# Chapter 11
# Biochar: A New Environmental Paradigm in Management of Agricultural Soils and Mitigation of GHG Emission

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**Abstract** Biochar, a co-product of the pyrolytic conversion of biomass and bio-wastes to biofuel is a carbon rich recalcitrant material. It has received much attention in the recent times for its prospective application in various fields viz. as a soil amendment for improving the physical, chemical, and biological qualities of agricultural soils, as an adsorbent for removal of various organic and inorganic contaminants in water, for removal of pesticides residues in soil, for correcting soil acidity, as a precursor for chemical synthesis, for industrial applications such as supercapacitor application, as a support material for fuel cells, for enhancement in biogas generation to name a few. In addition to all these, biochar's green-house gas mitigation potential, and C-sequestration potential are two most significant attributes that has made biochar a suitable component for SDGs. Further, these applications have made biochar as one of the most researched topics in recent times. The ease of biochar production is also another advantage which can be beneficial for farmers even with a marginal land holding. In this chapter, an attempt has been made to discuss the role of biochar in management of agricultural soils, as well as its vast environmental application possibilities.

**Keywords** Biochar · Soil amendment · Environmental management

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## 11.1 Introduction: Biochar as a Soil Amendment

Biochar is a charred carbon-enriched material intended to be used as a soil amendment to sequester carbon and enhance soil quality. Sustainable biochar is produced from waste biomass using modern thermochemical technologies. Addition of sustainable biochar to soil has many environmental and agricultural benefits, including waste reduction, energy production, carbon sequestration, water resource protection, and soil improvement. When used as a soil amendment, biochar has been reported to boost soil fertility and improve soil quality by raising soil pH, increasing moisture holding capacity, attracting more beneficial fungi and microbes, improving cation exchange capacity (CEC), and retaining nutrients in soil (Lehmann et al. 2006; Lehmann 2007a). Another major benefit associated with the use of biochar as a soil amendment is its ability to sequester carbon from the atmosphere-biosphere pool and transfer it to soil (Winsley 2007; Gaunt and Lehmann 2008; Laird 2008). Biochar usually has a greater sorption ability than natural soil organic matter due to its greater surface area, negative surface charge, and charge density (Liang et al. 2006). Biochar can not only efficiently remove many cationic chemicals including a variety of metal ions, but also absorb anionic nutrients such as phosphate ions, though the removal mechanism for this process is not fully understood (Lehmann 2007a). Thus, the addition of biochar to soil offers a potential environmental benefit by preventing the loss of nutrients and thereby protecting water resources. Biochar is considered much more effective than other organic matter in retaining and making nutrients available to plants. Its surface area and complex pore structure are hospitable to bacteria and fungi that plants need to absorb nutrients from the soil. Moreover, biochar is a more stable nutrient source than compost and manure (Chan et al. 2007).

### *11.1.1 Agronomic and Environmental Benefits of Biochar*

Biochars can provide agronomic and environmental benefits in soils through increased cation exchange capacity, reduced nutrient leaching, enhanced water holding capacity, reduced soil acidity and stimulation of microbial activity (Kookana et al. 2011; Lehmann and Joseph 2015).

#### 11.1.1.1 Crop Disease Management

A positive influence of biochar on reducing plant diseases such as rust in wheat and mildew in other crops was first reported some 170 years ago (Allen 1847) and drew attention in the last decade where several pathosystems were studied by different groups worldwide (Elad et al. 2010; Elmer and Pignatello 2011; Jaiswal et al. 2014; Copley et al. 2015; Jaiswal et al. 2015). Pathosystems included both foliar pathogens and soil borne pathogens (Elad et al. 2011; Graber et al. 2014a).Biochar application can enhance crop response to disease (Elad et al. 2011), and this enhancement can be attributed to an increase in soil pH (Novak et al. 2009), nutrient retention (Chan et al. 2007; Steiner et al. 2007), cation exchange capacity in soil (Steiner et al. 2007), transformations and turnover of P and S (Lehmann and Joseph 2009), and neutralization of phytotoxic compounds in soil (Wardle et al. 1998).

Biochar can reduce fungal foliar diseases caused by *Botrytis cinerea* and *Oidiopsis sicula* in tomato (*Solanum lycopersicum* L.) and pepper (*Capsicum annuum* L.) (Elad et al. 2010). Biochar induced defense responses of strawberry are functionally similar to induced systemic resistance (Harel et al. 2012). Moreover, biochar can reduce soil borne diseases caused by bacteria and fungi (Jaiswal et al. 2014). Incidence of bacterial wilt (*R. solanacearum*) in tomato was reduced due to biochar application derived from municipal biowaste (Nerome et al. 2005). Biochar induced plant disease suppression were attributed to several mechanisms (Hoitink and Fahy 1986; Lehmann et al. 2011; Noble and Coventry 2005) such as chemical components of biochar that directly inhibit growth of pathogens and the porous structure of biochar provide microbial habitats beneficial for bacterial abundance. Biochar promotes plant growth by providing nutrients and improving nutrient solubilization and uptake. The sorption property of biochar may change the mobility and activity of pathogens or modify signaling between pathogens and plants (Lehmann et al. 2011).

Adding biochar to soil and soilless media was found to suppress plant diseases caused by both foliar and soilborne pathogens (Elad et al. 2011; Frenkel et al. 2017; Graber et al. 2014b; Jaiswal et al. 2014). Biochar-elicited suppression of foliar fungal diseases is related to activation of plant defense system, given that biochar is spatially distant from the site of pathogen attack. Mechanisms responsible for biochar-related attenuation of soil borne diseases can be much more diverse. This is because the biochar and pathogens both reside in the soil, and can have direct and indirect interactions with each other (Graber et al. 2014b). Ways in which biochar could influence the progress of diseases caused by soil borne pathogens includes (1) changes in nutrient supply and availability (Elmer and Pignatello 2011); (2) alterations in soil physiochemical characteristics (Rogovska et al. 2017); (3) induction of systematic plant defenses (De Tender et al. 2016; Zwart and Kim 2012); (4) alteration of soil microbial abundance in terms of taxonomic, functional diversity and activity (De Tender et al. 2016; Jaiswal et al. 2017, 2018); (5) modification of pathogen growth, survival, virulence and activity (Akhter et al. 2016; Copley et al. 2015; Jaiswal et al. 2015, 2017, 2018) and (6) adsorption and inactivation of pathogenic enzymes and/or toxins. Ad-sorption of toxic metabolites by 3% biochar significantly reduced the severity of the disease-like symptoms caused by the toxic metabolites as compared to no-biochar control toxic metabolites treatments.

