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A review on biochar's effect on soil properties and crop growth

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Intensive cultivation of agricultural soils causes soil degradation which emphasizes the need for sustainable soil management. Biochar, a pyrolysed carbon rich material has gained great interests among the researchers because of its eco-friendly benefits in addition to soil quality enhancement. Reviews on biochar, mainly confined to its environmental benefits like carbon sequestration and climate change. In this review, we summarize i) the effect of biochar application on soil properties (physical, chemical, biological), ii) remediation potential of biochar in heavy metal contaminated soils and iii) its impact on crop productivity. The properties of biochar like pH, greater surface area, cation exchange capacity, and nutrient content positively influences the soil properties and ultimately improves the soil fertility. Their effectiveness depends on biochar type, its dosage, soil type, etc. General trends from this review indicated that biochar as an effective amendment in acid soils than the alkaline or calcareous soils. Furthermore, the biochar effects are studied mostly under controlled conditions in laboratory, which needs to be validated under field conditions having varied soil types and agro-climatic zones.

KEYWORDS

biochar, soil fertility, crop productivity, heavy metal remediation, pyrolysed carbon

Introduction

Intensive cultivation of agricultural soils could end in soil degradation, involving fertility decline, soil acidity or alkalinity, loss of organic matter, soil erosion, and soil pollution (De Meyer et al., 2011). Furthermore, the annihilation or diminution of soil properties like soil organic carbon decreases the stability of soil aggregates and causes soil degradation (Nunes et al., 2020). Therefore, it is necessary to come up with sustainable soil management practices to remediate the degraded soils. Various organic and inorganic wastes such as agricultural crop residues, forest waste, industrial waste, municipal solid waste, etc. were generated in massive quantities (Gabhane et al., 2020), from which, a majority are disposed directly through burning or dumping in fields polluting the air, soil and water. Several studies (Raut et al., 2008; Gabhane et al., 2016) have proposed that composting of these wastes as promising technique. However, composting is not found to be attractive because of its slow degradation rate (Gabhane et al., 2012). Also, utilization of composts and manures result in potential emissions of methane and ammonia, aggravating the global warming (Ding et al., 2016). In recent years, the interest towards the soil application of biochar has grownup considering the twin benefits of biochar on climate change mitigation and as an amendment

TABLE 1 Characteristics of different biochar.

Raw material	Temperature (°C)	pH	EC (dS cm^{-1})	SSA (m^3g^{-1})	Total C (%)	CEC (cmol (p^+) kg^{-1})	WHC (%)	References
Coconut shell	190–280	9.9	1.75	-	80.59	11.78	-	Sukartono et al. (2011)
Cow dung		8.9	1.77	-	23.53	16.79	-	
Rice husk	250–300	7.4	0.36	-	-	-	-	Abrishamkesh et al. (2015)
	450–500	8.4	0.48	-	-	-	-	
Greenwaste-leaves, grass clippings, twig, plant prunings	350	5.3	0.0017	3	65.2	-	-	Srinivasan and Sarmah (2015)
	450	5.8	0.0009	3	71.8	-	-	
	550	8.4	0.0018	153	75.4	-	-	
Corn cob	>600	9.5	0.0463	186	82.2	-	-	
Pinus radiata sawdust	700	9.7	0.0157	795	90.0	-	-	
Water hyacinth	250	7.24	-	-	-	9.3	-	Zhang et al. (2015)
	350	9.43	-	-	-	9.77	-	
	450	10.49	-	-	-	21.95	-	
	550	10.46	-	-	-	14.23	-	
Prosopis wood	450	8.73	2.2	-	-	9.76	-	Angaleeswari and Kamaludeen (2017)
Acacia wood	300	5.0	-	6.09	67.56	127.45	355.10	Pituya et al. (2017)
	400	6.2	-	100.56	68.68	96.81	380.20	
	500	7.7	-	376.51	73.26	64.40	365.70	
Cotton	400	-	-	0.2	-	-	-	Speratti et al. (2017)
	500	-	-	1.8	-	-	-	
	600	-	-	1.9	-	-	-	
Tobacco stalks	500	9.42	0.11	-	79	30	-	Bindu et al. (2015)
Oil Palm empty fruit bunches	500	8.91	0.41	-	67	-	-	Bindu et al. (2019)
Oil Palm trunk	500	9.97	0.18	-	57	-	-	
Oil Palm fronds	500	6.55	0.21	-	42	-	-	

[a]EC- electrical conductivity, SSA- specific surface area, WHC-Water Holding Capacity, CEC- cation exchange capacity.

to improve soil quality (Liu et al., 2014). Biochar is the recalcitrant carbon rich product (Mukherjee et al., 2014) obtained through a thermo-chemical process at the temperature range of 350°C-600°C in an oxygen-free environment and in some cases with abysmally low/limited oxygen (Amonette and Joseph, 2009). In the early phase, biochar was viewed as a source of energy, material for water purification, etc. The physical (surface morphology, surface area, porosity) and chemical (composition and functional groups) properties makes biochar an amicable adsorption material to remove the pollutants from aqueous medium (Tan et al., 2015).

This renewable resource is found to be efficient in soil fertility management. For instance, several studies (Spokas et al., 2012; Xu G. et al., 2014; Kammann et al., 2015; Schmidt et al., 2015) proposed that the nutrient loaded biochar acts as slow-release fertilizer for soil fertility enhancement. The chemical and physical properties of the biochar depend on the raw material utilized, pyrolysis temperature, furnace temperature, and residence time (Yaashikaa et al., 2020). Wide range of feed stocks were utilized for biochar production with their pH ranging from 8.2–13.0, total carbon content ranging between 33.0%–82.4%, N content of 0.18%–2.0% and with the C:N ratio of 19–221: 1 (DeLuca et al., 2009). Nutrient retention in the biochar depends on pyrolysis temperature. The volatilizing temperature varies with nutrients, i.e., nitrogen (200 °C), phosphorus and potassium (700°C–800 °C) and sulphur (375 °C). The biochar produced at high pyrolysis temperature of about 800 °C recorded higher pH, salt concentration, and extractable NO_3^-, whereas the biochars produced at low-temperature of 350 °C showed higher extractable P, NH_4^+, and phenols (DeLuca et al., 2009). The calcium and magnesium composition of biochar makes it an amendment to reclaim acidic soils.

Biochar, the pyrolysed residues have more residence time than unpyrolysed wastes and improves the soil fertility through their impacts on physico-chemical and biological properties of soil (Lehmann et al., 2011; Kuzyakov et al., 2014). Several studies

