher level, which are considered an ideal condition for utmost BNF (Liang et al. 2006). The BNF by common beans, as mentioned by nitrogen dilution, increased from 50 to 72% of total nitrogen uptake with gradual increasing addition rates of biochar (0, 31, 62, and 93 ton ha^{-1}) to a low fertility Oxisol (Rondón et al. 2003). In addition, high nutrient availabilities by BNF were effective in the biochar-added soils. Studies have shown that Rhizobium inoculates were significantly supported by biochar (Mishra et al. 2001). Furthermore, N_2 fixation was 15% higher with biochar at early stages of alfalfa development and was increased up to 27%, when nodules were developed. Biochar addition increases the net input of nitrogen into agricultural soils, but N_2 and nutrients of the legume were not improved, especially when higher amounts of biochar was added (Lehmann 2003). Similar findings have been observed in cowpea where N_2 and nutrients were increased in biochar-added agriculture soils while plant nitrogen and nutrients were decreased. The proper application rates of biochar with supplemented nutrients and nitrogen in agricultural soils can be increased without decreasing plant productivity. Biochar addition to soils promotes the growth of bacterial species involved in de-nitrification through molecular nitrogen. Microbial communities involved in the nitrification of ammonium to nitrite are less in number, while myco-bacterial nitrate reduction to ammonia increases with nitrogen fixation. Biochar has the ability to absorb ammonia and reduces the emission of N_2O from soil and endorse the phosphate-solubilizing bacteria by altering carbon fluxes through increasing the microbial communities that can degrade more recalcitrant carbon compounds and potentially decrease bacterial plant pathogens (Anderson et al. 2011).

Furthermore, it has been reported and recommended that biochar additions to soil can raise agricultural productivity (Sohi et al. 2010; Muhammad et al. 2017; Abbas et al. 2018; Ali et al. 2018). Research studies in the similar area (> 90%) showed that biochar increased the crop yield. Some reports showed that biochar addition to agricultural soils significantly improved the plant productivity, ranging from 20 to 220%. In contrast, literature revealed that studied crops are limited and do not contain work on grasslands, vegetation, and trees, or even perennial tropical crops (Blackwell et al. 2009; Rizwan et al. 2016b; Ali et al. 2017). The tropical soils are generally extremely leached, wrinkled, and acidic and some have high clay contents (Oxisols and Ultisols). The literature survey reveals that biochar addition to soils improves the agricultural production (Muhammad et al. 2017) and also increases the carbon sequestration in soil for longer time. Therefore, here, it is suggested to adopt the pyrolysis technology for waste management that consequently can achieve agronomic and environmental benefits from products of pyrolysis.

Effects of biochar on soil microbial community structure

Soil is the main organizing entity in terrestrial ecosystem and contains diverse microbial community structures. Soil ecosystems have complex physical and chemical nature with different aggregates embedded in solid, liquid, and gaseous matrix which frequently changes its response to perturbations, induced naturally or artificially (Lehmann et al. 2011; Rehman et al. 2015; Qayyum et al. 2017). Advance molecular techniques provided the opportunities to study the biodiversity and bio complexity of soil microbial communities (Coleman and Whitman 2005). Microbial diversity is always concerned with the functional features of any ecological unit. Numerous species of soil biota are involved in complex compound decomposition and nutrient cycling. It also differentiates the species diversity in soil system (Coleman 2001; Wardle 2002). Soil contains three major domains of life including two domains that contain prokaryotes such as bacteria and archaea and third domain contains protests, fungi, plants, and animals (Pace 1999). These three domains in terrestrial ecosystems are well represented, but soils may also contain some unknown microbial communities. Numerous meso-fauna, such as micro-arthropods (Behan-Pelletier and Newton 1999) and nematodes (Ettema and Yeates 2003), are present but these groups are less studied.