Biochar application at a rate of 3% and 5% by weight under tomato and pepper cultivation documented significant reduction in leaf symptoms caused by two common fungal pathogens i.e. powdery mildew and grey mould. Whole plant peppers after 60 days had 59% of powdery mildew infection in plots with biochar and only 17% infection with 5% biochar application. Grey mould in tomato after 59 days was significantly reduced from 66% infection in untreated plants to 2% under 3% biochar application. Biochar addition at a rate of 5% in the pepper crop reduced leaf infection from 18% (no biochar) to 6%. The reduced level of residual tars present in biochar induced resistance to the diseases and pest (Elad et al. 2010). Jaiswal et al. (2018) documented that biochars obtained from eucalyptus wood and pepper plant wastes can significantly adsorbed and deactivated enzyme exudates of pathogenic fungi *Fusarium oxysporum*.

Bonanomi et al. (2015) reviewed and summarized the data from 13 pathosystems that tested the effect of biochar on plant disease. In their analysis, 85% of the studies showed a positive influence of biochar in reducing plant disease severity, 12% had no effect, and only 3% showed that biochar additions were conducive to plant disease. However, their analysis did not consider the dose of the as a crucial factor on plant susceptibility/resistance to a disease.

#### 11.1.1.2 Abiotic Stress Management

Abiotic stress such as, drought, high soil salinity, heat, cold, oxidative stress and heavy metal toxicity is the common adverse environmental conditions that affect and limit crop productivity worldwide (Singh 2013, 2014, 2015, 2016; Singh and Boudh 2016; Kumar et al. 2017; Kumar and Singh 2017; Tiwari and Singh 2017). The abiotic stress conditions that most adversely affect crop yield are associated with water deficiency ion imbalance and temperature extremes (Gupta et al. 2014). Biochar is known to have a number of positive effects on plant ecophysiology. However, limited research has been carried out to date on the effects and mechanisms of biochar on plant ecophysiology under abiotic stresses. A series of experiments on rice seedlings treated with different concentrations of biochar leacheates (between 0 and 10% by weight) under cold stress (10 °C) was conducted by Yuan et al. 2017. Quantitative real-time PCR (qRT-PCR) and cold-resistant physiological indicator analysis at low temperatures revealed that the cold tolerance of rice seedlings increased after treatment with high concentrations of biochar leacheates (between 3% and 10% by weight). Results also show that the organic molecules in biochar leacheates enhance the cold resistance of plants when other interference factors are excluded. The positive influence of biochar on plant cold tolerance is because of surface organic molecules and their interaction with stress-related proteins (Yuan et al. 2017). As a direct source of plant soil nutrients; presence of biochar impact root growth, and plant performance (Prendergast-Miller et al. 2013). Thomas et al. 2013 reported that biochar mitigates negative effects on two herbaceous plant species via salt sorption and application is known to preserve rice pollen under high-temperature stress (Fahad et al. 2015). Biochar addition enhance drought tolerance of quinoa crop with improve the growth and higher leaf nitrogen content (Kammann et al. 2011).

The beneficial effects of biochar under limited water conditions have been widely reported (Akhtar et al. 2015b; Paneque et al. 2016; Ramzani et al. 2017; Rogovska et al. 2014). Biochar as soil amendment improved growth and biomass of plants under drought-stress. Use of biochar exhibited the highest vegetative growth and seed production of field-grown sunflower under non-irrigated conditions (Paneque et al. 2016). Enhanced tomato fruit quality, growth and yield was reported under deficit irrigation due to biochar application (Agbna et al. 2017). Similarly, use of biochar supports the growth of winter rapeseed under drought conditions (Bamminger et al. 2016). Likewise, Basso et al. (2013) found that application of hardwood biochar significantly increase soil water holding capacity and might be the reason of enhanced available water capacity (AWC – available water between field capacity and permanent wilting point) for crops. Tomato seedlings were protected from wilting due to improved soil moisture content with higher (30% v/v) rates of biochar as soil amendment in sandy soils (Mulcahy et al. 2013). Studies have shown that biochar may minimize water stress in plants when applied with microorganisms (Liu et al. 2017b; Nadeem et al. 2017). Egamberdieva et al. (2017) reported inoculation of biochar with *Bradyrhizobium sp*. enhance the growth, biomass, phosphorus and nitrogen uptake, and nodulation in lupin (*Lupinus angustifolius* L.) seedlings under drought stress as compared to the only microbial inoculation. Nadeem et al. (2017) reported inoculation of biochar with *Pseudomonas fluorescens* reduced the harmful impact of drought stress on cucumber (*Cucumis sativus L.*). Significant improvements were observed in chlorophyll and relative water contents, as well as a reduction in leaf electrolyte leakage demonstrating the effectiveness of this approach. In another study, Liu et al. (2017b) reported that inoculation of birch wood biochar with *Rhizophagus irregularis* under limited root zone water decreased water use efficiency, leaf area, nitrogen and phosphorous in potato and did not adversely impacted the root biomass and soil pH as compared to control. However, under limited irrigation soil amendment with wood derived biochar (30 $mg.ha^{-1}$) had no significant effect on soil biota groups such as protozoa, bacteria, fungi, nematodes and arthropods (Pressler et al. 2017). Application of biochar with arbuscular mycorrhizal (AM) fungi and other beneficial microbes (Vimal et al. 2018; Singh 2019; Vimal and Singh 2019) can enhance drought and salt tolerance of the host plant by physiological mechanisms in nutrient adsorption and biochemical mechanisms, e.g. hormones, osmotic adjustment and antioxidant systems. However, application of BC to the agricultural soil with AM fungi stimulated the growth of extra-radical hyphae in soil and increased mycorrhizal colonization of roots. As the water potential of the soil was the same with and without biochar amendment, it is unlikely that the observed effects on plant growth were related to possible benefits from the water holding capacity of the biochar (Mickan et al. 2016).

Biochar not only improves crop productivity under normal conditions but also improves crop yield under adverse conditions such as salinity and drought (Thomas et al. 2013; Haider et al. 2014). For example, biochar enhanced the permanent wilting point (Abel et al. 2013; Cornelissen et al. 2013a), while the quantity of water retained at field capacity improved to a larger extent compared to the water held at permanent wilting point, i.e., increased plant available water. Therefore, the increase in WHC of biochar amended soils can be used as an indicator of the overall rise in plant available water (Liu et al. 2015). Because of its porous nature, biochar can improve your soil's water retention and water holding capacity. This can be attributed to the micropores present in biochar, where a larger volume of pores correlates to better water retention and better water holding capacity. Biochar with a fine particle size can also improve these characteristics by packing with the soil to create tight pores that will hold the water against gravity (https://char-grow.com/biochar-impact-nutrient-water-retention).