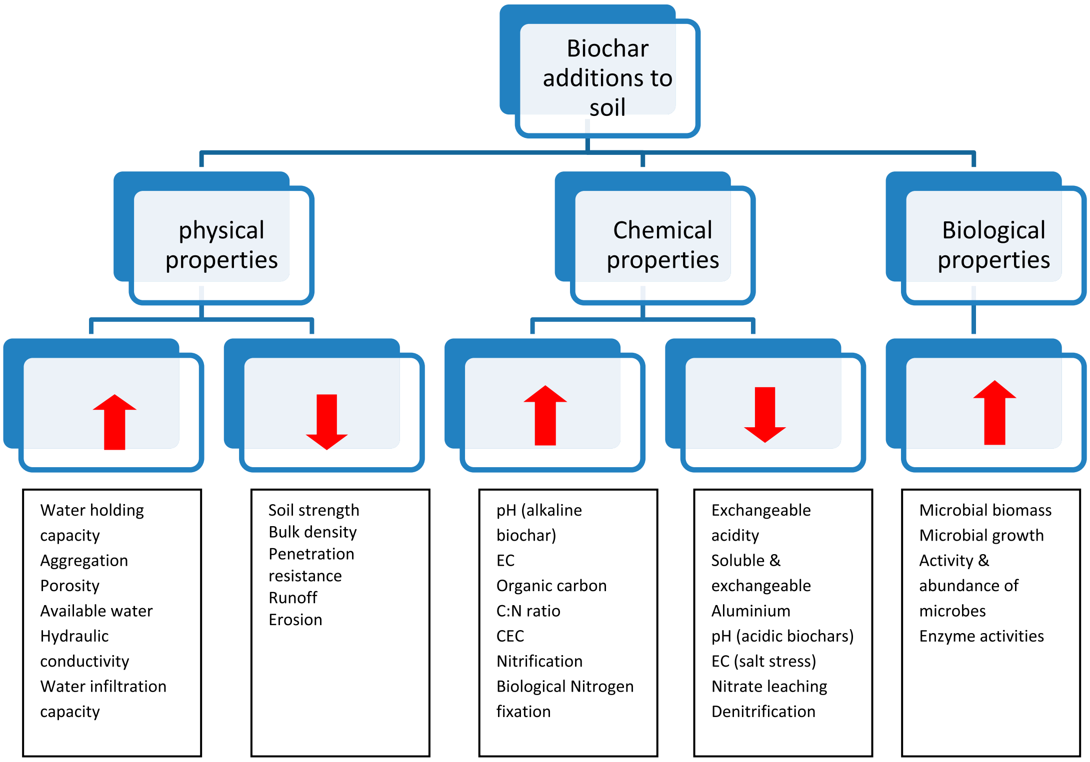

FIGURE 1
Effect of biochar additions on soil properties.

have suggested the positive impact of biochar additions on soil fertility, heavy metal remediation and crop productivity (Pandian et al., 2016; Novak et al., 2018b). However, there are studies stating the negative impact of biochar under certain conditions (Warnock et al., 2010; Revell et al., 2012). Different methods of application like surface application, and soil incorporation are followed. Li et al. (2020) recommended that surface application of biochar mixed with nitrogenous fertilizers as effective strategy to reduce nitrogen (N) losses. The biochar application rate is highly varied and is decided by the feedstock from which the biochar is produced, its composition and soil type to which it is to be applied. The characteristics of some biochar are furnished in Table 1. The biochar of about 5–50 t ha^{-1} have been utilized in the field experiments and there are no specific recommendations on application rates. It has been reported that biochar dosage of about 1% by weight or even lower than that are used in field crops (Major, 2013). If the biochar is applied to soil in higher doses, it may increase the carbon storage but it could cause reduction in crop productivity in soil by limiting N and widening the C: N ratio of soil (Lehmann et al., 2006). Application of higher doses of biochar to soils with substantial amounts of N and soils cropped with legumes or legume-based cropping system had returned greater profits.

Soil contamination is a global issue which threatens the human health and food security. The major toxic elements generated through anthropogenic activities are Cd, Co, Cr, Cu, Mn, Ni, Pb, and Zn, which often accumulates in the soil. About 5.0 million sites worldwide faces the soil contamination by toxic elements (Khan et al., 2021). The Ministry of Environment, Forest and Climate Change (MoEF&CC) has identified 320 locations of high probability of contamination with heavy metals (Cr, Pb, Hg, As, and Cu) and pesticides in India. Most of the reviews on biochar, mainly confined to its environmental benefits (Kumar et al., 2022), rather than its effect on agriculture. In this review, we summarize i) the effect of biochar application on soil properties (physical, chemical, biological), ii) remediation potential of biochar in heavy metal contaminated soils and iii) its impact on crop productivity.

Effect of biochar on soil properties

The biochar's effect on soil properties depends on the characteristics of both, soil to which it is to be applied and biochar's composition. The effect of biochar on soil properties is depicted in Figure 1 and the quantitative impact of biochar on different soil properties are furnished in Table 2.

Soil physical properties

The extent of changes in soil properties depends on characteristics of both biochar and soil to which it is to be applied (Joseph et al., 2021). Biochar application to soil has its influence on wettability of soil, water infiltration, water retention, aggregation and stability thereby helping in combating erosion, mitigating drought and nutrient loss and enhancing groundwater quality.

TABLE 2 Quantitative effect of biochar on different soil parameters.

S.No	Biochar (raw material and dose)	Parameter	Impact	References
1	Conifer charcoal and hard wood charcoal @ 0%–45% Volume	Soil moisture retention	Increased up to 18% in sandy soils Decreased by 11.1% in clayey soils	Tryon (1948)
2	Biochar (Meta analysis)	Cation exchange capacity	Increased up to 45%	Singh et al. (2022)
3	Mangrove (*Rhizophora apiculata)* biochar Application @10 t ha^{-1} in rice crop	Methane emissions	Decreased by 21.1% in first season and 24.9% in second season	Sriphirom et al. (2021)
4	Biochar from plant biomass @ 10 to 120 t ha^{-1}	Biological Nitrogen Fixation	Increased when biochar applied @ 10 t ha^{-1} but decreased @ 120 t ha^{-1}	Mia et al. (2014)
5	*Acacia mangium* bark biochar @ 10 L m^{-2}	Arbuscular Mycorrhizal fungi	Increased by 42%	Yamato et al. (2006)
6	Municipal bio-waste biochar @ 10wt%	Emission of nitrous oxides	Decreased by 89%	Yanai et al. (2007)
7	Mesquite biochar @ 10%	Bulk density	Decreased by 31%	Liu et al. (2016)
		Porosity	Increased by 12%–41%	
8	Biochar from green waste applied @ 5t ha^{-1}	Fertilizer use efficiency	Increased by 10%–30%	Gaunt and Cowie (2009)
9	Biochar from cacao (*Theobroma cacao*. L.) shell, oil palm (*Elaeis guineensis*. Jacq.) and rice (*Oryza sativa*. L.) husk @ 1% (30 t ha^{-1})	Liming effect	Soil pH increased by 0.5 units (Cacao shell biochar), 0.05 (oil palm shell biochar) and 0.04 units (Rice husk biochar)	Martinsen et al. (2015)
10	Biochar from Eucalyptus wood, bamboo, and rice husk @ 5–20 t ha^{-1}	Aluminium toxicity	Decreased soluble and exchangeable Al	Shetty and Prakash (2020)
11	Oil palm empty fruit bunch biochar @ 1 t ha^{-1}	Potassium availability	Increased the soil available potassium	Bindu et al. (2020)
12	Tobacco stalk biochar @ 1 t ha^{-1}	Liming effect	Improved the soil pH	Bindu et al. (2016)
13	Tobacco stalk biochar @ 1 t ha^{-1}	Nutrient leaching	Inhibited N and K leaching in light textured soils	Bindu et al. (2017)

Total porosity and bulk density

Biochar additions improved the porosity and thereby reduction in density of the soils (McElligott, 2011). The total porosity of the soil increases proportionately with increment in the biochar doses (Liu et al., 2020). The study conducted by Masulili et al. (2010) had showed an increase in total pores, available water and decrease in penetration resistance on application of rice husk biochar. Application of biochar increase the total porosity of the soil, which results in reduction of soil bulk density and increase in the infiltration rate (Herath et al., 2013). This reduction in soil bulk density has a positive effect on other soil physical (water holding capacity, aggregation, texture and structure), chemical and biological properties.