Biochar addition to soils has significant effects on microbial community structure, species richness, and changes in diversity with greater biochar concentrations (Pietikäinen et al. 2000; Yin et al. 2000). Significant microbial growth was observed in charcoal layers instead of the underlying horizon of a temperate forest soil. The small amount (7.9 ton carbon ha^{-1}) of biochar with fertilizers in highly weathered tropic soils significantly increases the microbial growth (Steiner et al. 2008). Furthermore, forest charcoal contains greater bacterial biomass. It indicates that biochar provides a favorable environment for large and diverse microbial groups in soils (Table 2). The type of biochar plays an important role in the development of microbial communities such as black carbon of woody material in soils that showed a significant change in the phospholipid fatty acid (PLFA) pattern of microbial communities during incubation (Wang et al. 2012). Microbial communities developing in soils according to available substrates get adopted in case of a new carbon source addition. Usually, different soils contain different microbial communities such as arable soils that generally contain less number of bacterial communities than the forest soils due to availability of carbon source. The soils treated with biochar generated from different substrate such as yeast and glucose-derived biochar (Steinbeiss et al. 2009) to the above-mentioned soils after incubation showed a significant change in the microbial community structure but gram-positive bacteria population abundantly flourished in soils treated with glucose-derived biochar. The majority of bacterial communities belonging to the groups of plant root associated are gram-negative bacteria, such as 42% in arable soil and 44% of the microbial biomass in forest soil. In both soils, 27% gram-positive and 11% were assigned to general bacterial population. The glucose-derived biochar addition to soils reduced bacterial population during incubation. Gram-positive and gram-negative bacteria decreased by 7–14%; in contrast,

Table 2 Summery on effect of biochars on soil microbial community structure and functions in different soils

Soil type	Carbon	Changes in microbial community structure	Soil fertility
Sandy texture (loamy kaolinitic)	Pecan shell-based biochar		Increase (pH, organic carbon, Ca, P, K, Mn) in treated soil and decreased in acidity Sulfur and Zinc.
Forest and arable soils	Yeast-derived biochar	Promotes the growth of fungi (Steinbeiss et al. 2009)	Specific biochar increase fertility in specific soils (Steinbeiss et al. 2009).
	Glucose-derived biochar	Utilized by G-negative bacteria (Steinbeiss et al. 2009)	
Agriculture soil Germany	Rye litters	In microbial community structure found, 4% general diversity and 1% diversity index in treated soils.	ND
	Wheat		ND
Sandy clay, loamy soil	Hardwood-derived biochar	Microbial population associated with the biochar is expected to increase after incorporation in to soil.	Soil respiration increased about 2.5 fold especially at 48 h. Reduced soil density from 1.14 to 0.81.Reduced water holding capacity from 36% to 30%.
Forest soil (humus)	Charcoal layer formed by fire	Microbial community structure and function was changed in humus underlying charcoal layer in forest soil, formed by wild fire.	Increase the soil pH and respiration mean while density was reduced.
Aquatic historian	Dissolved carbon	Microbial community composition along the DOC gradient is similar to the patterns of growth efficiency and growth rate in humic environment, at higher concentration of C *Proteobacteria*, *Cytophaga-Flavobacterium* and *Proteobacteria* at lower carbon concentration were dominant with incubation in humic environment (Eiler et al. 2003).	ND
Agriculture soil	ND	Microbial biomass increased as a result of biochar additions, with significant changes in microbial community structure.	ND
	Peat land	Carbon dioxide enrichment modified the structure of microbial communities, total microbial biomass is unaffected and biomass of heterotrophic bacteria increased by 48%, while the biomass of testate amoebae decreased by 13% (Eiler et al. 2003).	ND
Arable clay loam soil, filed application for 18 months	Wood waste biochar produced by fast pyrolysis, applied 3.9 mg ha^{-1}	Amoebic protozoal population was reduced while ciliates and flagellates were unchanged. The nematode population slightly increased specially in roots, fungi and bacteria feeders increased (Husk and Major 2011).	Reduced potassium concentration was observed in biochar amended fields (Husk and Major 2011)
Highly leached ultisol forest soils/boreal forest humus	Hard wood biochar from forest fire	No effect was observed on relative abundance of trophic groups (Matlack 2001). The collembolan growth was inhibited in charcoal rich soil (McCormack et al. 2013).	
Acid brown forest soils, 10–12 years exposure to kiln smoke	Charcoal kilen smoke	Nematode population was significantly increased (McCormack et al. 2013) and the diversity and abundance of collembolan and oribatid mites was observed (McCormack et al. 2013).	
Acidic pine forest humus, microcosm experiment	Wood ash 5/1 mg ha^{-1}	initially fungivorous nematodes and *Cognittiasphanetorum*population were reduced (Liiri et al. 2007; Nieminen and Haimi 2010), while wood ash increased the Cd content in *Cognittiasphanetorum* body tissues (Lundkvist 1998).	
Artificial soil (sand + kaolin + sphagnum) microcosm experiment	Poultry litter/ pine chip	Biochar specific mortality of *Eiseniafetida* was observed (Liesch et al. 2010).	

