Title: Biochar: a potential soil ameliorant for sustainable land, agriculture and environmental development

Running title: Biochar for soil system sustainability

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Abstract

Biochar or pyrogenic carbon, obtained from thermo-chemical conversion of biomass in an anaerobic or oxygen limited environment has been in use in agriculture since long back to Neolithic era. Its unique soil ameliorating properties, render it suitable for environmental remediation as well as sustainable crop production. It improves soil physicochemical properties and plant nutrient availability, facilitates biodiversity, and reduces emission of greenhouse gases, thereby subsiding global warming. Application of biochar reduces soil erosion, improves soil hydrological properties, and soil microbial dynamics. It has synergistic effects on plant growth, disease-pest resistance, and crop yield per unit area and time. Due to its soil ameliorative effects, and soil and water conserving ability, it can very well be used in organic farming, pemaculture, dryland farming, conservation agriculture, and land remediation. Cheaper production cost, simple and easy pyrolytic technologies, easy availability of feedstock and bio-wastes in many developing countries and its long-term effects in soil not only build up soil carbon pool but also help support small and marginal farmers in resource-rich but economically deprived countries for sustainable agriculture and environment. In this review, efforts have been made to elucidate various methods of biochar synthesis, its characteristics and effects on soil properties, and plant growth and development, its role in sustainable agriculture and remediation of the environment.

Keywords Amendment, amelioration, degraded land, remediation, sustainable development

1. Introduction

All those factors that govern plant characteristics and adaptation are broadly grouped under genetic and environmental factors. Genetic factor is the manifestation of the genetic makeup of a plant while environmental factors are external and refer to all those factors that influence expression of thre genes (Bareja, 2011). Abiotic environmental factors viz. light, moisture, oxygen, carbon dioxide, nutrients, and temperature; biotic factors such as microbes and macrobes regulate the plant growth and development. Healthy soil is expected to supplement all these factors in adequate quantities and in suitable proportions.

Soil exerts the maximum influence on plant nutrients, rhizosphere temperature, moisture, aeration and microbial population. It also provides strength to the plant for standing upright without lodging. A set of interrelated and interdependent bio-physicochemical properties determine soil heath. Healthy soil is the foundation for a productive, profitable, and environment-friendly sustainable agriculture system (White, & Barberchek, 2017). However, the very essence of raising a crop in its native area is vitiated under spatial and temporal relocation in commercial farming. Continuous cropping over years, despite chemical fertilizer application, depletes many essential plant nutrients, mostly micronutrients, from the soil. Monoculture and extensive use of chemical fertilizers, addressing only one or more primary plant nutrients, not only reduce crop yield substantially but also deteriorate the soil health irreparably (Rawat, Saxena, & Sanwal, 2017). Absence of green manuring and restricted use of organic manures exhaust the soil carbon pool that influences soil biota. Besides fertilizers, synthetic pesticides having high persistence also have perilous effects on modern agriculture-system. Due to long-term application of a set of fertilizers and pesticides, a shift in structural diversity occurs leading to disease-pest resistance and resurgence (Wu *et al.* 2012). In some areas, more specifically adjoining to opencast mining, the concentration of heavy metals crosses the threshold limits for crop as well as soil biota (Rawat, Saxena, & Sanwal, 2017), that must be taken care of with utmost diligence.

The greatest challenge before us in the 21st century is to feed the ever-burgeoning population approaching the carrying capacity of the earth. It is high time for the global community to reorient the present agriculture production management system towards sustainable development goals through an integrated and holistic approach. Judicious application of chemical fertilizers, enrichment of soil carbon-pool through green-organic amendments, and use of eco-friendly macro- and microorganisms could enhance the system productivity, profitability and cater to the needs of the teeming millions without degrading the environment. Slash and burn and/or char system of agriculture and residue incorporation owe their unique significance since the advent of agriculture on this planet. They not only supplement all essential plant nutrients in a balanced form but also ameliorate soil for a healthy biodiversity. While selecting any ameliorant for reclamation and restoration of the land its cost-effectiveness, persistent effect, bulkiness, easy adaptability, and environmental compatibility must be looked into in a holistic manner (Rawat, Saxena, & Sanwal, 2017).

Among many options of carbon sequestration and soil fertility restoration on this planet the use of biochar has been the most popular and widely adopted ancient sustainable approach (Lahori *et al.* 2017). Biochar is a fine-grained, carbon-rich, porous organic derivative, a by-product from anaerobic thermo-chemical combustion of any organic matter including wood, crop residues, animal excreta, and household wastes (Amonette, & Joseph, 2009). Burning of biomass, under complete or almost complete absence of oxygen, also produces oil and gas as co-products depending on the substrate characteristics and processing conditions (Ramesh, 2019; Lehmann, Gaunt, & Rondon, 2006). The quality of biochar is determined by its brittleness, porosity, lightweight, high surface area, and metallic sound produced on finger tapping. The quantity biochar produced is usually 50% of the initial volume of the substrates used for pyrolysis (Ramesh, 2019) that may occur naturally in forests or be manmade.