Soil aggregation

Aggregation of soil particles is greatly influenced by biochar incorporation in soils. Application of maize straw and peanut hull biochar at 7.8 t ha^{-1} in combination with inorganic fertilizers increased the proportion of macro-aggregates and mean weight diameter of the aggregates (Ma et al., 2016). The effect of biochar on stability of aggregates depends on soil texture. Soil aggregation in coarse textured soils (sandy) are more sensitive than fine textured on biochar additions (Ouyang et al., 2013). Liu et al. (2012) studied four soil types of loess plateau, China and reported an improvement in water stable aggregates in silty loam soils whereas no significant effect on sandy loam soils. But contradictorily, Hardie et al. (2014) reported a decrement in aggregate stability on biochar application. Biochar addition on soil aggregation and its stability depends on the biochar interaction with soil organic matter, microorganisms and minerals. (Domingo-Olive et al., 2016). The biochar provides habitat to the microorganisms and protects them from desiccation and predators. The microorganisms secrete polysaccharides that increase the soil aggregation (Aslam et al., 2014).

Available water content and hydraulic conductivity

Biochar when applied as a soil amendment improved the water quality, soil moisture retention and its availability to plants (Steiner et al., 2007). Their effect on available water depends on soil texture. Application of biochar increased plant available water content in sandy soil, whereas it decreased in clayey soils (Glaser et al., 2002). The hydraulic conductivity of the sandy soils reduced with biochar additions (Uzoma et al., 2011), whereas the biochar had no significant effect on soil moisture content in loamy sand (Hardie et al., 2014). Major et al. (2010) reported that biochar addition increased saturated hydraulic conductivity from 2.70 to 13.4 cm h^{-1}.

Water infiltration, run-off and soil erosion

Application of biochar increased the water infiltration, reduced the water runoff and thereby erosion of soil particles (Doan et al., 2015; Sun et al., 2018). This reduced soil loss might be due to increased mean weight of the soil aggregates. In sandy soils, application of biochar declined the diffusion distance of the horizontal wetting front whereas, the diffusion distance of the vertical wetting front declined initially followed by a increase (Pu et al., 2019). The infiltration rate improved by 1.7 times in non-calcareous loamy sand with application of 2% biochar produced at 620°C from mixed wood sieving whereas the calcareous loamy soils had no significant effect on this biochar application (Abrol et al., 2016). Contradiction to this, there are studies stating reduced water infiltration due to hydrophobicity of the biochar (Jeffery et al., 2015). Supporting this, Jien and Wang (2013) reported reduced soil loss by 50% and 60% on biochar application at 2.5% and 5% w/w, respectively in *Typic Paleudults*. Contradictory results of effect of biochar on soil erosion were also observed (Peng et al., 2016). Erosion of silty loam loess increased with higher rates of biochar application, whereas the erosion reduced with application of biochar particles of larger size (Li et al., 2019). It is clear that, biochar of different particle sizes is required for different soil textures to reduce the water runoff and erosion. The biochar produced under slow pyrolysis from the mangrove tree (*Rhizophora apiculata*) in combination with alternate wetting and drying practices in the field reduced the irrigation water usage of rice crop by 12.7% (Sriphirom et al., 2020).

Soil structure and texture

Biochar application improves platy soil to granular/crumb structures that are highly suitable for agriculture. Application of biochar had significant effect on soil texture and this effect was found to be short termed (Brodowski et al., 2007). The possible mechanisms defining the improvement in soil physical properties on biochar application are high porosity, its adsorptive nature, provision of microbial habitat and contents of total organic carbon content (Aslam et al., 2014).

Soil chemical properties

Soil pH

The simple measure of soil dynamics is the soil reaction. Soil pH is greatly influenced by biochar application (Xu et al., 2006). The biochar of alkaline nature (pH of leachates >7.0) resulted from higher pyrolysis temperature, lower heating rate and longer residence time whereas, the acidic biochars were produced at lower temperature, higher heating rate and shorter residence time (Uronic Stefanko and Leszczynska, 2020). Biochar had a liming effect on acid soils (Yuan et al., 2013). The presence of oxides, hydroxides and carbonates of alkaline metals in the biochar resulted in soil pH increase (Dai et al., 2017. The negatively charged functional groups like carboxyl, hydroxyl and phenolic groups bind the H^+ ions from soil solution, this in turn reduced the activity of H^+ ions and increased soil pH (Chintala et al., 2014). Conversely, Zhang et al. (2019) found reduction in pH of alkaline soils, which could be due to the production of acids on oxidation of biochars. The contents of $NaHCO_3$ and Na_2CO_3 present in alkaline soils got converted to Ca $(HCO_3)_2$ and $CaCO_3$ and had caused the reduction in soil pH (Liu et al., 2020. Several authors (Senesi and Plaza, 2007; Dias et al., 2010) stated that acidic compounds produced from decomposition of soil organic matter lowered the pH of alkaline soils. For calcareous soils also, biochar additions increased the soil pH (Alazzaz et al., 2020). However, application of acidic biochars produced through slow pyrolysis and steam activation reduced the soil pH between 0.2 and 0.4 units in calcareous soils (Ippolito et al., 2016). Even at higher rates of biochar application, the buffering capacity of the soils prevented the major changes in soil reaction (Ippolito et al., 2014). Application of poultry litter biochar of alkaline nature raised the soil pH above 8.0, where the availability of nutrients for the plants got declined (Novak et al., 2014). Under salt stress conditions, application of water hyacinth derived biochar increased the soil pH and the increase was directly proportional to the biochar dose (Premalatha et al., 2023).

Electrical conductivity

The electrical conductivity (EC) of the biochar ranges from 0.04 to 54.2 dSm^{-1} (Rajkovich et al., 2012; Smider and Singh, 2014). The EC of the soil increased by14 times at 120 tha^{-1} biochar application rates (Mia et al., 2014). The soluble compounds (organic and mineral) released on reaction of biochar with water, resulted in increase of soil EC (Joseph et al., 2021). Pandian et al. (2016) observed an increase in EC of the acidic red soil on biochar addition. The physical entrapment of salts in the pores of biochar resulted in the reduction of EC in salt affected soils (Thomas et al., 2013). The biochar was found to mitigate the salinity stress. Under salt stress conditions, EC decreased with increased rate of biochar application (Premalatha et al., 2023).

Soil organic carbon

Biochar additions improved the organic carbon of the soil due to its high carbon content of recalcitrant nature (Zhang et al., 2012). Supporting this Shenbagavalli and Mahimairaja, (2012) observed a 33%–35% higher SOC content on incorporation of different levels of biochar. The increase in SOC on biochar addition is the additive effect of carbon from biochar, microorganisms, rhizosphere decomposition and root exudates (Pandian et al., 2016). Application of biochar from corn stover with high ash content and low volatile matter decreased the C mineralization in mollisols (Purakayastha et al., 2016).

Cation exchange capacity

Higher surface area, hydroxyl and carboxy functional groups, and variable charges of biochar improve the cation exchange capacity (CEC) of the soils (Van Zwieten et al., 2010). Van Zwieten et al. (2009) evidenced a positive linear correlation between biochar application rates and CEC. Fresh biochars had little capacity to retain cations in soil but with the passage of time, biochar on undergoing surface oxidation had increased carboxyl groups thereby had increased negative charges and ultimately had resulted in sorption of cations. Conversely, application of 4 months aged wood biochar reduced the CEC by 10% in 70 days incubation compared to fresh biochar (Zhao et al., 2015). In a laboratory incubation study, addition of 3% and 6% w/w hardwood biochar had no change in CEC of the sandy soils (Basso et al., 2013). This confirmed that the effects of biochar application on soil properties are dynamic.