In another study, biochar addition to a fertile sandy clay loam soil in a boreal climate relieved the temporary water deficit leading improvement in harvestable yield (Tammeorg et al. 2014). Haider et al. (2014) quoted that biochar induced plant growth in a poor sandy soil is due to better soil-plant water relations as observed in terms of improved relative water content and leaf osmotic potential) and photosynthesis (due to lowered stomatal resistance and increased electron transport rate of photosystem II) under both well-watered and drought conditions. Biochar application at higher rates can mitigate adverse effects of salt stress for plant growth (Kim et al. 2016; Akhtar et al. 2015a). For instance, topdressing with biochar at 50 t $ha^{-1}$ mitigated salt-induced mortality in *Abutilon theophrasti* and extended the survival rate of *Prunella vulgaris*. Plants of *A.theophrasti* receiving both biochar and salts had growth rates similar to plants devoid of salt addition (Thomas et al. 2013). Recently, Akhtar et al. (2015a) reported enhanced tuber productivity of potato crop in salt-affected soils under application of biochar due to enhanced Na+ absorption and mainteinance of higher K+ content in xylem. The authors further observed positive residual effects of biochar application in lowered Na+ uptake in the following wheat crop under salinity stress (Akhtar et al. 2015b). Therefore, biochar has the potential to mitigate salinity-induced reductions in mineral uptake, and may be a novel technique to alleviate the effects of salinization in arable and salt contaminated soils (Thomas et al. 2013; Kim et al. 2016).

#### 11.1.1.3 Crop Productivity

Soil organic carbon (SOC) is known to play an important role in maintaining soil fertility and crop productivity (Díaz-Zorita et al. 2002; Lal 2004; Pan et al. 2009). Enhancing SOC stocks in croplands with good management practices has the significant contribution to climate change mitigation in agriculture (Smith et al. 2007b, 2008a). Direct incorporation of crop residues as well as organic manure to soils has been traditionally performed to maintain soil resilience and carbon (C) stocks. However, the residence time of these C sources in soil is relatively short because of mineralization, perhaps less than 30 years (Lehmann et al. 2006). Moreover, such an incorporation of fresh organic matter would potentially lead to an increase in the production of methane ($CH_4$) in rice fields (Yan et al. 2005; Shang et al. 2011). In contrast, C from biochar could be stabilized in soil for long periods, potentially hundreds of years (Lehmann et al. 2006; Kleber 2010; Schmidt et al. 2011; Woolf and Lehmann 2012). Furthermore, biochar soil amendment (BSA) has been shown to effectively reduce nitrogen (N) fertilizer-induced nitrous oxide ($N_2O$) emissions from agricultural soils (Yanai et al. 2007; Liu et al. 2012; Zhang et al. 2010) with no or minimal increase in $CO_2$ and $CH_4$ emissions (Spokas and Reicosky 2009; Karhu et al. 2011; Zhang et al. 2012a). Thus, biochar, produced via pyrolysis of biomass, has been recommended as an option to enhance SOC sequestration and mitigate greenhouse gas (GHG) emissions with the co-benefits of improving soil productivity and ecosystem functioning in world agriculture (Lehmann et al. 2006; Sohi 2012; Sohi et al. 2010; Woolf et al. 2010).

Many earlier studies on biochar focused on the potential of biochar from bio wastes to mitigate GHG emissions in agriculture (Lehmann 2007a; Spokas and Reicosky 2009; van Zwieten et al. 2009; Knoblauch et al. 2011; Singh et al. 2010a; Sohi et al. 2010; Taghizadeh-Toosi et al. 2011; Vaccari et al. 2011; Liu et al. 2012). Sohi (2012) addressed co benefits of biochar for soil and environmental quality, plant nutrition, and health as well as ecosystem functioning. The significant and persistent increase in crop productivity with BSA suggests a major benefit for agricultural production besides its role in mitigating GHG emission. BSA could provide a practical option to meet the challenge of food security in a changing climate.

Crop productivity responses to BSA also varied with crop type. Generally, greater positive responses were found in experiments with legumes, vegetables and grasses. The average increase in crop productivity was 30.3, 28.6, and 13.9% respectively for legume crops, vegetables, and grasses and 8.4, 11.3, and 6.6% respectively for maize, wheat, and rice. Yield increases with BSA were greater than biomass increases for maize. Whereas, the reverse was true for wheat. This indicates the differential influence of biochar on crop productivity.

Biochars used in the reported experiments were derived from almost 20 different types of biomass and were grouped into six general types of crop residues, wood, manure, sludge, municipal waste, and mixtures of wood and sludge. Wood and crop residue biochars documented an average (12.1 and 2.6% respectively) increase of constant crop productivity while manure biochar showed generally greater (29%) productivity with variable responses across the experiments. However, biochar from municipal waste significantly decreased crop productivity by 12.8% on average. Crop productivity response was also dependent on the pyrolyzing temperature during biochar production. Greater increase in crop productivity were seen with biochar produced at temperatures of >350 °C from wood, >550 °C for crop residues and 350– 550 °C for manure biochar. Meanwhile, crop productivity responses were generally negative (−7.9% on average) with non-alkaline (pH <7.0) biochars though generally positive with alkaline biochar (pH >7.0). Finally, crop productivity changes with BSA were not shown to be proportional to biochar application rate up to 20–40 t $ha^{-1}$ although the increase in crop productivity diminished at biochar application rate of >40 t $ha^{-1}$ (Liu et al. 2013)

The response of crop productivity was shown to vary with biochar type, pyrolysis temperature and the feedstock used. It had been well established that both the physicochemical properties and nutrient contents of biochars are affected by the feedstock type (Spokas and Reicosky 2009; Qin et al. 2012). While biochar from wood and crop residues exerted consistent positive yield increase, the greatest mean increase was observed with manure biochar. Manure biochars have been generally considered very significant for improving soil fertility by promoting soil structure development (Joseph et al. 2010) in addition to their large amounts of plant available nutrients (Hass et al. 2012). The negative effects with municipal waste biochar observed by Rajkovich et al. (2012) reported a great decline in crop productivity by 80% under application of food waste biochar at a higher (91 t $ha^{-1}$) rate. Presence of higher sodium (ten times) food waste biochar compared to wood and straw biochar increased soil salinity and inhibited plant growth. Crop productivity was significantly increased with biochar produced at higher pyrolyzing temperatures; presumably as a result of the liming effect as biochar pH generally increases with increasing temperature for pyrolysis (Rajkovich et al. 2012). However, there was an interaction of feedstock and pyrolysis temperature on crop productivity to BSA. Biochars produced at both low and high pyrolysis temperatures generally contained very limited N. Pyrolyzing at temperature more than 450 °C would result in losses of N in manure biochar. Higher nutrient contents and crop yields were found with the application of manure biochar pyrolyzed at temperatures of <500 °C compared to more recalcitrant biochar produced at even higher temperatures (Chan et al. 2008).