2. Characteristics of biochar

Biochar has unique physicochemical properties which are governed by the type and size of the biomass as well as pyrolytic temperature and duration (Sohi et al. 2010). Biogeochemical characteristics of biochar determine its effectiveness and efficacy in agronomic applications and impact on soil processes. Seven key properties viz. pH, volatile compounds, ash content, bulk density, water-holding capacity, porosity, and specific surface area are vital for adjudging its quality (Okimori, Ogawa, & Takahashi, 2003; Sohi *et al.* 2010).

Research of (Windeatt et al., 2014) on slow pyrolysis of eight different crop residues at 600 ^{0}C resulted in biochar yield ranging from 27.7% (sugarcane bagasse) to 39% (rice) with an average ultimate carbon content of 51% (TABLE 1). The quantity of the pyrolytic oil was highest in cotton (53.6%) followed by palm shell and sugarcane bagasse, each with 50.3% oil. The oil content of rice husk was the least (33.5%) among the six crop residues under study. The maximum gas was released in olive pomace (29.2%) and the lowest was in wheat straw (17.6%). Coconut shell (222.5 m^2 g^{-1}) and palm shell (220 m^2 g^{-1}) had significantly higher surface area while wheat straw (6.3 m^2 g^{-1}) and olive pomace (1.2 m^2 g^{-1}) recorded very negligible oil. The pH of wheat straw biochar was the highest (11.6) followed by olive pomace (10.5), cotton stalk (10.3), rice husk (9.9), cotton fibre (9.6), sugarcane bagasse (8.6), coconut shell (8.5) and palm shell (6.1). Rice husk produced the highest ash of 47% followed by wheat straw (23.4%) and coconut fibre (13.4%). Coconut shell (4.1%) and palm shell (6.7%) biochar had significantly lower ash content.

Biochar carbon sequestration potential was reported to be 21.3-32.5%. With the current global availability of crop residues about 373 M t of bichar could be produced that has potential to sequester 0.55 Pg of carbon dioxide in the soil (Jayne et al., 2014). Crop residues are slender, leafy, bulky and loose unlike compact wood hence are difficult to transport and feed in the pyrolysis chamber. Wang et al. (2013) have reported higher ash content in straw biochar from rice, wheat and maize than bamboo and elm wood biochar. The total nitrogen recovery of *Gliricidia* twig (38.1%), *Eucalyptus* twig (35.7%), *Eucalyptus* bark (28.5%), *Pongamia* shell (24.9%) and *Leucaena* twig (20.9%); total phosphorous recovery of *Gliricidia* twig and *Pongamia* shell (68.4%), *Eucalyptus* twig (67.4%), *Leucaena* twig (51.8%) and *Eucalyptus* bark (46.2%); and total potassium of *Eucalyptus* bark (35.7%), *Gliricidia* twig (35.1%), *Eucalyptus* twig (31.7%), *Pongamia* shell (29.1%) and *Leucaena* twig (24.2%) were in descending order (Venkatesh et al. 2018; Venkatesh et al. 2016).

Irrespective of the source of residues, the mass-yield of biochar declines with the increase in temperature (Purakayastha *et al.* 2012). Pyrolytic temperature is positively correlated with the surface area of biochar. An increase in pyrolytic temperature from 400 to 900 ºC increases the surface area of biochar from 120 to 460 m^2 g^{-1} (Day et al. 2005). Thus, the release of nutrients from biochar could be controlled by doping desired quantities of biochar created at low temperature (Day et al. 2005), while biochar produced at high temperatures would act as material analogous to activated carbon (Ogawa, Okimori, & Takahashi, 2006). Biochar produced at low temperature are hydrophobic in nature and hence store relatively lesser water in soil. However, after a long time, no significant difference in moisture retention capacity is observed due to a difference in pyrolytic temperature (Sohi et al., 2010) possibly due to the disintegration of biochar that equalizes the particle size as well as the surface area in long run. An increase in the pyrolytic temperature from 400 to 600 ºC decreases the volatile component, sulfur and nitrogen contents, but increases ash and fixed carbon contents in biochar (Purakayastha et al. 2012). Thus biochar prepared at 600 ºC is more stable in soil due to wider C:N ratio. Bera et al. (2018) observed lower bulk density and particle density of biochar from wheat and maize than rice and pearl millet prepared at 400 ºC. The water holding capacity of wheat biochar was the highest (747%) while in pearl millet biochar it was the lowest (386%) at 400 ^{0}C.