Soil available nutrients

The processes like adsorption and immobilization are promoted in soil after biochar application, which in turn causes decline in leaching of nutrients. Biochar has the capacity to adsorb and retain cations in exchangeable forms than other forms as they have greater surface area and surface negative charge (Clough et al., 2013. Through this mechanism, nutrients and chemicals are retained in soil improving the fertilizer use efficiency with sustainable crop yields. As the biochar prevents the washing out of nutrients, enrichment of an ecosystem with chemical nutrients and impairment of water ecosystem can be controlled. By preventing the losses, more nutrients can be retained in the soil and external dependence of synthetics can be reduced. Nutrient concentration of biochar varied widely and depends on the feedstock, pyrolysis temperature, residence time and heating rate (Adhikari et al., 2019). The functional groups such as hydroxyl, carboxylic, ketone, chromene and lactone groups present in the biochar strongly adsorb the nutrient ions and reduce the losses (Schmidt et al., 2015). Supporting this, several studies (Qian et al., 2014; Yao et al., 2015; Mandal et al., 2016; Wen et al., 2017; Chen et al., 2018; Cao et al., 2019) had reported higher nutrient use efficiency on utilization of biochar-based fertilizers. Lehmann (2007) reported that biochar is not a fertilizer but it reduces the fertilizer use and improves the soil quality. Application of biochar at 15% w/w was optimal for the growth of Indian mustard (Park et al., 2011) whereas 5% w/w biochar promoted the maize growth (Zheng et al., 2013). In a study conducted by Suppadit et al. (2012), application of 15% w/w biochar affected the nut growth. The suppressive effect on excessive use of biochar was due to highly porous nature of the biochar which accelerated the loss of water and nutrients from the soil (Xu et al., 2016). Therefore, study on the appropriate dose of biochar for the particular soil and crop is required. The effect of biochar on nutrient availability and crop growth was found to be variable (Fang et al., 2016 which depends on chemical composition of biochar, application dose, soil pH, nutrient status of soils and microbial interaction with biochar (Singh et al., 2019. Biochar contributes significant quantities of macro and micro nutrients. They are considered as slow-release fertilizers (Schneider and Haderlein, 2016).

Nitrogen

Biochar addition reduced the concentration of NH_4^+ in soil due to higher assimilation of NH_4^+ or oxidation of NH_4^+ to NO_3^- (Harter et al., 2014). Sorption of NH_4^+ to the oxygenated carbonyl and carboxyl functional groups reduced the NH_4^+ availability for nitrification. This was supported by the higher concentration of nitrates in soil on incremental doses of biochar (Abbruzzini et al., 2019). Contradictorily, Thomazini et al. (2015), through their incubation study reported increased concentration of NH_4^+ in forest soils. Biochar application declined the NO_3 leaching (Laird et al., 2010), which is attributed by the hydroxyl and alkyl functional groups of biochar Supporting this, Mukherjee et al. (2014) reported a 33% reduction in leaching of nitrates on biochar application @ 0.01 kg per kg of silty loam soil. This was also supported by Sika and Hardie (2014) in sandy soils. Many studies (Jeffery et al., 2011; Jones et al., 2012; Abbruzzini et al., 2019) reported that biochar incorporation increased the soil N availability, N uptake and nitrogen use efficiency by the crops. Higher doses of biochar stimulate the nitrification process (Edwards et al., 2018). Incorporation of biochar to the tropical wheat growing soils reduced the N_2O emissions by 71% (Abbruzzini et al., 2019). Meta-analysis by Gao Y. et al. (2020) reported 12% and 11% reduction in nitrate and ammonium contents of top soil, respectively.

Biochar sorbed the ammonia more efficiently and reduced the volatilization of ammonia (Iyobe et al., 2004). Conversely, several studies (Liu Z. et al., 2017; Nguyen et al., 2017) reported that application of biochar stimulated ammonia volatilization and N immobilization and ultimately reduced mineral N concentration of soil. Nguyen et al. (2017) observed reduced nitrification and abundance of genes encoding ammonia monooxygenase (amoA gene) on co-application of urea with high CEC biochar whereas the reduction was less in low CEC biochar. N immobilization on biochar application is short -lived (Abbruzzini et al., 2019). Supporting this, Martin et al. (2015) opinioned that biochar addition stimulated the activity of N immobilizing heterotrophs limiting the nitrification. Biochar based controlled release nitrogen fertilizers reduced denitrification and abundance of nirS and nirK genes, whereas it increased soil nitrification and amoA gene abundance (Liao et al., 2020). Conversely, stimulation of denitrification process on biochar addition was reported which decreased soil N (Singh et al., 2010; Harter et al., 2014). Supporting this, Cayuela et al. (2013) stated that biochar facilitates the electron transfer to denitrifiers in soil which on combination with liming effect of biochar accelerate the denitrification process. The nosZ gene encoding nitrous oxide reductase, a key enzyme for dentrification increased on biochar application (Harter et al., 2014).

Application of biochar 5–20 t ha^{-1} increased the nitrogen use efficiency (NUE) by wheat cultivated in saline soils of China, whereas overuse (>20tha^{-1}) had negative effect on NUE (Sun et al., 2019). Application of maize stalk biochar for Zucchini plants in calcareous sandy soils, improved partial factor productivity and agronomic efficiency for N whereas the effects were found to be insignificant for P (Amin and Eissa, 2017). Tian et al. (2021) reported that application of rice straw biochar at 10 t ha^{-1} replaced 20% nitrogen fertilizer and NUE and yield of rapeseed in calcareous soils of China. Wang et al. (2015) found that addition of biochar in acidic soils reduced the population of ammonia oxidizing bacteria. Utilization of biochar based controlled release fertilizers improved the population of Cyanobacteria and Saccharibacteria involved in N fixation and organic compounds degradation, respectively and ultimately had improved soil fertility (Liao et al., 2020.

Higher soil moisture retention and root growth on biochar addition favored maximum nitrogen fixation by groundnut crop (Pandian et al., 2016). Higher biological nitrogen fixation (BNF) in common beans were observed at biochar dose of 78 t ha^{-1} (Rondon et al., 2007) whereas biochar at100 tha^{-1} recorded higher BNF in soybean (Tagoe et al., 2008). Variation between the above results was due to biochar properties, response of the crop species to biochar or soil nutrient status (Mia et al., 2014). BNF and nodulation in clover was higher at biochar rates of 10 t ha^{-1} and recorded a significant reduction beyond that dose (Mia et al., 2014). The synergistic effect on BNF was due to greater bioavailability of essential nutrients like boron (B) and Molybdenum (Mo) (Rondon et al., 2007) on experimenting in an acidic tropical soil with common beans. Increased soil salinity on biochar incorporation reduced the BNF (Revell et al., 2012).

Phosphorus

The pyrolysis temperature has its effect on the availability of P in the biochar. A high concentration of labile calcium phosphates is found in low temperature biochars whereas stable P forms are dominant in temperature above 600°C (Bruun et al., 2017). The concentration of total and water-soluble nutrients (P &K) was higher in animal-based biochar (poultry manure) compared to lignocellulosic (harwood and softwood) biochars (Novak et al., 2013; Novak et al., 2018b). Novak and Busscher (2012) stated that the nutrients which were unassimilated by the animals would be released in excreta and it attributed to higher nutrient contents.

In addition to direct release of P from biochar through ligand exchange, desorption or dissolution (Chathurika et al., 2016), biochar also improves the P availability through P adsorption against leaching (Madiba et al., 2016), mineralization of organic P through enhanced microbial growth (Dume et al., 2017. For instance, biochar addition to acidic soils resembles the liming effect and improves the P availability through rise in soil pH (Biederman and Harpole, 2013 Biochar derived from biosolid sludge was a P rich material (Li et al., 2019). Biochar produced at pyrolysis temperature between 300°C and 500°C had high P contents whereas the biochar produced at >500°C had significantly less labile P due to formation of insoluble and stable forms of P (Adhikari et al., 2019; Li et al., 2019). Similarly, biochar from blady grass (*Imperata cylindrical*) had extractable $p > 700$ μgP g^{-1} biochar (Zhang H. et al., 2016) whereas it was 152 g kg^{-1} in animal bone chips biochar (Siebers and Leinweber, 2013). Uzoma et al. (2011) reported that woody biochar produced at 500°C had extractable P of about 23 g kg^{-1} whereas it was only 1.2 gkg^{-1} in same biochar produced at 300°C. Organic, inorganic, available P and total P increased on application of biochar derived from biosolid sludge in acid soils (Figueiredo et al., 2020). Biochar improved the arbuscular mycorrhizae colonization by 6% and enhanced the uptake of sparingly soluble P ($FePO_4$) and increased root access to soluble P (NaH_2PO_4) by beans (Vanek and Lehmann, 2015).