Along with improved soil health, increased crop yield is generally reported with application of biochar to soils. However, many of the published experiments are highly variable and dependent on many factors, mainly the initial soil properties and biochar characteristics. Positive crop and biomass yield was found for biochars produced from wood, paper pulp, wood chips and poultry litter. Liu et al. (2012) reviewed published data from 59 pot experiments and 57 field experiments from 21 countries and found increased crop productivity by 11% on average Benefits at field application was noted at a rate below 30 tons/ha. They reported that increases in crop productivity varied with crop type with greater increases for legume crops (30%), vegetables (29%), and grasses (14%) compared to cereal crops corn (8%), wheat (11%), and rice (7%). Biederman and Harpole (2013) analyzed the results of 371 independent studies. This meta-analysis showed that the addition of biochar to soils resulted in increased aboveground productivity, crop yield, soil microbial biomass, rhizobia nodulation, plant tissue content of K, soil phosphorus (P), soil potassium (K), total soil nitrogen (N), and total soil carbon (C) compared with control conditions. The yield gains were attributed to the combined effect of increased nutrient availability (P and N) and improved soil chemical conditions. However, there exists the concern of heavy metal contamination from biochars produced from sewage sludge. The inconsistency of sewage sludge might contain differing amounts of toxic metals which limit the land application due to the possibility of food chain contamination. Several studies have indicated the strong potential of biochar application for improving crop yields, particularly on nutrient-poor soils (Van Zwieten et al. 2010a; Zhang et al. 2012a) (Table 11.1).

Biochar application may substantially improve soil fertility and crop productivity (Lehmann and Joseph 2015). For instance, biochar application (68 t $ha^{-1}$) increased rice (*Oryza sativa* L.) and cowpea (*Vigna unguiculata* (L.) Walp) biomass by 20 and 50% respectively. Increased grain yields in durum wheat (*Triticum durum* L.) by up to 30%, was observed due to biochar application but there was no effect was noted on grain N content (Vaccari et al. 2011). Oguntunde et al. (2004) recorded increases of 91 and 44% in grain and biomass yield, respectively, in maize (Zea

**Table 11.1** Influence of biochar application on crop yields based on the literatures

| Crops | Bio char feed stocks | Type of soil | Doses | Yield response | References |
|---|---|---|---|---|---|
| Amaranthus | Water hyacinth, domestic organic waste | Calcareous Fluvisols | 10 t $ha^{-1}$ | 17–64% increase in yield | Piash et al. (2019) |
| Lettuce | Fecal matter | Silty loam and sandy loam | 0,10,20,30 t $ha^{-1}$ | Increased crop yield | Woldetsadik et al. (2017) |
| Maize | Corncob | Alfisols | 2% w/w | Increased crop yield | Mensah and Frimpong (2018) |
| Cotton | Hardwood | Fine, kaolinitic, thermic Rhodic Kandiudults | 0, 22.4, 44.8, 89.6, and 134.4 Mg $ha^{-1}$ | No difference in yield | Sorensen and Lamb (2016) |
| Corn | Hardwood | Fine, kaolinitic, thermic Rhodic Kandiudults | 0, 22.4, 44.8, 89.6, and 134.4 Mg $ha^{-1}$ | No difference in yield | Sorensen and Lamb (2016) |
| Peanut | Hardwood | Fine, kaolinitic, thermic Rhodic Kandiudults | 0, 22.4, 44.8, 89.6, and 134.4 Mg $ha^{-1}$ | No difference in yield | Sorensen and Lamb (2016) |
| Cotton | Corn straw | Inceptisol | 0, 5, 10, and 20 t $ha^{-1}$ | Increased yields by 8.1–17.1%, 9.6–13.5%, and 8.1–18.6% in 2013, 2014, and 2015, respectively | Tian et al. (2018) |
| Maize | Acacia wood | Clay | 50 + 50 Mg $ha^{-1}$ | Seasonal yield increase was average around 1.2 Mg $ha^{-1}$ | Katterer et al. (2019) |
| Soybean | Acacia wood | Clay | 50 + 50 Mg $ha^{-1}$ | Seasonal yield increase was average around 0.4 Mg $ha^{-1}$ | Katterer et al. (2019) |
| Corn | Pine chips | Ultisols (loamy sand) | 30,000 kg $ha^{-1}$ | No significant difference in yield | Novak et al. (2019) |

mays L.) on charcoal-amended soils when compared with adjacent field soils in Ghana. Likewise, almost double maize yield in degraded soils was obtained from application of Eucalyptus-derived biochar in in Kenya (Kimetu et al. 2008). Improvement of rice grain yield (upland) in soils with lower P availability was found with addition of biochar in Loas. However, at sites with low native N supply, biochar application reduced the leaf chlorophyll contents suggesting that biochar may reduce grain yield in N-deficient soils if additional N is not applied (Asai et al. 2009; Nelson et al. 2011). The effect on crop yields particularly in nutrient-rich soils remains uncertain. Several other studies have revealed only small improvements or even reductions in grain yield with biochar application in nutrient-rich soils (Deenik et al. 2010; Gaskin et al. 2010; Van Zwieten et al. 2010a). For instance, Gaskin et al. (2010) noted a linear decrease in grain yield with increasing rates of biochar application. Meta-analysis on biochar application and crop productivity (either yield or aboveground biomass) by Jeffery et al. (2011) documented an overall small (~10%) but significant improvement in grain yield from biochar application, and identified a liming effect and increase in soil WHC as principal reasons for biochar-induced yield gain (Jeffery et al. 2011). Among biochar feedstocks, poultry litter was the best (28%), while biosolids had a negative effect (−28%) on crop productivity (Jeffery et al. 2011). In another study conducted for 3 years by Feng et al. (2014) reported that annual yield of either summer maize or winter wheat was not enhanced significantly due to biochar application; however, cumulative yield over the first 4 growing seasons were significantly higher. Spokas et al. (2012) analysed 44 published articles on biochar and found that about half of them claimed biochars improved crop yield while the others had no or negative effect on crop yield. Biochar-induced increases in specific surface area, CEC, soil porosity (Thies and Rillig 2009), WHC, nutrient retention (Glaser et al. 2002; Lehmann and Rondon 2006; Yamato et al. 2006), and liming effect (Rondon et al. 2007; Liu et al. 2013) are mainly responsible for improved crop productivity. For example, biochar obtained from crop biomass ashes can provide a P source similar to that of commercial P and K fertilizer (Schiemenz and Eichler-Loebermann 2010; Luo et al. 2014) or may improve the supply of Ca and Mg (Major et al. 2010).