The pH of biochar is temperature-dependent. Lower pyrolytic temperature results in lower pH and electrical conductivity (EC), due to the presence of carboxyl group in it while higher temperature increases the pH due to more ash content. More ash means more of basic elements such as K, Ca, Mg and Na in it. The IBI has prescribed for at least 10% carbon in commercial biochar which means that 90% of it is ash. The pH of biochars produced from different feedstock such as pearl millet, grass clipping, cotton trash, eucalyptus, etc. varied from 8.2 to 13 (Jha et al. 2010). The pH of a finer fraction (9.08) in wood waste biochar was higher than coarse fraction (8.71) of the biochar derived from husk and paper fibre (Prasad et al. 2019). The C:N ratio of poultry litter biochar was the highest (221) in hardwood sawdust biochar while the lowest (19) was reported in poultry litter biochar. Total carbon content in biochar from different feedstock varied from 33 to 82.4% (Bera et al. 2018). The original composition of the feedstock as well as the maximum pyrolytic temperature and heating duration has strong influence on the retention of nutrients. Nitrogen and sulfur compounds tend to volatilize at a temperature above 200 and 375 °C, respectively whereas potash and phosphorous go away between 700 and 800 °C (DeLuca et al. 2006). An increase in pyrolytic temperature decreased the cation exchange capacity (CEC) of biochar significantly (Bera et al. 2018; Zhao et al. 2013; Song, & Guo, 2012) due to the temperature-induced loss of carboxylic and hydroxyl group (–COO– and –OH) responsible for the CEC in biochar (*Bera et al. 2018)*. The CEC of maize biochar produced at pyrolytic temperature of 400 ^{0}C was the highest (52.4 cmol P^{+} kg^{-1}) followed by rice, pearl millet and wheat biochar as reported by Bera et al. (2018).

Biochar contains an appreciable quantity of Ca, Mg, K and P and thus, it can be used as liming material or amendment in acid soils. However, presence of sodium may be detrimental for plant growth. Finer biochar contains higher levels of total Cu, Zn and Mn (Prasad et al., 2019). The IBI has notified standardized procedures for evaluating biochar for soil application based on proximate and elemental composition, pH, porosity, EC, CEC, hydrogen/carbon and oxygen/carbon ratios, etc.

Sometimes potential toxic elements such as Asc, Cd, Cr, Co, Cu, Pb, Mo, Hg, Ni, Se, Zn, B, Cl and Na are present in the feedstock at variable concentrations. Polyaromatic hydrocarbon (PAHs) and dioxins/furans could be formed during pyrolysis process which acts as potential pollutants. However, the IBI has established guidelines for testing of such potential pollutants (Verheijen *et al*. 2010).

3. Biochar for the sustainable land and agriculture development

3.1. Restoration of degraded lands

Acid soil—Biochar has ameliorative effects on acid soil depending on its pyrolytic temperature and ash content. As soil acidity is a serious constraint for crop production, mostly in high rainfall areas, biochar could be a cheaper alternative to lime, at least partially at moderate dose (e.g. 2 to 4%) (Berek, Hue, & Ahmad, 2011). Increase in pH of acid soil by addition of rice straw biochar at 80 g kg^{-1} soil has been reported by Tarin et al. (2020) in a one year greenhouse pot experiment with *Fokienia hodginsii*. In another pot experiment with rice crop, the maximum increase in pH of acid soil, as well as reduction in soluble and exchangeable aluminium (Al), was observed under amendment of *Eucalyptus* wood biochar compared to bamboo and rice husk biochar (Shetty, & Prakash, 2020). So also, increase in soil pH, and decrease in exchangeable acidity and Al by addition of rice husk biochar and sawdust biochar produced from fast pyrolysis was reported by Wang, & Liu, (2017). In between corn stover biochar and switch grass biochar, the former was relatively better in increasing the soil pH (Chintala et al. 2014).