Meta-analysis of Glaser and Lehr, (2019) stated that addition of biochars improved the soil P availability in acidic and neutral soils by a factor 5.1 whereas non-significant effect was found in alkaline soils. Similar findings were reported by Xu et al. (2018). Contradictory to this, increased soil P availability on biochar addition in calcareous sandy soils was reported (Amin, 2018). DeLuca et al. (2015) reported higher P availability on biochar addition in alkaline soils. Application of rice straw biochar at 10 g kg^{-1} improved the soil pH and P availability whereas it reduced exchangeable Al^{3+} in acidic red soils. The liming effect of biochar helped in alleviating P deficiency and Al toxicity (Zhu et al., 2014). In acid soils, P binds to Al or Fe oxides/hydroxides which on biochar addition got solubilized and was made available to the crops (Borno et al., 2018. In contrast to higher availability of P, addition of biochar with low P concentration in acid soils reduced the P availability (Schneider and Haderlein, 2016) through sorption (Trazzi et al., 2016; Ngatia et al., 2017), immobilization (Mitchell et al., 2016; Xu et al., 2018) and precipitation (Gao Y. et al., 2020). The organic acids released from biochar compete with phosphate ions and increase the soil P availability (Schneider and Haderlein, 2016). For maize, sewage sludge biochar at 30tha^{-1} enhanced root growth which inturn increased rhizodeposition and microbial activity and ultimately P availability in acidic Ultisols (Gonzaga et al., 2022). Borno et al. (2018) reported higher P fixation in alkaline soils amended with biochar.

Effect of biochar additions on P availability of the soil depends on soil texture. Zhang H. et al. (2016) reported a 25% higher P availability in heavy textured soils than coarse textured sandy soils on biochar addition. This effect was contradictory to Liu et al. (2013), who reported greater P availability in sandy soils. A meta-analysis showed that application of biochar upto 10 t ha^{-1} enhanced the soil P availability and P uptake especially in heavy textured, acidic P deficient soils (Tesfaye et al., 2021). Incorporation of biochar was found to be an effective strategy in enhancing the availability of legacy P in acid soils and not applicable for other alkaline soils with low legacy P (Alotaibi et al., 2021). Phosphorus laden maize stalk biochar releases the P slowly, acting as a slow-release fertilizer and hence improves phosphorus use efficiency (Li et al., 2020). Angst and Sohi, (2013) reported the potential substitution of certain proportion of inorganic P fertilizers by biochar.

Potassium

Unlike other nutrients, potassium present in the raw material would be converted to their salts of higher solubility (Karim et al., 2017). Biochar amendment increased the soluble and exchangeable fractions of K (Oram et al., 2014). The poultry manure contains the salts like KCl, KNO_3, and $Ca_3(PO_4)_2$, of which potassic salts were highly soluble compared to calcium (Sigua et al., 2016. This contributed to higher concentration of potassium from leachates of biochar amended soils; Wang et al. (2018) reported on the prolonged effects of biochar application on K uptake prolonged in soils dominated with 2:1 K bearing minerals. Biochar application enhanced soil K availability and growth of K- dissolving bacteria in alfisols and entisols. Biochar improved the soil K availability and supplemented the inorganic K fertilizers (Singh et al., 2019). Addition of K from the ash fraction of biochar increases the exchangeable K levels in soil and reduces the leaching losses (Qayyum et al., 2020. Biochar itself contain significant quantities of cations like K, Ca, Mg and application of that improved their levels in the soil (Jien and Wang, 2013). Alazzaz et al. (2020) reported that biochar derived from the olive mill solid waste should be restricted in calcareous loamy sand soils as it reduced the concentration of P, Ca, Mg and Mn in maize shoots. In calcareous loamy sand soils, biochar application increased the available K, Na, Ca, Mg, AB- DTPA extractable Fe and Mn whereas it reduced AB- DTPA extractable Zn. Though application of biochar improved the soil nutrient status, care should be taken before amending the soils with biochar considering the negative effects like EC and exchangeable Na. It increases the risk of salinity particularly in alkaline soils.

Aluminium

Biochar plays a vital role in detoxification of Al toxicity. There was a significant reduction in the soluble and exchangeable forms of aluminium (Al) on biochar addition (wood biochar at 20 t ha^{-1}) and plays a vital role in Al detoxification (Shetty et al., 2021). Contradictorily, a negligible effect of biochar on reduction of Al toxicity in Al enriched acidic mine spoils was reported by Novak et al. (2018a). The efficiency of biochar on Al amelioration depends on calcium carbonate equivalent of the biochar.

Soil biological properties

Microbial population

Addition of biochar to the soil has the capability to modify the physical and chemical properties thereby providing a habitat conducive for microorganisms (Xu H. J. et al., 2014). Microbial attraction to biochar depends on surface hydrophobicity. Optimal amount of biochar in combination with fertilizers helps in improving the microbial population thereby increasing the nutrient release (chemical properties). Supporting the above statement, Warnock et al. (2007) evidenced an increase in microbial activity on biochar application due to the alteration of soil physico-chemical properties, detoxification of allelochemicals on biochar and refugia for smaller organisms. Improved microbial activity on biochar application is due to their higher water holding potentials (Steiner et al., 2008). The pores present in the biochar serves as habitat for soil microorganisms and protects them from other predatory micro athropods present in the soil (Jaafar et al., 2014; Quilliam et al. (2013) reported that the macropores of size greater than 200 nm serves as an idle habitat for soil bacteria. The micro and meso pores of biochar stores water and dissolved substances required for the microbial metabolism (Brewer and Brown, 2012). Higher surface area of biochar improved the microbial colonization. The black colour of the biochar absorbs more heat, which improved the rate of microbial growth and enzymatic activity (Gul et al., 2015). Biochar's alkaline nature favored the growth of gram-positive soil bacteria than the gram-negative bacteria (Farrell et al., 2013). Zimmermann et al. (2012) reported that with increase in the age of biochar, the pH declined and had supported the growth of fungi. Addition of pine wood biochar-bacterial mixture (*Enterobacter cloacae* UW5 strains) in the sandy loam soils increased the population density of bacteria by 16% after 4 weeks incubation period (Hale et al., 2015). Quilliam et al. (2013) reported poor microbial colonization on biochar application to the soils, which might due to the lower nutrient content in biochar compared to the bulk soil and higher sorption of substances with lower molecular weight.

The activity and abundance of microbes got enhanced by biochar additions, which ultimately had affected the nutrient cycling (Grossman et al., 2010). A meta-analysis review by Schmidt et al. (2021) stated that microbial biomass in acidic and neutral soils was improved by biochar incorporation but not in alkaline soils. Bollmann et al. (2005) reported that biochar application to acid soils increases soil pH suitable for nitrifying organisms like *Nitrosospira amoA, Nitrosospira briensis* thereby increased the nitrification rate and nutrients immobilization. Addition of 0.6 g of corn stover biochar to 100 mL nutrient broth had showed fivefold increase in growth of *Bacillus mucilaginosus* (K-dissolving bacteria) and 80% higher K- dissolving activity (Liu S. et al, 2017). Supporting this, Wang et al. (2018) reported enhanced growth of K- dissolving bacteria on biochar incorporation. The allelochemicals were sorbed by biochar and increased the AM (mycorrhizal fungi) colonization (Elmer and Pignatello, 2011). Conversely, biochar on sorption of toxic volatile organic compounds affected the microbial growth (Gurtler et al., 2014). Application of biochar had increased AM population by 40% (Ishii and Kadoya, 1994) and it would be helpful in sustained crop production, restoration of ecosystem, carbon sequestration and mitigation of climate change. Contradictorily, Warnock et al. (2010) reported that application of pine biochar @ 2.0% and 4.0%w/w declined the arbuscular mycorrhizal fungal abundance in both root and soil.