Biochar amendment has a synergistic effect with fertilizers in improving crop yield; for example, maize yield increased with biochar and fertilizer application more than fertilizer alone in acidic soil in Indonesia (Yamato et al. 2006). In another study, Steiner et al. (2007) harvested 4–12 times more rice and sorghum (*Sorghum bicolor* L.) yield by application of charcoal (11.25 t $ha^{-1}$) with compost and/or fertilizer than by using fertilizer alone. Similar results on biochar induced doubling of rice and sorghum grain yield was reported while applied with NPK fertilizers (Christoph et al. 2007). Mau and Utami (2014) also recorded increase in maize yield due to increased P availability and uptake under combined application of biochar and inoculation of AM fungal spores; however, biochar amendment alone did not improve maize growth or P uptake. In a field study conducted on a boreal sandy clay loam, biochar as soil amendment (10 t $ha^{-1}$) improved grain numbers in wheat (dry year) probably by alleviating the water deficit (Tammeorg et al. 2014). In crux, biochar application has the potential to improve crop productivity on a variety of soils under normal and less than optimal environmental conditions if prepared and used wisely.

### *11.1.2 Soil Health Management*

Soil health is the capacity of a soil to sustain biological productivity, environmental quality and promote plant and animal health through self-regulation, stability, resilience and lack of stress symptoms within ecosystem boundaries. Although, another terminology ‘Soil Quality’ has often been used simultaneously, they involve two different concepts. What constitutes a high-quality soil may depend on the intended use or the role of soil management system. For example, a good quality soil for engineering construction many not suited for agricultural production (Brady and Well 2012).

Let’s have an example of Soil Health of *Terra Preta* (= Dark in Portuguese) soil of Amazon basin. In general, the highly weathered Oxisols and Ultisols of Amazon basin are dominated by iron and aluminium oxides clays. Due to high soil acidity and low Cation Exchange Capacity (CEC) these soils possess very low level of soil fertility, have little capacity to sustain nutrients and therefore poor in health. Conversely, soil scientists exploring this area were mystified and surprised when they found around twenty hectares of dark coloured, high organic matter containing, fertile healthy soils along the Amazon river and some of its tributaries. When they conducted $^{14}C$ isotopic study they found that most of the carbon of these soils were accumulated several thousand years ago. Now it is believed that these patches of highly fertile healthy soils were created by the ancient dwellers of that vicinity that lived in miniature agricultural settlements carved out of the Amazon rainforest. These dwellers farmed this soil regularly for many years in such a way that they enhanced the soil health rather than degraded by agricultural use. Even today some of the *Terra Preta* soils are dug and sold in local markets for their high fertility value. Soil analysis revealed that *Terra Preta* soils are rich in calcium and phosphorus than that of the surrounding soils of Amazon basin because of the amendments with human excrement and bones of animals eaten by the ancient inhabitants. However, the unique aspect of these soils is that much of the carbon in them is present as Charcoal. The complex aromatic structure makes the charcoal recalcitrant because of its resistance to microbial degradation results in very high and stable accumulation of organic carbon as well as high nutrient availability for plant growth. Again, the small bits of charcoal found in Terra Preta soils are very porous in nature that greatly enhances water holding capacity of these soils and capacity to retain nutrients in the form of dissolve organic compounds. Thus soil scientists studying the effect of this unique anthropogenic activity on soil health reported that adding charcoal or biochar to soils may significantly enliven soil health and make the soil defiant to degradation in agricultural use. It is also reported that the conversion of biomass carbon to biochar leads to sequestration of about 50% of the initial carbon compared to the low amounts retained after burning (3%) and biological decomposition (less than 10–20% after 5–10 years) (Lehmann et al. 2006).

Soil Health with application of biochar may be governed by a number of physicochemical and biological attributes and processes and expressed by different quantitative and qualitative measures of these attributes as also by outcomes that are

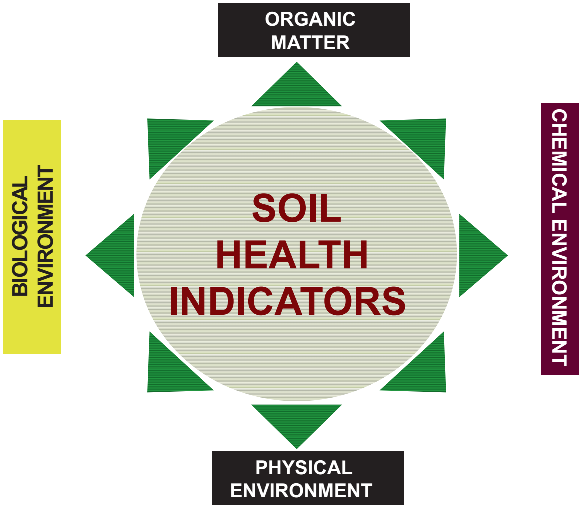


**Fig. 11.1** Indicators of soil health

governed by the soil such as productivity, nutrient and water use efficiencies and quality of produce. Gaunt and Lehmann, (Gaunt and Lehmann 2008) pointed out that the application of biocahr may improve soil health by altering its physical, chemical and biological environment principally by improving soil organic carbon status. Therefore, apart from soil physical, chemical and biological environment organic matter must be kept as distinct indicator of soil health (Fig. 11.1).

#### 11.1.2.1 Soil Physical, Chemical and Biological Health

Hypothetically, four mechanisms have been proposed to elucidate how application of biochar might help in improvement of soil physico-chemical and biological health. These are: (1) direct modification of soil chemistry through inherent chemical composition of biochar. (2) provides chemically active surfaces that alters the dynamics of available nutrients or otherwise catalyze important soil reactions and (3) modifies physical character of the soil in a way that benefits root growth and/or nutrient and water retention and acquisition and (4) modifies soil biological health through priming effect.