Saline soil—Soil salinity is one of the greatest challenges for agriculture and food security across the globe not only in coastal belts but also in areas under overexploited groundwater irrigation. Biochar amendment could be the befitting answer to alleviate salt stress in crops. Its long-term effects on reducing Na^+ uptake in succeeding crops is although not so clearly understood but the greenhouse pot-culture column leaching experiment in wheat conducted by Akhtar, Andersen, & Liu (2015) have pointed out reduced plant sodium uptake by transient Na^+ binding due to its high adsorption capacity and increased release of mineral nutrients (particularly K^+, Ca^{+2} and Mg^{+2}) into the soil solution that was finally reflected in growth, physiology and yield of wheat. This result was corroborated in a biochar-soil incubation experiment by Moradi et al. (2019) that showed reduction in soil sodium concentration due to sodium absorption by biochar. In another pot experiment on green gram, biochar amendment showed higher plant growth, relative water content, shoot/root ratio, specific root length, vascular cylinder, cortical parenchyma areas, root indole-3-acxetic acid (IAA)/abscisic acid (ABA) ratio, and IAA/ aminoclopropane-1-carbosylic acid (ACC) ratio (Nikpour-Rashidabad, Tavasolee, & Farhangi-Abriz, 2019). Hence, the ability of biochar in reducing salinity stress may be considered in remediation of saline soils.

Removal heavy metals and pesticides—Presence of heavy metals and pesticides in the soil render it unsuitable for profitable crop production so also are detrimental to human health and soil biodiversity. However, biochar amendment could successfully drain out such toxic materials from the soil at varying levels as evident from the results of many researchers. Zhao et al. (2019) in a mixture of multiple heavy metals observed adsorption capacity dependent on the substrate feedstock and pyrolysis conditions of the biochar in the order of sewage sludge> agriculture biomass> wood biomass. Such adsorption mechanisms of biochar include physical adsorption, ion exchange, electrostatic interaction, complexation and precipitation (He et al. 2019) while cation exchange being the most important in removal of multiple heavy metals (Zhao et al. 2019). Biochar in comparison to the activated carbon was found to have lower energy demand (6.1 MJ kg^{-1} and 97 MJ kg^{-1}) and global warming potential (-0.9 kg CO_2 eq. kg^{-1} and 6.6 kg CO_2 eq. kg^{-1}) (Alhashimi, & Aktas, 2017). The adsorption cost of biochar as estimated was lower than activated carbon to remove chromium and zinc with a 95% confidence but the adsorption cost for lead and copper were comparable. Hence, precise engineering of biochar could be as effective as activated carbon and at a lower cost (Alhashimi, & Aktas, 2017). Moreover, Younis et al. (2015) in a study on biochar amendment with nickel in *Spinacea oleracia* L. reported reduced Ni concentration in root and shoot with increase in concentration of cotton stick biochar from 3% to 5%. So also, biochar amendment at 5% level was found to have increased soil pH, total nitrogen, soil organic carbon, and available P and K while availability of Cu, Pb and Cd decreased (Mokaram-Kashtiban, Hosseini, & Younesi, 2019).

The adsorption kinetics of biochar increases with pyrolysis temperature, biochar dosage, higher soil pH in acid medium, smaller char-size and reaction time. Its role in removal of pesticides and herbicides such as Imidachloprid (Zhao et al. 2018; Mandal, Singh, & Purakayastha, 2017), Pymetrozine (Ponnam et al. 2019), Diazion (Xi et al. 2014), Atrazine (Mandal, Singh, & Purakayastha, 2017), Triazine and Organophosphate (Uchimiya, Wartelle, & Boddu, 2012) has been well proven. Biochar produced from the bark of *Azardirachta indica* could be used as a potential adsorbent for removal of synthetic organic pollutants such as Bentazone from the watershed systems (Ponnam et al. 2020).

3.2. Organic farming

Biochar has been used to improve soil conditions and maintain soil fertility for many centuries, from the basket willow stands of north Great Britain to the citrus fields of Japan to the *Terra preta* of Amazon basin. Its use in modern agriculture is to improve soil tilth and promote sustainable agriculture (DeLuca, & Gao, 2019). Incorporation of such carbon-rich material in soil helps in resource recycling, prevents loss of soil nutrients including nitrogen and enhances their availability, stabilises soil carbon pool, removes toxins, ameliorates soil physicochemical properties, maintains soil biodiversity, and increases crop yield sustainably. Since no chemical or synthetic additive is allowed in organic farming, need-based biochar application could prove beneficial to successful modern sustainable organic farming systems.

3.3. Dryland farming

Biochar application has shown positive response to deficit moisture stress in arid and semi-arid regions. In a study conducted by Zoghi et al. (2019), biochar soil amendment at 30 g kg^{-1} soil enhanced photosynthesis and stomatal conductance in Chestnut-leaved oak (*Quercus castaneifolia*) under water-deficit stress. In another experiment, biochar could increase plant height, leaf number and chlorophyll concentration while significant reduction in electrolyte leakage and lipid peroxidation were noted in drought stressed barley plants (Hafez at al. 2020a). The efficiency of Phtosystem-II (quantum yield PS-II), a stress marker in plants increased with biochar application over control even at lower concentration of 1.5 t ha^{-1} in sunflower (Maria et al. 2017). In maize, stomatal conductance, leaf water potential as well as transpiration and photosynthesis were maintained in biochar application at 2 and 3% reflecting increase in water holding capacity under declining moisture regime in sandy soil (Ahmed et al. 2016). Biochar treatment in wheat crop amplified soil physicochemical attributes that improved physiological traits, antioxidant enzymes and yield attributes under water deficit condition (Hafez et al. 2020b) whereas quinoa crop biochar enhanced bioavailability of nutrients, their translocation from soil to plant and seed (Ramzani et al. 2017).