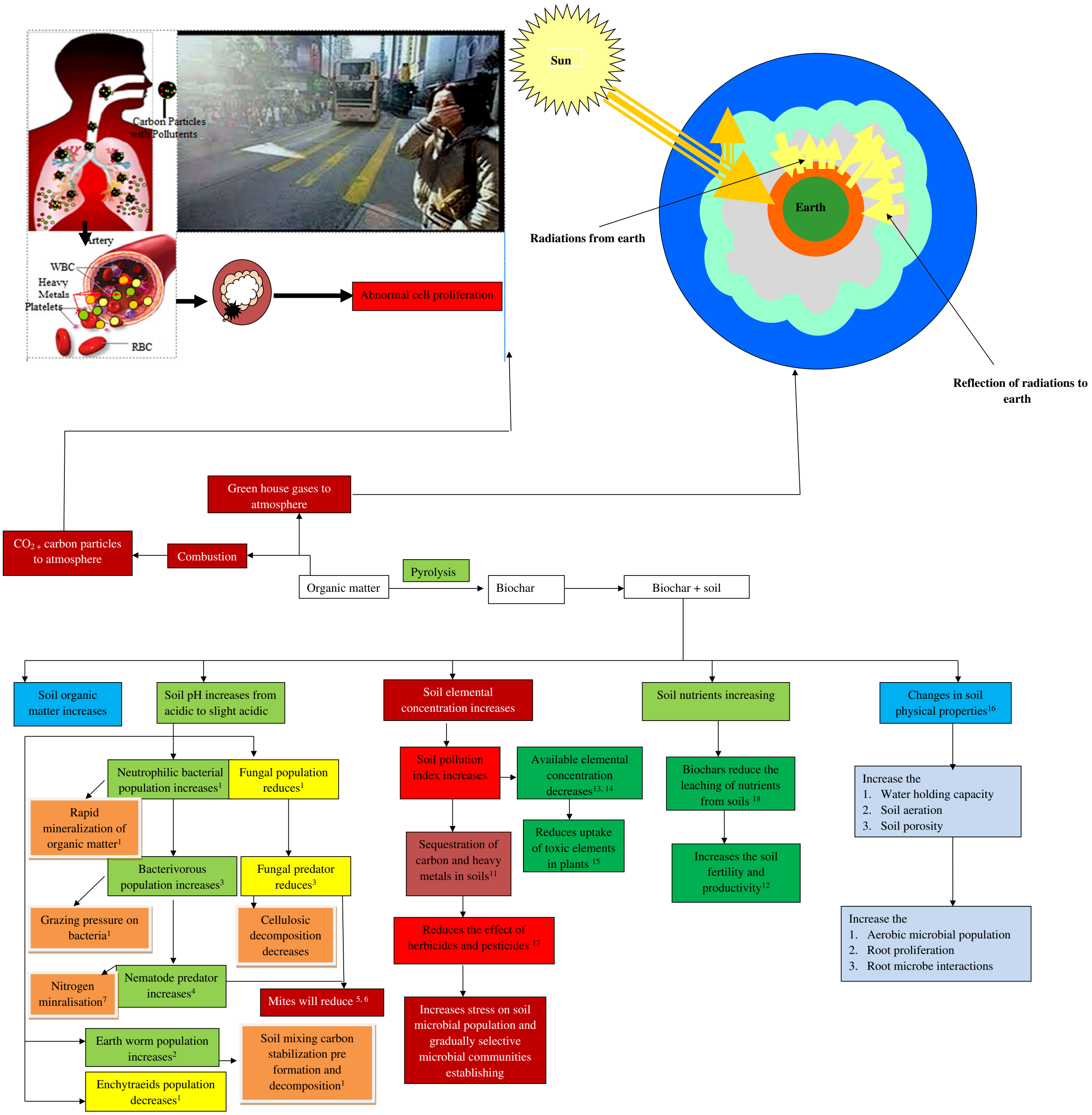
Table 2 (continued)