The first mechanism may result in a momentary shift in crop productivity in positive direction; the extent and duration of which will be governed by the natural phenomenon of biochar weathering and the upshots of crop uptake. This could happen where the biochar has considerable mineral nutrients content, or equally enhance in CEC in due course of time as the weathering progress. The benefits provided by the second and third mechanisms depend upon recalcitrant nature of biochar. It depends upon the half life of biochar carbon that principally varies depending on feed stock and temperature at which biochars are produced and may also accordingly be finite, even though over a much longer period of time. This would include the impact of pours biochar on water retention or lowering bulk density and increasing the total porosity of soil. The fourth mechanism of priming effect depicts about raise in soil organic matter decomposition rate after addition of fresh organic matter in soil which is often supposed to as a result from escalation of microbial activity on account of higher availability of energy released from decay of fresh organic matter (Zimmerman et al. 2011). However, both positive and negative priming have also been reported by earlier workers (Wardle et al. 2008; Kuzyakov et al. 2000; Kuzyakov 2010; Zimmerman et al. 2011). Possible causes of positive priming might be the positive co-metabolic effect of labile part of organic matter on growth of microorganisms and provision of habitat for microbes that protects them from predation and simultaneously supports microbial growth through co-locating labile organic matter on surfaces of the biochar. Other mechanisms include altering soil reaction, availability of nutrients and/or water holding capacity, which have a say in positive priming (Fontaine et al. 2003). Probable reasons of negative priming are adsorption of organic matter through encapsulation and absorptive protection where encapsulation takes place within biochar pores that exclude biota and their extracellular enzymes from access to the organic matter and absorptive protection onto external bio-char surfaces. Biochar induced stabilization or protection of comparatively labile organic matter in soil within organo-mineral fractions and a transient shift of microbial communities to exploit relatively more labile C in biochar, a phenomenon known as preferential substrate utilization, may also contribute to negative priming and predominant in low C soil receiving nutrient application (Fontaine et al. 2003).

The magnitude and relative importance of first three mechanisms in a particular setting will evolve over time as the slow process of chemical and physical modification results in a gradually increasing concentration of smaller, partially oxidized particles.

#### 11.1.2.2 Soil Fertility

Soil fertility is the capacity of the soil to supply nutrients to plants in adequate amounts and in suitable proportions to produce crop of economic value and to maintain soil health. The addition of biochar to agricultural soil is receiving considerable interest because of its positive impact on soil fertility (Quayle 2010). At local scale, increase in soil organic carbon levels due to addition of biochar shape agro-ecosystem function and influence soil fertility by altering soil physical, chemical and biological properties (Milne et al. 2007). The ability of soil to retain nutrients can be increased using biochar (Sohi et al. 2010). Biochar application reduces leaching loss of soil nutrients, enhances plant nutrient availability, reduces toxicity of aluminium to plant roots and micro-biota in acid soils and bio-availability of heavy metals like Pb, Cd etc. (Lehmann et al. 2006; Rondon et al. 2005; Yanai et al. 2007; Mukherjee and Lal 2014). It reduces soil acidity (Zwieten et al. 2010), sequesters recalcitrant carbon in soils and thus improves soil fertility and mitigate climate change (Fowles 2007; Glaser et al. 2002; Laird 2008; Lehmann 2007a, b; Lehmann et al. 2006; Marris 2006; Sohi et al. 2010). This help to uphold the growth of microbes specially the bioactivity of beneficial soil microorganisms (Marris 2006), improves soil organic matter and consequently plant growth (Sanchez et al. 2009; Glaser et al. 2002), soil porosity. Reduces bulk density and improved water holding capacity of soil (Rasa et al. 2018). Biochar has the potential to boost up conventional agricultural productivity and augment the capacity of the farmers to play a part in carbon markets ahead of the routine approach by directly applying carbon into the soil (McHenry 2009). The combined application of biochar along with inorganic fertilizer has the potential to increase crop productivity, therefore providing additional income, and reducing quantity of inorganic fertilizer use and importation (De Gryze et al. 2010; Quayle 2010).

## 11.2 Biochar in Environmental Management

In recent time research interest on use of biochars produced from different feedstock as environmental management is increasing prominently. Earlier research reports on positive impact of biochar application on seedling growth (Retan 1915) and soil chemistry (Tryon 1948) are available. According to Lehmann (2009) and Schmidt et al. (2002) biochar contains higher percentage of recalcitrant organic C which is more stable (hundreds to thousands of years) in soil than any other commonly used amendments and also enhances the availability of nutrients and maintain soil quality beyond a fertilizer effect. Biochar can be used for environmental management through improving productivity, reduce pollution, climate change mitigation, waste management and energy production. In this section we will discuss the use of biochar in environmental management from the fact of its ability to soil carbon sequestration, mitigation of greenhouse gas (GHGs) emission and soil and water pollution.

### *11.2.1 Soil Carbon Sequestration*

Soil carbon sequestration is a process of long term or permanent (100 years) storage of $CO_2$ from atmosphere to soil (Stockmann et al. 2013; Shin et al. 2019). Biochar is a carbon rich product derived from biomass burning in anaerobic environment, it contains high amount of recalcitrant organic carbon and least prone to chemical and microbial degradation and remain in soil for hundreds to thousands of years increasing soil carbon storage capacity (Schmidt et al. 2002; Roberts et al. 2010; Wang et al. 2014a; Lehmann 2007b), can improve soil physicochemical property, fertility and crop productivity. Highly porous, high cation exchange capacity, larger surface area and adsorption ability are some significant properties of biochar (Luo et al. 2016). As soil amendment; biochar is a good carbon sequester and is suggested as an effective countermeasure for increasing GHGs emission to atmosphere (Lal