4. Effects of biochar on the environment

4.1. Soil physical properties

The impact of biochar as an amendment depends on the key properties such as large surface area (SA) and presence of micropores (Mukherjee, Zimmerman, & Harris, 2011; Nguyen, Brown, & Ball, 2004; Braida *et al*. 2003) that potentially alter pore size distribution, bulk density (BD), water holding capacity (WHC), and penetration resistance (PR) of soils. The surface area of biochar depends on the combustion temperature even if produced from the same feedstock. Surface area increases with an increase in peak combustion (Mukherjee, Zimmerman, & Harris, 2011; Nguyen, Brown, & Ball, 2004; Braida *et al*. 2003; Wang, Sato, & Xing, 2006) as tar volatilize at higher temperatures (650–750 °C) thereby increasing the temperature while a further rise in temperature, the micropore structure collapses and the SA decreases (Lua, & Guo, 1998). Its stability in the environment and its mobility into deeper soil profiles over time (Hammes et al. 2008) suggests high recalcitrant nature of biochar in nature in soil over hundreds of years as seen in the Amazon basin. The effect of biochar on soil physical properties depends on feedstock, pyrolytic condition, application rate and environmental condition (Mukherjee, & Lal, 2013). Surface area of soil decides the water holding capacity as well as aeration, microbial activity and nutrient retention ability (Van Zwieten et al. 2009; Liang et al. 2006). Although many studies reveal the effect of pyrolytic temperature on SA of biochar but very limited literature is available to ascertain the effect of biochar on the SA of amended soil. However, biochar is reported to have increased the SA of biochar 4.8 times compared to untreated soil (Liang et al. 2006), micropores increased at the expense of macropores (micropores <2 nm, mesopores 2-50 nm and macropores > 50 nm) (Jones, Haynes, & Phillips, 2010).

Application of biochar decreases the bulk density (BD) of soil (Liang et al. 2006; Jones, Haynes, & Phillips, 2010), even at 2% level of soil amendment (Chen et al. 2011). In some instances, increase in BD was observed with passage of time due to compaction and column leaching effects (Rogovska et al. 2011) but the rate of increase is lower than manure amended soil and control (Rogovska et al. 2011). A decrease in BD of biochar amended soil improves soil aggregation, physical condition, aeration and hydrology (Atkinson, Fitzgerald, & Hipps, 2010). Data on the effect of biochar on soil aggregate is scarce except some reports of elevated water stable aggregates (WSA) under low temperature hydrochar (220 ^{0}C) application in greenhouse experiments. However, greenhouse incubation is reported to have 2-5 times higher rate of WSA formation compared to laboratory incubation (George et al. 2012). A very less information is available on how biochar influences WSA formation either through mycorrhizal fungi, active carbon, black carbon or plant-roots. Reports of humic acid amendment, an active ingredient in biochar, positively improves soil characteristics by buffering soil pH and chelating micronutrients by increasing concentration of –COOH- and -

OH groups (Kudeyarova, 2007; Mackowiak, Grossl, & Bugbee, 2019). This indicates that biochar may form active complexes on ageing that help in soil binding and aggregate formation.

Increase in penetration resistance (PR) reduced after 96 days of mixing of pecan shell biochar with Norfolk loamy sand (Dobbie, & Smith, 2001). This indicates that the BD may not change and aggregation percentage may decrease in short run resulting in no significant smothering effect of biochar amendment on soil compaction, but with time, bichar may change soil properties (Mukherjee, 2011; Cheng, & Lehmann, 2009). Soil type is also an important factor to define the effect of biochar on PR as another experiment reported reduction in PR with application of the same biochar on another soil type (Busscher et al. 2010). Hence, additional research is required to study the effect of different biochar amendments on aggregation and PR in different soil types.