Soil type	Carbon	Changes in microbial community structure	Soil fertility
Agriculture ferrosol soils/calcareous ex industrial soils/ artificial soil	Paper mill waste, hard wood, and apple wood biochars	*Eiseniafetidag* rowth was increased in biochar treated ferrosol soil (Van Zwieten et al. 2010) and hard wood biochar reduced contaminant accumulation in *Eiseniafetida* (Gómez-Brandón et al. 2011).	
Psammaquent soil	Swine manure, fruit peels, Phragmitesaustralis and *Brassica rapa*biochars 1 and 3% for 90 days	PLFAs derived from bacteria, fungi, *actinomycetes*, G + ve and G − ve bacteria and sulfate reducers were higher with fruit peel biochar at 3% and 1%, respectively, followed by Swine Manure at 1% and *Phragmitesaustralis*biochar at 3%, than in the control soil. Protozoa PLFAs only increased in *Phragmitesaustralis* biochar 3% and *Brassica rapa* 1% treatments (Muhammad et al. 2014)).	Potassium and Carbon concentrations were increased while available nitrogen concentrations were decreased in all biochar treatments compared to control (Muhammad et al. 2014).

ND not determined

yeast-derived biochar addition did not change the bacterial PLFA content in soils. The proportion of fungal biomass increased 16% in both soil types, such as 11% in forest soil and 12% in arable soil of the microbial community that were made up of fungal biomass (Figs. 1 and 2). Furthermore, soil microbial diversity, population size, community composition, and activity are affected in biochar-amended soils as well as soil microorganisms that are able to change the amount and properties of biochar within the soil. Significant influence on nutritional cycling for availability to plants and higher microbial activities (CO_2 production and organic matter decomposition) were found in soils exposed to black carbon aerosols derived from the making of charcoal. Biochar serves as a suitable habitat for extra radical hyphae of fungi which sporulate in their micropores due to minor competition with saprophytes and acts as seed for *arbuscular* fungi (*mycorrhizae*) (Saito and Marumoto 2002). The *arbuscular mycorrhizae* significantly increase the infection in the roots. The addition of biochar to alfalfa enhanced the growth from 40 to 80%. Similarly, mycorrhizal infection was increased when soil was amended with biochar (7 g $kg^{-1}$of soil) inoculated with spores of *Glomusetunicatum*, for the yield improvement of onion (Matsubara et al. 1995). Biochar in soils may be responsible for greater microbial activity and microbial diversity due to surface area and surface hydrophobicity of microorganisms and black carbon. A strong microbial affinity to biochar can be expected from the adhesive phenomenon of microorganisms to solid surfaces, increases with higher surface hydrophobicity of solids (Mills 2003). Strong adhesion of microorganism to organic surfaces can be achieved due to divalent cations and specifically of calcium (Mills 2003). The mechanism is not yet clear, either electrostatic bondage or increased hydrophobicity.