Microbial biomass carbon

Application of biochar influences the microbial biomass carbon significantly. Rutigliano et al. (2011) observed no changes in microbial biomass in biochar amended soils. Similarly, Mitchell et al. (2015) reported no changes in MBC (microbial biomass carbon) on short term (20–30 days) whereas the biochar additions improved the MBC after 1 year. Application of high temperature wood biochar (≥600°C) derived from eucalyptus reduced the MBC by 28% in sandy soils (Dempster et al., 2012). Conversely, Ameloot et al. (2013) reported a 29% increase in MBC in sandy loam soils on application of biochar produced from willow wood at 700°C. Similarly, Luo et al. (2013) reported greater MBC in clay loam soils amended with biochar produced at 700°C. There is a need of applying organic amendments in conjugation with biochar to offset the short-term reduction effect on MBC.

Enzymes

Enzymes are the substances secreted by plant roots or soil microorganisms which influence the nutrient bioavailability (Gianfreda, 2015). As biochar addition affect the microbial response (activity, abundance and community structure), enzymatic activity is also influenced by their addition. The interaction of biochar with the substrate and enzyme strongly influences the soil enzymatic activity (Lammirato et al., 2011). The enzymatic activity can either be promoted or limited, when the substrate and enzymes had sorbed to the functional groups present in the biochar (Czimczik and Masiello, 2007). The positive effect of biochar on soil enzymes were observed in some studies (Park et al., 2011; Kumar et al., 2013), whereas Lehmann et al. (2011) reported conversely. This increase in enzymatic activities on biochar addition was reported to be induced by higher soil organic carbon, microbial biomass carbon and nitrogen pools which serve as the organic substrates for such enzymes (Wang et al., 2015). The application of rice husk biochar at 12tha^{-1} significantly improved the activities of soil urease, catalase, alkaline phosphatase and invertase (Oladele, 2019). Soil invertase activity was positively correlated with soil organic carbon, available nitrogen and phosphorus (Zhang et al., 2005). Shahzad et al. (2014) reported an increased activity of phosphatase on biochar addition, which signify greater proportion of bio-available phosphorus. Sakin et al. (2021) reported that addition of almond shell biochar had significant positive effect on dehydrogenase and urease activities. Jing et al. (2020) reported no significant correlation between enzyme activity and soil organic carbon. The invertase activity was correlated with NH_4^+-N and NO_3^--N, whereas the urease activity was positively correlated with available nitrogen and phosphorus. This improved enzymatic activity on biochar additions was due to the stimulated root growth of the plants to exude these enzymes (Kotroczo et al., 2014). Activity of dehydrogenase in soils that were incubated with high temperature biochars (700°C) decreased by 47% whereas, addition of low temperature biochar (350°C) improved the dehydrogenase activity by 73% (Ameloot et al., 2013). Irrespective of soil types, biochar addition increased the activity

TABLE 3 Effect of biochar on heavy metal availability.

Biochar source	Biochar rate	Site details	Heavy metal species	Effect and possible mechanism	References
Dairy manure	2.5% & 5% wt	Shooting range site and a battery recycling site	Pb	Formation of $Pb_5(PO_4)_3(OH)$ formation reduced the TCPL and $CaCl_2$ extractable Pb	Cao et al. (2011)
Hardwood	20% volume	Former copper mine site	Cu and Pb	Reduction in soluble metal fractions by electrostatic sorption and precipitation	Karami et al. (2011)
Wheat straw	0 to 40 t ha^{-1}	Smelter contaminated soils	Cd	Reduction in concentration of $CaCl_2$- Cd	Cui et al. (2012)
Rice straw	3%–5% wt	Oxisols and Ultisols	Pb	Electrostatic interaction and surface complexation between Pb2+ and functional groups like -COO- in biochar	Jiang et al. (2012)
Soyabean stover	0%–20%	Loamy sand- firing range soil	Pb	Immobilization of Pb	Moon et al. (2013)
Municipal biowaste	0 to 40 t ha^{-1}	Hydroagric Stagnic Anthrosol	Cd, Cu, Ni, Pb, Zn	Significant reduction in availability of Cd, whereas Cu, Ni & Pb is not influenced	Bian et al. (2014)
Wheat straw	0 to 40 t ha^{-1}	Clay	Cd, Pb	Extractable Cd, Pb decreased due to increase in soil pH	Bian et al. (2014)
Unfertilized dates	0.5%–2.0 % wt	Sandy loam	Cd, Ni	Decreased available Cd & Ni fractions	Ehsan et al. (2014)
Cassava stem	5%–15% wt	Silty clay loam	Cd, Zn	Reduction in bioavailability of Cd & Zn	Prapagdee et al. (2014)
Peanut, Soybean, Canola, Rice	5% wt	Oxisol and ultisol	Pb (II)	Increased cation exchange capacity and pH of soil, increased the adsorption capacity of Pb (II)	Jiang et al. (2014)
Conocarpus	0%–5 % wt	Mining area soil	Fe, Mn, Zn, Cu, Cd, Pb	Decreased available heavy metal fractions due to immobilization	Al-Wabel et al. (2015)
Woody biomass (*Glyricidia sepium*)	1%–5 % wt	Serpentine soil	Ni, Cr, Mn	Immobilization of Cr, Ni, Mn in soil	Herath et al. (2015)
Rice hull	0%–10% volume	Sandy loam	Cd, Cu, Pb, Zn	Increased heavy metal adsorption due to increase in soil pH	Kim et al. (2015)
Sugarcane straw	1.5%–5 % wt	Clay loam	Zn, Cd, Pb	Reduction in bioavailable heavy metal fractions	Puga et al. (2015)
Miscanthus straw	2.5%–5 % wt	Sandy loam- former sewage field	Cd, Cu, Pb, Zn	Reduction of soluble metals in soil	Wagner et al. (2015)
Soybean stover, pine needles	10%	Sandy loam	Cu, Pb	Immobilization of Cu, Pb in soil	Ahmad et al. (2016)
Wheat straw	0 to 40 t ha^{-1}	Farmlands irrigated with wastewater from smelters and fertilizer plant	Cd & Pb	Decrease in bioavailable Cd & Pb fractions	Cui et al. (2016)
Hardwood	2% wt	Soils contaminated by chemical industries	Ni & Zn	Through chemisorption, biochar reduced the metal leaching and increased its residual fractions	Shen et al. (2016)
Bamboo, rice straw	0%–5 % wt	Sandy loam	Cd, Cu, Pb, Zn	Increased cation exchange capacity and pH of soil decreased the heavy metal concentrations	Yang et al. (2016)
Waste wood	1%–5%	Tannery waste soil	Cr	Reduction in $CaCl_2$ extractable Cr due to immobilization	Bashir et al. (2018)
Wood	5%–15%	Mining soils	Cd, Cu, Pb, Zn	Reduction in $CaCl_2$ extractable Cd by its retention with carbonates, Pb with oxyhydroxides, Cu & Zn with carbonates and oxyhydroxides	Ippolito et al. (2017)
Barley straw, tomato green waste, chicken manure, duck manure, swine manure	0%–5% wt	Sandy loam	Cd	Immobilization of Cd	Khan et al. (2017)
Chicken manure	0%–10% wt	Sandy	Cu	Exchangeable Cu fractions decreased whereas the residual fractions increased	Meier et al. (2017)

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TABLE 3 (*Continued*) Effect of biochar on heavy metal availability.