Soil hydrological properties such as water holding capacity, moisture content, water infiltration rate, hydraulic conductivity, etc. are influenced by its surface area, porosity, bulk density, carbon content, and aggregate stability. Several studies have indicated the response of biochar at even 0.5% ($g\ g^{-1}$) sufficient to improve WHC of soil depending on the soil type (Laird et al. 2010); Jones, Haynes, & Phillips, 2010). Biochar-amended Clarion soil retained up to 15% more water compared to unamended controls (Laird et al. 2010). Positive effects of biochar on soil water holding capacity and porosity were also reported by Igaz et al. (2018). However, the effect of biochar on WHC is texture dependent as Tayler 1948 (Jones, Haynes, & Phillips, 2010) observed increased water retention in sandy soil, but no effect in loamy soil and decreased moisture content in clayey soil. Hence, a careful choice for biochar and soil combination may be taken into consideration (Jones, Haynes, & Phillips, 2010).

4.2. Soil chemical properties

Biochar amendment increases soil chemical properties such as soil organic matter, pH, N, P, K, Ca, Mg, and CEC (Adekiya et al. 2020). Adekiya et al. (2020) in their pot experiment with addition of cashew tree-wood biochar observed increase in pH, P, K, and exchangeable sodium percent (ESP) in rice-cowpea sequence at 150 and 250 days after application. In field experiment at Rawalpindi, Pakistan Ullah et al. (2018) reported a significant increase in EC, organic carbon, P and K but no significant effect on soil pH, nitrate and nitrogen due to application of wheat straw and sugarcane bagasse biochar. Rice husk biochar, obtained at pyrolytic temperature of 500 ^{0}C for three hours, elevated K availability in acid soils of Mazandaran province in Iran and hence, it could be considered as source of K in soil fertility management (Ghorbani, & Amirahmadi, 2018). Its positive effects on soil organic carbon, hydrolytic acidity, base saturation, and cation exchange capacity were also reported by Igaz et al. (2018).

Biochar application may enhance mineralization of soil organic carbon fractions, releasing plant nutrients (Hamer et al. 2004; Wardle, Nilsson, & Zackrisson, 2008). *In vitro* incubation of biochar increased soil pH, total N, phyto available N, P and K than corresponding level of biomass treated soils but the soil organic carbon declined with biochar application (Khan, Chowdhury, & Hug, 2014). Higher availability of trace nutrients (Mo, Fe, Mg and Mn) as well as macronutrients (K and P) was observed under sole application of biochar to soil (Rondon et al. 2007) while its application with cow manure biochar resulted in an appreciable increase in pH, total C and N; available N, P, and K; and exchangeable Ca, Mg and K in the soil (Uzoma et al. 2011; Nigussie et al. 2012). Brantley et al. (2016) reported enhanced nutrient availability by application of poultry-litter biochar in N and P fertilized plots and Steiner et al. (2008) observed higher N use efficiency with application of 18.1% biochar in NPK fertilized plots (Steiner et al. 2008). Thus, nutrient transformation not only depends on the characteristics of biochar but also on other organic and inorganic amendments

(Dey, & Mandal, 2020). Xu et al. (2014) reported higher rice production with combined application of biochar produced from manure and litter. N mineralization in soil depends on the type of biochar and their interactions with other amendments (Dey, & Mandal, 2020).

Bioavailability of P in soil increased with application of biochar to soil (Xu et al. 2014) due to high concentration of ash (77%) in biochar (Zhai et al. 2014). An increase in P availability in soil at 8 weeks of application was reported to be due to the combined effects of Mycorrhizae and biochar (Mau, & Utami, 2014). Adsorption of cations such as Fe^{+3} and Al^{+3} by biochar delays the process of adsorption and precipitation of P in soil (Wang et al. 2012). However, P retention was reported to have increased with biochar application in a column of soil that reduced P leachate in solution (Novak et al. 2012). Similarly, combined application of biochar and plant litter lowered CEC with no significant effect on P availability (Satriawan, & Handayanto, 2015). Meta analysis of 108 pair wise comparisons conducted by Glaser, & Lehr (2019) indicated increased P availability by a factor of 3.4-5.9 (95% confidence level) independent of feedstock. However, biochar produced at < 600 ^{0}C and applied @ > 10 ton ha^{-1} could only increase the P availability. The P availability in acid and neutral (pH 6.5-7.5) soils was 5.1 to 2.4 times, respectively while in alkaline (pH >7.5) soils no significant effect was seen (Glaser, & Lehr, 2019).

Plant residues and biochar have a significant impact on K and S mineralization in soil. Liang et al. (2014) in their experiment observed enhancement in exchangeable K due to addition of biochar to soil (Liang et al. 2014). Wang et al. (2018) reported higher K release in Entisol than Alfisol due to addition of biochar in soil (Wang et al. 2018). Blum et al. (2013) reported the maximum leaching of S from the soil due to release of mineral S and hydrolysis of ester-S after addition of biochar. Biochar application lowers the surface albedo and absorbs solar radiation that enhances S mineralization rates in soil (Stevenson, & Cole, 1999). However, many researchers (Nelissen et al. 2014; Sun et al. 2014) are still not in full agreement with the ameliorative effects and crop yielding ability of biochar which need to be scrutinized further.