Biochar generated from different feedstocks influence the particular microbial communities in specific soils, which are summarized in Table 2. Biochar, produced from wood waste, was applied to arable clay loam soils, and the results after 18 months depicted that biochar significantly reduce the protozoal population except ciliates and flagellates. In the same treatment, nematode population was slightly increased especially in plant roots (Husk and Major 2011; McCormack et al. 2013). The hard wood biochar obtained from forest fire, applied to highly leached ultisol forest soils. It increased the taxonomic richness and showed no effect on relative loads of trophic groups. In boreal forest soils of Canada containing hard wood biochar that inhibited the *Collembola* growth and in oxisol soils, it showed no effect on *pontoscolexcorethrurus* population (Matlack 2001; McCormack et al. 2013). The acid brown forest soil exposed to charcoal smoke for 10–12 years in Poland significantly increased the nematode population and wood ash to acidic pine forest humus in 357 days, initially reducing fungivorous nematodes while *Collemobia* and *Oribatide* populations were significantly increased (Liiri et al. 2007; McCormack et al. 2013). The poultry litter and pine chip biochar applied to artificial soils increased the mortality rate of *Eiseniafetida* (Liesch et al. 2010). The paper mill waste, hard wood, and apple wood biochar were applied to agriculture ferrosol, ex-industrial calcareous, and artificial soils, respectively. The *Eiseniafetida* growth was increased in paper mill waste biochar-treated ferrosol agriculture soil (Van Zwieten et al. 2010) and hard wood biochar reduced the contaminant accumulation in *Eiseniafetida* (Gómez-Brandón et al. 2011). The wet biochar increased the *Eiseniafetida* population in soil (Liu et al. 2011). Microbial community composition with an aged dissolved organic matter in a humic environment showed the increased bacterial



biomass production linearly with the dissolved organic carbon (DOC) concentrations. The microbial biomass production is limited by carbon supply and the bacterial growth rate in the exponential phase exhibited a hyperbolic response to the DOC concentrations and maximum growth rate was constrained by the substrate concentration at low DOC values (Eiler et al. 2003). Naturally formed biochar such as wild fire forms a layer of black carbon on forest soil. This carbon layer supported the specific microbial communities developed in underlying humus due to the absorbance of water-soluble compounds released from overlying layer of leafs. Biochar has an adsorbing capacity resembling to activated carbon and absorbed substances by underlying charcoal layer during incubation. The adsorbent harbors different microbial groups. The basal respiration rate showed differences with different compounds related to different microbial communities and the amount of microbial biomass and number of bacteria did not differ between humus under different adsorbents. Different microbial communities developed in humus under different carbon, liberated different compounds form overlaying leaf layer, which was related to the increased pH of the humus with specific compounds. These studies suggested that charcoal from burning can support microbial communities, which are though small in size but have higher specific growth rate