Biochar source	Biochar rate	Site details	Heavy metal species	Effect and possible mechanism	References
Tobacco stalk, dead pigs	0%–5% wt	Clay loam	Cd, Zn	Cd, Zn decreased in soil due to increase in soil pH	Yang et al. (2017)
Rice straw	1%–2%	Area Mining, mineral processing and known for melting plants	Cd	Decreased Cd concentration in soil pore water	Yin et al. (2017)
Rice husk	5%	Loamy sand textured mining soil	Cd, Cu, Ni, Zn	Under oxic conditions, contents of dissolved Cu, Cd, Ni & Zn increased- due to introduced DOC	El-Naggar et al. (2018)
Rice straw	10%	Smelter contaminated soils	As	Increased As content in soil pore water	Kim et al. (2018)
Poultry litter and biosolids	3% wt	Urban soil	Pb	Formation of pyromorphite and Pb-phosphate reduced PBET extractable Pb	Netherway et al. (2019)
Rape straw and rice straw	0%–5%	Soils near lead mining site	Pb & Cu	Decreased phytoavailable Pb & Cu fractions	Salam et al. (2019)
Rice hull	24 t ha^{-1}	Farmland soil polluted with Hg	Hg	Decreased Hg concentration in soil pore water	Xing et al. (2019)
Rice straw	0 to 20 t ha^{-1}		Cd	Reduction in concentration of $CaCl_2$- Cd	Sui et al. (2020)

of alkaline phosphomonoesterase whereas acidic phosphomonoesterase activity inhibited (Neble et al., 2007; Jin et al., 2016). The study by Masto et al. (2013) showed the increased activity of phosphomonoesterase (both acidic and alkaline) on biochar addition in red soils. Application of biochar mixed with compost increased the enzymatic activities (dehydrogenase and phosphatase) and nutrient availability in saline soils (Liu et al., 2021). Biochar addition to the vermicomposting of sewage sludge reduces the toxicity and bioavailability of heavy metals, which in turn improved the growth, and reproduction of earth worms (Khan et al., 2020). However, some studies showed reduction in earthworm biomass on biochar addition (Malinska et al., 2016).

Remediation of heavy metal contaminated soils

Environmental sustainability is under threat by the worldwide problem of soil contamination. Various *in situ* and *ex situ* remediation techniques are developed in order to restore the ecosystem services in the contaminated soils. Biochar as an amendment in remediation of heavy metal contaminated soils has been investigated. It is not an eradication technique but it transforms the soluble toxic heavy metals to less soluble and unavailable form. Varied capacities and efficiencies of the biochar on remediation of heavy metal contaminated soils have been documented and a detailed information on the effect of biochar on heavy metals is furnished in Table 3. The speciation of the heavy metals and its transformation is greatly influenced by biochar (Wu et al., 2017). Biochar reduced the acid extractable heavy metal fractions and increased the organic bound and residual fractions (Dai et al., 2018) whereas, the bioavailable fractions especially As increased on biochar additions in some studies (Qiao et al., 2018). The feedstock for biochar, its dosage, application method, soil properties and heavy metal species are the factors influencing the biochar's effectiveness on soil remediation (Wang et al., 2021). A considerable reduction in bioavailability of heavy metals on biochar additions is due to the mechanisms of immobilization (Venegas et al., 2016), cation exchange and electrostatic interaction (Uchimiya et al., 2011), surface complexation (Karami et al., 2011), and chemical precipitation (metal hydroxide formation, precipitates of carbonate, or phosphate). The porous structure and surface functional groups of the biochar enables the immobilization of the heavy metals (Kavitha et al., 2018) and thereby reduce its availability. The proportion of reduction in available heavy metal fractions depends on water management. Under intermittent irrigation, biochar potentially alleviates the adverse heavy metal pollution (Chen et al., 2021). Biochar reduces the metal ions (Cr) leaching by its action on redox reactions of metals (Choppala et al., 2012). Contradictorily, mobilization of arsenic due to enhanced pH on biochar application reported by Hartley et al. (2009). The effect of biochar on heavy metal availability and its uptake by plants is depicted in Figure 2.

Crop yield

As the soil properties (physical, chemical and biological) get improves on biochar application, this in turn enhances crop yield. Quantitative effect of biochar on crop yield is given in Table 4. Biochar application improved the seed germination, root density and crop yield. Application of biochar at higher doses in combination with chemical fertilizers (NPK) improved the crop yield. In acid soils (pH < 5.2), application of biochar enhanced the yield of carrot and bean (Rondon et al., 2004). According to Lehmann et al. (2006), application of biochar upto 140 t ha^{-1}on highly weathered soils of humid tropical regions increased the crop yield, but this was not suitable for all situations and crops. Accordingly, Rondon et al. (2004) found that biomass yield in beans increased with application of biochar upto 60 t ha^{-1} but when dose increased to 90 t ha^{-1}, it reached the same value as

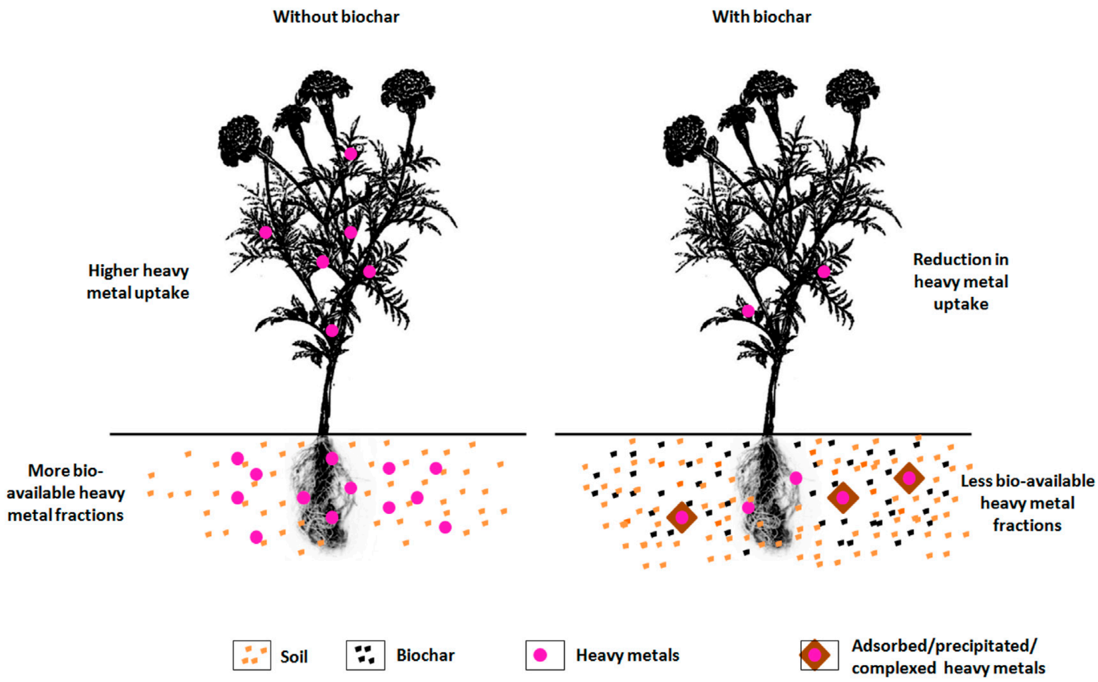

FIGURE 2
Effect of biochar on heavy metal availability and uptake.

TABLE 4 Quantitative impact of biochar on crop yield.