1999; Mukherjee et al. 2014; Deng et al. 2017). An increase (0.4% per year in global scale) of agricultural soil organic carbon due to biochar addition can compensate global emission of GHGs by anthropogenic sources (Minasny et al. 2017). Downie et al. (2011) reported significantly elevated soil carbon stocks, compared to the adjacent soil in a 650 and 1,609 years old historic charcoal added soil in ancient Australian Aboriginal oven mounds. Biochar can be implemented in global scale to mitigate climate change by potentially sequester up to 12% of anthropogenic GHGs emissions (Woolf et al. 2010) in an ecologically sustainable system. Biomass like straw, when converted to biochar through gasification process contain aromatic carbon compounds having high stability and potential for carbon sequestration than the original feedstock in amended soil (Hansen et al. 2015, 2016; Wiedner et al. 2013). Along with reduced soil organic carbon decomposition, biochar can also adsorb significant amount of soil- dissolved carbon (Lu et al. 2014). Hailegnaw et al. (2019) also reported reduction of nitrate and dissolved organic carbon in soil amended with wood chip biochar. In a study by Béghin-Tanneau et al. (2019) documented significant ability of anaerobically digested exogenous organic matter (EOM) to sequester carbon in soil compared to undigested EOM. It was due to higher stability and negative priming effect of digested-EOM that reduced native soil organic matter (SOM) respiration compared to low stability and positive priming effect of undigested-EOM that enhanced native SOM respiration. Béghin-Tanneau et al. (2019) also noted a reduction of $CO_2$ emission by 27% along with carbon sequestration compared to maize silage amendment in soil. Huang et al. (2018) found reduction of $CO_2$ flux from a rape-maize cropping system with increased net C sequestration without reducing crop yield and net primary productivity under sole biochar treatment compared to straw, straw with straw decay bacterium, mixed straw and biochar treatment. This may be due to lower labile organic carbon (LOC), especially microbial biomass carbon fraction in biochar treated soil. While increase $CO_2$ emission from crop straw added soil is because of availability of higher C substrate for microorganism causing lower carbon sequestration (Dendooven et al. (2012). Chemical property of biochar, such as lower hydrogen to carbon (H/C) and oxygen to carbon (O/C) ration makes it highly stable for microbial degradation (Schimmelpfennig and Glaser 2012). Similarly, Hansen et al. (2015) also found higher microbial degradation of straw carbon compared to straw gasification biochar resulting in 80% of added straw carbon respiring as $CO_2$ compared to 3% of the biochar added after 110 days of incubation. This indicates the potentiality of the biochar in soil carbon sequestration. Although, some researcher documented negative response of biochar amendment to crop yield such as lettuce and ryegrass (Marks et al. 2014). While biochar pellet blended with biochar and pig manure compost (4:6 ratio) application was found effective for carbon sequestration in rice cultivation without decreasing crop yield (Shin et al. 2019). Thammasom et al. (2016) noted an increase of soil carbon sequestration (1.87 to 13.37 tons $ha^{-1}$) with application of wood biochar, while a reduction (0.92 to 2.56 tons $ha^{-1}$) of the same was noted under rice straw application. Kimetu and Lehmann (2010) documented reduced loss of soil $CO_2$–C by 27% under biochar application contrarily *Tithionia diversifolia* green manure increased soil $CO_2$ C loss by 22%, while biochar also increased intra aggregate C per respired C by 6.8 times relative to the *Tithionia diversifolia* green manure additions, indicating more efficient stabilisation capacity of biochar. Charcoal produce from sustainable system using biomass on application to soil can remove carbon from short term photosynthesis cycle to long term reservoir. Thus the energy generated through biochar production can be certified as carbon negative and can act as revenue source from both sale and tradable carbon credits by virtue of increase forest cover and reduce greenhouse gases emission (Mathews 2008). Pyrolysis temperature plays a crucial role on aromaticity of the produced biochar (Yip et al. 2010), which in turn affect the recalcitrance property in soil and thus the carbon sequestration potential. As an option to carbon sequestration, reduce or delay nutrient leaching like nitrate is beneficial for both environment and plants (Liu et al. 2017a; Ghorbani et al. 2019). Holding nutrients for long and improving soil aggregation, biochar application can consequently mitigate $CO_2$ emission (Xu et al. 2011a). Biochar production method greatly affect the carbon sequestration capability. In a study Santín et al. (2017) found lower carbon sequestration potential of wildfire charcoal produced at high temperature than the most slow-pyrolysed biochars. Their findings challenge the common opinion "natural charcoal and biochar are well suited as proxies for each other".

### *11.2.2 Greenhouse Gas Emission*

Mitigation of greenhouse gas emission is an area of growing importance and concern due to global warming and increasing rate of GHG emission globally. $CO_2$, $CH_4$ and $N_2O$ are three main greenhouse gases responsible for 90% of anthropogenic climate warming (IPCC 2013). IPCC (2013) also reported an increase of global average surface temperature by 0.85 °C during 1880–2012 based on multiple independently produce datasets and suggest an increase of 0.3–4.8 °C temperature by the end of this century. Environmental management through greenhouse gas mitigation include reduction and avoidance of emission along with removal of GHGs existing in the atmosphere (Smith et al. 2007a). Choosing biochar as soil amendment is an approach to mitigate climate change by reducing greenhouse gas emissions from soil. Application of biochar in soil has direct and indirect influence on soil physico-chemical properties, soil microbial diversity, abundance and function of soil microbial diversity that in turn affect production and emission of greenhouse gas. However, the potentiality of biochar in reducing GHG emission is controversial. Soil GHG significantly decreased or remain unchanged in some studied (Case et al. 2014; Quin et al. 2015; Liu et al. 2016; Scheer et al. 2011) while increased in others (Wang et al. 2012; He et al. 2017; Song et al. 2016). Some of the variables that influence the GHGs emission from soil environment under biochar treatments are study duration, soil texture and pH, feedstock used for biochar preparation, pH of the produced biochar and application rate and vegetation (Sohi et al. 2010; Woolf and Lehmann 2012; Hilscher and Knicker 2011; Lorenz and Lal 2014). Jones et al. (2011b), Luo et al. (2017) and Liang et al. (2010) documented the effect of biochar application on soil bulk density, pH, water holding capacity, cation exchange capacity, carbon and nitrogen dynamics and plant productivity, which have a significant effect on soil $CO_2$ and $N_2O$ emissions. According to He et al. (2017); application of fertilizer and experimental condition influence $CO_2$ emission; they noted significant increase in $CO_2$ emission when biochar was applied in unfertilized soil, while it decreased when applied in fertilized soil in laboratory condition, but did not find any significant effect of biochar in field condition. Sun et al. (2014) found that biochar application in the at a rate of 30 t $ha^{-1}$ reduced (31.5%) $CO_2$ emission from a pine forest soil. While in a field experiment in paddy soil amended with wheat straw biochar enhanced $CO_2$ emissions (12%), but $N_2O$ emissions was reduced (41.8%) (Zhang et al. 2012b). However, studies of Wang et al. (2014b), Malghani et al. (2013) and Zhou et al. (2017) revealed no significant effect of biochar on $CO_2$ emission. Elevated $CO_2$ emission was noted in a temperate forest soil under application of sugar maple biochar at a rate of 5, 10 and 20 t $ha^{-1}$ (Mitchell et al. (2015). Hawthorne et al. (2017) also reported significantly greater $CO_2$ fluxes from application of 10% biochar compared to 1% biochar in a Douglas-fir forest soil. The enhancement of $CO_2$ emission might be the addition of labile C from biochar and increased belowground net primary productivity (BNPP) (Zimmerman et al. 2011; Yoo and Kang 2012; Mukherjee and Lal 2013). While the cause behind suppressed $CO_2$ emission might be the absorption of soil $CO_2$ molecules by the large biochar surfaces and reduced enzymatic activity of microbes (Case et al. 2014; Liang et al. 2010; Liu et al. 2009).