In Indonesia, biochar application in maize influenced soil pH, N, P, K, Ca, Mg, and CEC positively compared to cattle dung biochar (Sukartono et al. 2011). In Nigeria, an experiment with cocoyam (*Xanthosoma sagittifolium* L.) showed positive results of biochar application on soil organic matter, pH, N, P, K, Ca, Mg, and CEC (Adekiya et al. 2020). However, studies conducted in sandy Podzol soil revealed that biochar alone could not provide enough nutrients for healthy plant growth (Syuhada, & Shamshuddin, 2016).

4.3. Soil biota

Biochar, depending on its characteristics and residence time, soil type, prevailing climate, and land management practices, influences soil microbial activity, abundance and community composition. As application of biochar is being practiced over hundreds of years, the microbes might have adapted to changing soil environments with varying structures and functions over long period. Since soil microbes play vital role in soil ecosystem functions and services such as biogeochemical cycles, maintenance of soil fertility and health, disease suppression, etc. it is imperative to study the long-term effects of biochar on soil biota along with soil fertility (Palansooriya et al. 2019). Hoverer, Hardy et al. (2019) in their study of charcoal kiln sites in forest and cropland reported overwriting of long-term effects of charcoal on soil microbiota. Such alternation was possibly due to modification in ecological niche (pH and nutrient availability) rather than source of C available to biota. Liao et al. (2016) in their experiment with addition of cotton straw biochar at 4.5 t ha^{-1} reported 32%, 58% and 13% increase in microbial biomass C, microbial N, and basal respiration, respectively compared with no application of biochar. The activity of three key enzymes related to carbon cycle viz. cellobihydrolase (CBH), b-glucosidase, and N-acetylglucosaminidase increased with biochar application at 2.25 and 4.5 t ha^{-1}. Application of biochar at 4.5 t ha^{-1} shifted the microbial population to bacteria (both Gram-positive and Gram-negative) and actinomycetes (Liao et al. 2016). Dangi et al. (2020) in an experiment for two consecutive years reported improvement in soil health and productivity of pepper crop with combined application of inorganic fertilizers and organic N or organic N and biochar. Mengyang et al. (2019) reported significant effects of biochar and inorganic fertilizers on bacterial population in acid soils and hence advocated for biochar and fertilizer application schemes in China. The release of CO_2 in acid soils was 1.5 to 3.5 times more than neutral and alkaline soils due to accelerated degradation of native organic carbon and biochar. Such rapid degradation of organic carbon could be attributed to higher proportion (25-36%) of Gram positive bacteria in acid soil and hence have direct impact on the carbon sequestration (Sheng, Zhan, & Zhu, 2016).

4.4. Soil erodibility

Soil erodibility is influenced by soil texture, organic matter, compaction, moisture, and vegetation cover. Biochar is used for geo-environmental applications such as covering landfills due to its vegetation potential (Kumar et al. 2019). Addition of biochar decreased erosion in dry state while erodibility increased with an increase in moisture content. However, the rate of erosion decreased with an increase in biochar concentration due to surface functional group and particle gradation of biochar (Kumar et al. 2019). Jien, & Wang (2013) reported reduction in soil loss by 50% and 64% with addition of biochar at 2.5% and 5% rate, respectively compared to control (0%) in acidic Ultisol. Biochar acts as sponge that significantly reduces runoff and increases infiltration (Krounbi et al. 2019). Sustainable hydrologic management practice with reduction of soil erosion by 10-69% and increase in rainwater storage by 20-59% could be achieved through application of biochar (Cai et al.

2020). However, Zhang et al. (2019) in a rainfall simulated experiment reported reduction in total runoff by 2.4-10.8% while total soil loss and interrill erodibility increased by 20.8-50.8% and 20.4-29.2%, respectively with addition of biochar at 2-8% (Zhang et al. 2019).

4.5. Environmental remediation

Anthropogenic activities such as mining, smelting, sewage-sludge release, pesticide and fertilizer use, oil spilling, etc. have resulted in the accumulation of pollutants and degradation of the environment. Natural environmental processes very often fail to keep pace with the rate of such waste generation posing serious ecological threats and human health issues. Some heavy metal(loid)s that persist over many years and get accumulated in the ecosystem can only be immobilized by bioremediation (Sun, Zhang, & Su, 2018). Bioremediation is deliberate breakdown of substrates at a faster rate by using naturally occurring or genetically engineered organisms to clean the environment. Examples of bioremediation could be phytoremediation, bioventing, bioleaching, land farming, bioreactor, composting, rhizofiltration, bioaugmentation and biostimulation.