Crop	Biochar source and dose	Soil properties	Effect	References
Cow pea and Rice	Woody biomass, 10% & 20%	Ferralsol	Application of charcoal increased the biomass yield compared to control	Lehmann et al. (2003)
Maize, Cowpea, Peanut	Acacia mangium bark, 10 L m^{-2}	-	Biochar application increased the yield of the crops significantly	Yamato et al. (2006)
Radish	Green waste, 0 to 100 t ha^{-1}	Alfisol	Application of biochar did not have any significant effect on dry matter yield whereas biochar in combination with N fertilizer had significant increase up to 266% at 100 t ha^{-1} biochar	Chan et al. (2007)
Rice & Sorghum	Forest wood, 5.5 & 11 t ha^{-1}	Ferralsol	Charcoal in combination with NPK application doubled the grain production	Steiner et al. (2007)
Radish	Poultry litter (450 & 500 C), 0 to 50 t ha^{-1}	Alfisol	Biochar produced at 450 C improved the yield significantly whereas, additional increase in yield was observed on N fertilizer application	Chan et al. (2008)
Rice	Wood residues, 0 to 16 t ha^{-1}	-	Biochar application without N fertilizers reduced the yield in soils having low indigenous N supply	Asai et al. (2009)
Corn	Peanut hull and pine chip, 0 to 22.4 t ha^{-1}	Ultisol	Highest yield depression at 22.4 t ha^{-1} peanut hull biochar with N fertilizer whereas, pine chip biochar showed a yield decline in first season and no such effects in second season	Gaskin et al. (2010)
Cherry Tomato	Wastewater sludge, 10 t ha^{-1}	Chromosol	Application of biochar increased the yield by 64% compared to control whereas, biochar in combination with fertilizers increased the yield by 97% compared to biochar alone	Hossain et al. (2010)
Maize	Biomass, 0 to 20 t ha^{-1}	Oxisol	Biochar showed insignificant effects on yield during first year of application, whereas, it increased the yield with higher doses in the next 3 years	Major et al. (2010)

(Continued on following page)

TABLE 4 (*Continued*) Quantitative impact of biochar on crop yield.

Crop	Biochar source and dose	Soil properties	Effect	References
Rice	Rice husk biochar, 4.13 kg m^{-2}	Anthraquic gleysols, Humic nitisols, Gleyic acrisols	Increased yield ranging from 16%–35%	Haefele et al. (2011)
Durum wheat	Coppiced woodlands, 30 & 60 t ha^{-1}	Silty loam	Up to 30% increase in yield	Vaccari et al. (2011)
Tomato	Eucalyptus globulus, 0 to 5 t ha^{-1}	Sandy loam	No significant effect on crop yield	Nzanza et al. (2012)
Soybean	Oak tree, 10 t ha^{-1}	Loam	Significant increase in dry matter production	Lee et al. (2013)
Wheat, potato	Hardwood (80%) and softwood (20%) mixture, 0% & 5% w/w	Sandy loam	Biochar application improved the growth and yield of wheat and potato crop significantly	Akhtar et al. (2015a), Akhtar et al. (2015b)
Radish	0 to 2.5 t ha^{-1}	Loamy sand	Increased dry matter production	Nabavinia et al. (2015)
Wheat and maize	Rice straw, 2 t ha^{-1}	Clayey	Biochar application the yield of maize and wheat crop significantly	Amer (2016)
Maize	Rice hull, 1%–5% w/w	Reclaimed tidal land soil	Biochar application have positive effects on maize yield	Kim et al. (2016)
Mung bean	0 to 100 t ha^{-1}	-	Higher grain yield of 4.2 g/pot obtained at 25 t ha^{-1}	Rab et al. (2016)
Maize & Common bean	Eucalyptus, 10 to 50 t ha^{-1}	Acidic soils	Significant increase in crop yield	Raboin et al. (2016)
Tomato	Conocarpus, 0%–8% w/w	Sandy soil	Increased the yield by 14%–43.3% compared to control	Usman et al. (2016)
Maize	Maize straw, 0 to 30 t ha^{-1}	Clay loam	Yield increase is proportionate to the biochar dose. At 30 t ha^{-1}, the yield increased by 13% & 14%, respectively in the year 1 &2	Xiao et al. (2016)
Maize	Wheat straw, 0 to 40 t ha^{-1}	Calcareous inceptisol	Biochar application the yield of maize crop significantly	Zhang et al. (2016b)
Sorghum	Acacia seyal, 0 to 10 t ha^{-1}	Vertisol	Biochar had no significant effects on yield of sorghum	Deng et al. (2017)
Wheat & Corn	5 to 20 t ha^{-1}	Sandy loam	Increase in yield of wheat and corn	Mousa (2017)
Maize	Sorghum and rice husk, 2 t ha^{-1}	Ochrosols and lateritic soils	Integrated application of biochar and inorganic fertilizers significantly increased the maize yield	Calys-Tagoe et al. (2019)
Rice	Rice straw, 20 & 40 t ha^{-1}	HYdragric Anthrosol	Increased rice yield	Yang et al. (2019)
Cocoyam	Hardwood, 0 to 30 t ha^{-1}	Alfisol	Biochar application significantly increased the yield	Adekiya et al. (2020)
Onion	Softwood, 29 & 58 t ha^{-1}	Sandy loam	The effect of biochar on crop yield is neutral	Gao et al. (2020b)
Cucumber, sweet potato and rape	Litchi branch, 10 to 30 t ha^{-1}	Acidic red soil	Positive effect on crop yield	Jiang et al. (2020)
Maize, Okra, Cassava	Corn cob, 10 t ha^{-1}	Haplic acrisol	Application of biochar in combination with compost and NPK fertilizers increased the crop yield significantly	Frimpong et al. (2021)

that of control plots. Masulili et al. (2010) conducted an experiment with rice husk biochar to study its reclamating capacity in acid soils. Among the different treatments, the rice plants in the biochar amended soils recorded greater yield attributes and yield.

In a study conducted at Colombia in *isohyperthermic kaolinitic Typic Haplustox*, application of biochar (at 0, 8 and 20 t ha^{-1}) for 4 years showed no significant effect on maize yield in first year but in subsequent years, there was an improvement in yield (Major et al., 2010). Supporting this, the meta-analyses by Jeffery et al. (2017) stated that biochar application at the rate of 30 tha^{-1}, decreased the crop yields by 3% in temperate areas. Higher rates of biochar application reduced the crop growth and yield (Kammann et al., 2011). Application of biochar at higher rates (50% w/w) reduces the plant growth and flowering in *Viola cornuta* (Regmi et al., 2022).

Conclusion and future prospects

The following conclusions are drawn from this review.

- Benefits of biochar application on soil fertility

Application of biochar increase the total porosity of the soils, which reduces the soil bulk density, improves the soil aggregation and moisture content. The biochar itself is having substantial quantities of plant nutrients, the effect on soil fertility varies with properties of biochar and the characteristics of the soil. Since most of the biochar produced are alkaline in nature, application to acidic soils improves the nutrient availability, but enhanced salt concentration on biochar addition increases the risk of salinity in alkaline soils. So, care has to be taken before amending the soil with biochar. Biochar provides habitat conducive for the soil micro-organisms, thereby improve the soil biological properties.

- Effectiveness of biochar

The effect of biochar on soil properties, heavy metal remediation or crop yield depends on biochar type, its dose, soil type, agroclimatic condition, crop species, etc. The effects hence are always soil and site-specific.

- Need for long term field trials to study the effectiveness of biochar

The effect of biochar on soil properties are studied mostly under laboratory conditions on short term basis, the long term or aging effect of biochar in field conditions is needed in detail to develop valid recommendation under varied soil and climatic conditions. The economic feasibility of biochar additions needs to be addressed in future.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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