◀ **Fig. 1** The expected flowing sound effects of organic matter decomposition, burning and as biochar in soil, environment, and human health. Biochar additions to soils increase the soil pH values. In this illustration, we demonstrate the sound effects of elevating soil pH from acidic to vaguely acidic (McCormack et al. 2013). Light green boxes mentioned the possible increases or abundance of specific microbial communities due to increased pH such as alkaline pH supports the bacterial feeders, their predators, and earth worms (McCormack et al. 2013). The dark orange boxes indicating the functions of alleviated microbial communities in soils and illustrate that increased bacterial population increases the mineralization process of soils. The increased Bacterivorous population exerts grazing pressure on bacteria and increased nematode predators enhance the nitrogen mineralization (Culman et al. 2010; McCormack et al. 2013). The yellow boxes indicating the predicted decreases in specific microbial communities in biochar-amended soils (Bardgett et al. 1996; Räty and Huhta 2003). The red boxes indicating the net negative effect of biochars on soils such as decrease in herbicide and pesticide affects as well as increases the soil pollution index (Jones et al. 2011). Dark red boxes, indicating the stress of sequester elements on microbial community structure. Dark green boxes indicating the net positive effects of biochar on crop and soil quality (Jones et al. 2011; Park et al. 2011; Pudasaini et al. 2012). The blue and dark blue boxes indicating the improvement of soil physical properties due to biochar amendment as well as facilitating the microbial and plant root growth. The upper left part of the figure illustrates the negative effect of organic matter decomposition and burning global warming as green house gas affect where the yellow arrows illustrating the reflection of radiation from soil to atmosphere and again to earth due to green house gases. The right path of the figure explains the carbon aerosols generating during burning carrying the toxic elements, and by inhalation, the particles transmit to the human body and blood stream and cause complications. 1 (Bardgett 2005), 2 (Lavelle et al. 1995), 3 (Räty and Huhta 2003), 4 (Mulder et al. 2003), 5 (Hågvar and Abrahamsen 1980), 6 (Hågvar and Amundsen 1981), 7 (Culman et al. 2010; Park et al. 2005), 8 (Park et al. 2005), 9. (Dimitriou et al. 2006), 10 (Chagnon et al. 2001), 11 (Liang et al. 2012), 12 (Jeffery et al. 2011), 13 (Park et al. 2011), 14 (Hossain et al. 2010), 15 (Namgay et al. 2010), 16 (Namgay et al. 2010), 17 (Jones et al. 2011), 18 (Pudasaini et al. 2012)

than those of the humus. Although the charcoal layer induces changes in the microbial community of the humus without reducing the number of humus microbes, peat lands are considered intermediate lands between terrestrial and aquatic environment, CO_2 treatment to peat lands not only are found to change the total microbial biomass but microbial community structure was also altered. The microbial biomass increased up to 48%, and contribution of bacterial biomass to total biomass increase was 40–49% (Antal and Grønli 2003). Biochar-amended soils changes the bacterial community structure > 5% such as *Bradyrhizobiaceae* (8%), *Hyphomicrobiaceae* (14%), *Streptosporangineae* (6%), and *Thermomonosporaceae* (8%), where the biochar had a positive influence on microbial communities of *Streptomycetaceae* and *Micromonosporaceae* and negatively affected the *Bradyrhizobiaceae* and *Hyphomicrobiaceae* and both species have significant role in nitrogen cycling (Anderson et al. 2011). Black soil of China amended with fertilizer and cow manure biochar combinations have changed the bacterial community structure and function. Microbial community structure and function in the manure treated soil were found similar to the control soil. The manure increases the soil microbial population size, without affecting the bacterial community structure and the chemical fertilizer increases the diversity of soil microbial community. Catabolic activity has also been found similar in the chemical fertilizer and chemical fertilizer with manure treatments, but the composition structure of the soil microbes differed between them (Wei et al. 2008). Furthermore, biochar type and application rates to Psammaquent soils induced different chemical changes in the soil than in the control soil. Protozoa PLFAs only increased in PA 3% and *Brassica rapa* 1% biochar treatments as we illustrated in our recently published study (Fig. 3).

Future challenges and perspective

Organic matter type, pyrolysis conditions, and liquid material obtained from the process and their potential application and public awareness are still not sufficient. It needs proper attention as well as market positions. The elementary principles by which biochar influences the function of soil and the broader agro environment are inadequately defined and accordingly current information to predict the effects on biochar are not enough. In diminutive tenured experiments, biochar have shown to usually improve plant growth and soil nutritional conditions and reduce the net N_2O release to atmosphere. Nevertheless, the clarifications for these benefits are not fully illustrated, and neither the quantitative unpredictability in response nor the resilience of the sound effects was specified.