The ability of biochar in reducing emission of GHGs such as methane, nitrous oxide and carbon dioxide; leaching of nutrients, and surface runoff as well, apart from its role in increasing soil carbon pool, water holding capacity, microbial population, and bioremediation of pollutants, help support in sustainable environmental remediation and agricultural development (Singh, Tiwari, & Singh, 2020). Due to its long-term persistent nature, it interacts with all those naturally bio resistant materials. Addition of biochar increases microbial abundance and activity in soil and groundwater. It increases soil aeration by increasing pore space and reducing bulk density (Gundale, & DeLuca, 2006) and absorbs salt readily (Thomas et al. 2013). Low-temperature biochar has greater reactivity in soils than higher temperature biochar (Steinbeiss et al. 2009).

The primary role of biochar in bioremediation is to stimulate microbial growth and ameliorate physicochemical parameters of the environment (Vimal et al. 2017) for the removal of contaminants *in-situ* and *ex-situ* (Gautam et al. 2017). The combined contamination of metals, metalloids and organic pollutants which is otherwise very difficult to remediate by a single process could effectively be taken care of by biochar alone (Chen, & Yuan, 2011; Sneath et al. 2013). Moreover, consortia biochar with iron has been developed to reduce leaching down of copper and arsenic from soil in the mining sites where neither biochar (1% w/w) nor iron alone could successfully do so (Sneath et al. 2013).

Biochar is an important solid sorbent that immobilizes inorganic and organic pollutants by proficient mechanism of precipitation, ionic metal attraction, ion exchange (Qian, & Chen, 2013; Ahmad et al. 2014), and polar and non-polar organic attraction (Ahmad et al. 2014) even more efficiently than activated charcoal in some cases. Lead absorption by biochar was found to be six times more efficient than activated charcoal (Cao et al. 2009). Doping of Si in biochar could efficiently reduce Al phytotoxicity by making Si-Al complex in soil (Qian, Chen, & Chen, 2016). Removal of heavy metals such as As, Cu, Cd, Ni, Pb, and Zn by addition of biochar due to increase in pH and nonelectrostatic adsorption has been reported by Beesley, Mereno-Jim'enez, & Gomez-Eyles, (2010); Park et al. (2011), Uchimiya et al. (2012); Jianga et al. (2012); Khan, Hussain, & Hejazi (2004).

Biochar alone, or magnetized biochar oxidized with iron oxide during ageing process, could act as efficient sorption material for removal of organic and inorganic pollutants from agricultural as well as environmental fields (Chen, & Yuan, 2011). Reports of bioremediation of herbicides and pesticides such as simazine (Jones, Edwards-Jones, & Murphy, 2011); chloropyriphos, diuron and carbofuran (Yu, Ying, & Kookana, 2006); Atrazine (Cao et al., 2009); and Terbuthylazine (Wang et al. 2010) implies that vast scope is there for applicability of biochar in fixing environmental pollutions arising from injudicious chemical farming, and much research is needed for further investigating the mechanism behind bioremediation.

5. Future prospects and constraints in biochar systems

The role of biochar in environmental remediation and agricultural production systems is now an undoubted fact. However, its in-depth study on ISO-based life cycle assessments in various systems has not yet been well attended. The potential of biochar and biochar systems is manifold. It can be potentially linked to many sectors for green-growth, development and climate resilience. Decision tools are made available to select appropriate biochar system technologies that are required to respond to local environmental, agronomic, social constraints and opportunities (Scholz et al. 2014).

6. Conclusion

Biochar amendment is an age-old practice of improving soil quality as well as increasing crop productivity in a sustainable manner. It has tremendous ameliorating ability that can very well smother problematic soils and increase agricultural production through facilitated bioavailability of essential plant nutrients and improved soil physicochemical properties. It plays significant role in improving environmental quality thereby favoring biodiversity of an area and reducing global warming. Its unique physicochemical characteristics render it suitable for organic farming, dryland farming, conservation agriculture and land reclamation. The lower cost of production of biochar from locally available wastes and feedstock and its long-term effects on soil not only build up soil carbon pool but also help support small and marginal farmers in resource-rich but economically deprived countries for sustainable crop agriculture and environment. However, sustained efforts are essentially required for further on-farm research and experimentation to validate the widely tested results that yet have mostly been conducted in laboratories and greenhouses.

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There is no conflict of interest among the authors.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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