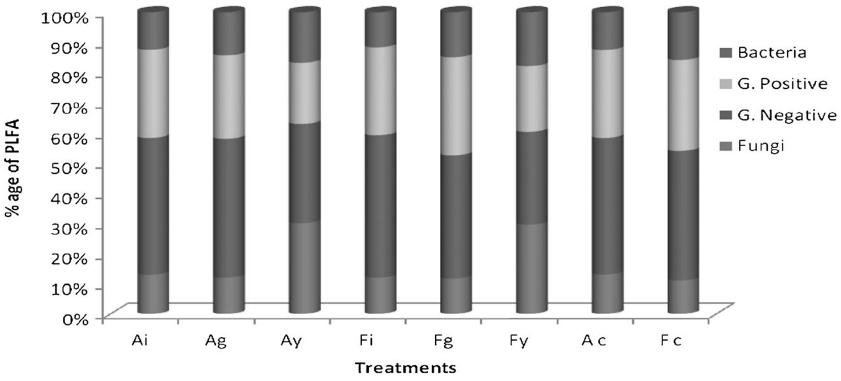


Fig. 2 Change in microbial community structure in biochar amended soils (Ai) arable soil without incubation, (Ag), arable soil + glucose-derived biochar, (Ay) arable soil + yeast-derived biochar, (Fi) forest soil without incubation, (Fg) forest soil + glucose-derived biochar, (Fy) foresr soil + yeast-derived biochar, (Ac) arable control soil (Fc) forest control soil

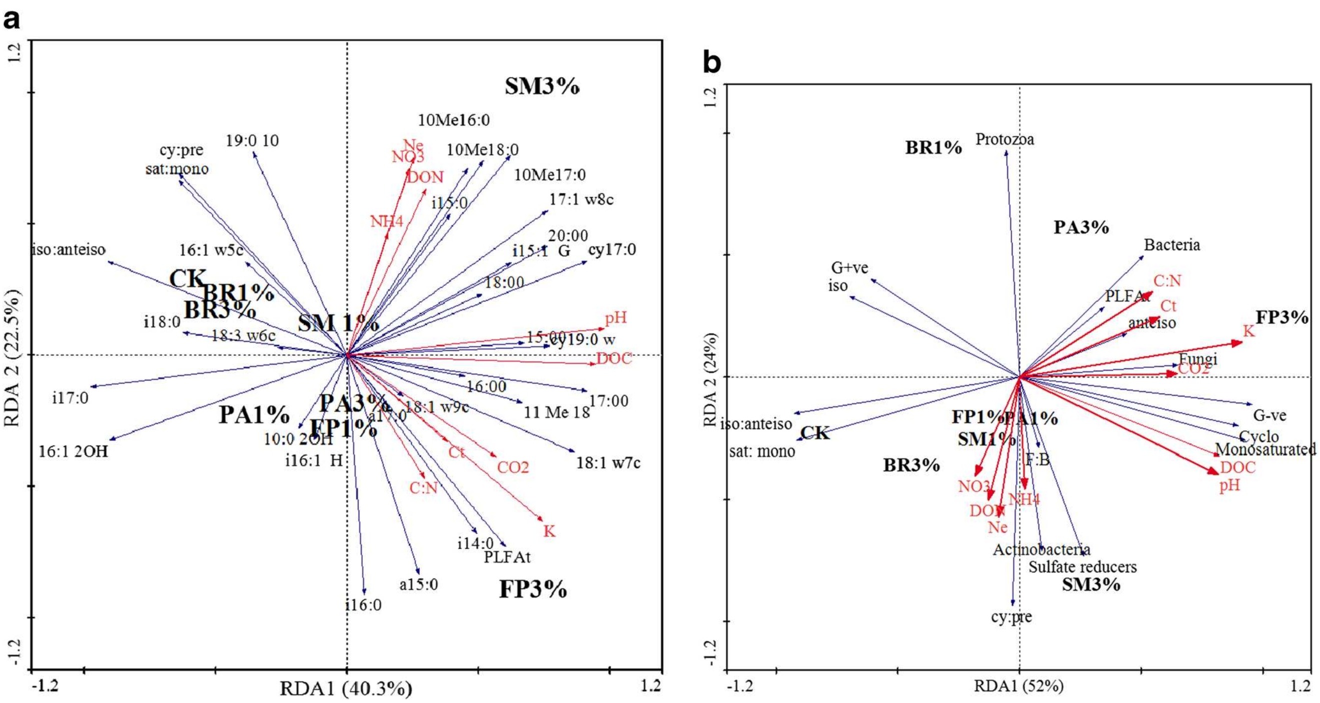


Fig. 3 **a** Influence of swine manure (SM), fruit peels (FP), Phragmitesaustralis (PA), and Brassica rapa (BR) biochars on PLFA markers and soil properties. **b** Microbial communities and soil properties within different treatments of biochars, where (G-ve) Gram negative, (G + ve) Gram positive, (cy/pre) cyclopropane and their precursor ratio, (sat/mono) saturated and monosaturated PLFA ratio, (PLFAt) total PLFAs, (F/B) fungi and bacteria ratio, (Ne) sum of exchangeable NH^{4+} and NO_3^-, (DOC) dissolved organic carbon, (DON) dissolved organic nitrogen (Muhammad et al. 2014)

As a result, soil biochar dynamics are required to be purposefully examined to deliver understanding in several domains.

Influence on soil microbial communities and their functions

At present, the net influence of physical shelter given to microbial communities and proofs for a sufficient way of those same communities to labile and soluble carbon fractions have not been recognized. The stable proportion of biochar and fine mineral particles, adsorption durability, and their influence on microbial community has not been clearly illustrated. The function of microbial and plant root secretions in the presence of absorbed mineral particle on biochar surfaces regarding to effects on plants and microbial communities needs clear investigations. Basically, the obvious divergence among high stability, soil organic matter accumulation, and noticeable improvement of soil microbial actions needs to be addressed.

Soil pollution index

Biochar additions to soils influence the soil quality index. If heavy metal concentrations are higher in biochars and soils after amendment, it can exceed the permissible limits. In this regard, limited information is available and needs further investigation and specifications of biochar type and application rates to soils, which can help to obtain the potential benefits from biochar applications.

Nutrient efficiency or deficiency

Understanding the relation among biochar function and its relations with nutrients and crop roots may facilitate the enhanced use of fertilizers, with associated benefits to disseminate pollution in water courses and wetlands. Furthermore, biochar adsorption potentially influences the micronutrients to plants for uptake which can exert negative effects on plants that are clearly not investigated.

Function of herbicides and pesticides

Biochar applications to agricultural soils influence the function of applied pesticides and herbicides. It is needed to investigate the suitable amount of applied pest and herbicides which can perform the proper function.

Effects of biochar on soil physical properties

Biochar improves the soil water-holding water retention, macro aggregation. Technique for spreading and integration of biochar in soil are basic requisite to alleviate lateral movement, and the potential for surface flow and loss at depth needs to be specified.

Biochar stability

The strength of biochar carbon is essential to rewarding its part as a major CO_2 sink, but to carry out an agronomic function, it should also remain within the applied soils. The environmental function or impact of biochar once it has moved through a soil profile, into water bodies, is yet to be assessed. In sequence on the degree to which corporeal crash of biochar modifies the equilibrium in its properties, predominantly with esteem to soil water dynamics, exchange capability and soil micro- and macro-aggregation is lacking. Techniques are immediately required to evaluate the durable biological constancy of specific biochar possibly extrapolating from the dynamics of unusually elevated initial rates of loss in soil.

Conclusion

Literature reviewed in this study provides information about the effects of biochar on environment, health, physicochemical properties of soil, microbial community structure, and their functions in soil. Biochar produced at different conditions from different feedstocks can be used for soil amendments to improve the soil fertility and crop yield. From soil, during respiration and microbial decomposition, carbon emits to the atmosphere and causes environmental pollution leading to health hazards as well as climatic changes by producing greenhouse effect. Negative effects of carbon can be reduced by optimizing the biochar production. Biochar production and application to soils are suitable strategy to reduce the negative effects. Literature illustrated that specific biochar facilitates the specific type of microbial communities in amended soils which can lead specific and selected microbial activities. Moreover, this review highlighted the areas which need further attention from researchers and clear investigation to obtain the optimum benefits from biochar.

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