Widespread use of synthetic nitrogen (N) fertilizer is the primary cause of agricultural soil emission of $N_2O$ (Smith et al. 2008b). Rondon et al. (2005) first reported reduction in $N_2O$ emissions in a greenhouse experiment after biochar amendment in soil. They recorded reduction of $N_2O$ emissions by 50% under soybean cropping and by 80% for grass growing in a low-fertile oxisol. In a meta-analysis of biochar effect on $N_2O$ emissions both in long and short term studies, Cayuela et al. (2015) found that soil $N_2O$ emissions was reduced by 54 ± 3% at lab scale and 28 ± 16% at the field scale. Sun et al. (2014) also noted a significant decreased of cumulative $N_2O$ emissions (25.5%) in a pine forest, when biochar was incorporated to the soil at 30 t $ha^{-1}$. Bass et al. (2016) found an interaction of cropping system with biochar on $N_2O$ emission, they noted a decrease of $N_2O$ emission under papaya cultivation while no effect was noted under banana cultivation. Fidel et al. (2019) noted a suppressive effect of biochar on $N_2O$ emission in a continuous corn cropping system while did not found any effect on $CO_2$ emission. They also suggested that both soil moisture and temperature play role in $CO_2$ and $N_2O$ emission. Contrastingly enhanced emission of soil $N_2O$ was recorded by Hawthorne et al. (2017) in a forest soil when 10% biochar was applied but did not find any significant effect under 1% of biochar application. Cayuela et al. (2013) also found direct correlation between $N_2O$ emission and biochar application rate. While in a study in temperate hardwood forest, no significant effect was noted for 5 t $ha^{-1}$ biochar application on soil $N_2O$ emission (Sackett et al. 2015). The primary mechanism of reduction of soil $N_2O$ emission by biochar application might be the increased oxygen in soil due to soil aeration, which will inhibit denitrification of soil by microorganisms, that mostly occurs in low oxygen condition (Bateman and Baggs 2005; Taghizadeh-Toosi et al. 2011; Van Zwieten et al. 2010b; Hale et al. 2012). Another reason is absorption of inorganic nitrogen pool ($NH^{4+}$, $NO^{3-}$ etc) by the biochar (Cornelissen et al. 2013b), which in turn will decrease nitrogen availability for nitrifiers and denitrifiers, reducing $N_2O$ emission (Singh et al. 2010a; Clough et al. 2013). While rises in $N_2O$ emissions may be due to increased soil water content influenced by biochar addition, that helps denitrification, or due to release of biochar embodied-N (Lorenz and Lal 2014). Soil pH is another important factor which is influenced due to biochar addition. An optimum rage of pH is preferable for reducing $N_2O$ emission from agricultural soil because denitrifies have a wider pH optimum in the range of pH 4–8, while for the nitrifiers, the optimum range of pH is slightly acidic to slightly alkaline (Mørkved et al. 2007; Liu et al. 2010).

Biochar is also used to reduce the emission of soil methane ($CH_4$). Chicken manure biochar (10%, w/w) was found to significantly increase $CH_4$ uptake in forest soils (Yu et al. (2013). Xiao (2016) reported significantly higher efficiency of biochar in $CH_4$ uptake regardless of the application rate in a chestnut plantation in china. While, Sackett et al. (2015) reported no significant difference in $CH_4$ flux in biochar-treated and control soils in a temperate hardwood forest. Hawthorne et al. (2017) observed contrasting results, where significant reduction in soil $CH_4$ uptake under biochar application (1 or 10% w/w) was noted. This increased uptake of $CH_4$ in soil might be due to increase soil pH under biochar addition, which in turn facilitate the growth of methanotrophs (Jeffery et al. 2016; Anders et al. 2013) along with biochar induced decrease in soil bulk density and porosity favours aerobic methanotrophs and $CH_4$ oxidation and uptake by soil microbes (Brassard et al. 2016; Feng et al. 2012; Karhu et al. 2011; Van Zwieten et al. 2009). Enhanced $CH_4$ emission might be ascribed to the chemicals inhibitory effect of biochar on soil methanotrophs (Spokas 2013). Thus, the efficacy of biochar for GHGs mitigation is largely uncertain due to various factors involved in the reduction and enhancement of soil GHG emissions.

### *11.2.3 Soil and Water Pollution*

Anthropogenic contaminants caused by rapid urbanization and industrialization are triggering degradation of water and soil quality in ecological environment. Soil and water are two basic needs for survival of lives. Soil serves as the main medium for plant growth, support human and animals, sustain plant and animal productivity, improve the quality of water and air (Zhou and Song 2004; Zhang et al. 2012c). Soil pollution can be remediated through physical, chemical and biological methods (Mendez and Maier 2008), but physical and chemical methods are not suitable for large scale management of arable soil, due to higher cost and the disadvantages of complexity and secondary pollution (Houben et al. 2013). Though biological remediation approaches are cheap and feasible, but its efficiency on improvement of soil quality is not constant because of its susceptibility to environment (Arthur et al.

2005) Biochar seized attention as a promising multi-beneficial remediating agent to stabilize soil contaminants, such as organic molecules, heavy metals, pesticides, herbicide etc. (Kong et al. 2014; Cheng and Lehmann 2009; Yuan et al. 2018; O'Connor et al. 2018). It acts as a soil conditioner via enhancing cation exchange capacity (CEC), pH and water holding capacity. Inorganic nutrients such as potassium, phosphorous, calcium, silica, boron and molybdenum are added to soil, making them bioavailable for plants as biochar is rich in inorganic nutrients derived from the feedstock (Page-Dumroese et al. 2015; Liu et al. 2014; Xiao et al. 2018; Xu et al. 2013). Cao and Harris (2010) confirm increased availability of nutrients (P, Mg and Ca) with increase of pyrolysis temperature. Moreover, addition of biochar to soil may effectively reduce eutrophication of nearby water bodies, and also underground waters pollution due to reduced leaching of nitrogen and phosphorus (Laird et al. 2010; Kookana et al. 2011). Soil contaminated with both organic and inorganic pollutants can be remediated with addition of biochar by reducing toxin bioavailability by both organic and inorganic pollutants (Ajayi and Horn 2017; Yao et al. 2012). Among the inorganic pollutants; heavy metals are non-biodegradable and persist in soil for very long (Sun et al. 2008). Thus lowering bioavailability of heavy metal is crucial to remediate contaminated soil. Biochar have negatively charged surfaces and functional groups that can strongly attract (electrostatic adsorption, ion exchange) metal ions having small ionic radii and high charges, or can stabilized metal via complexation or precipitation due to high soil pH introduced by biochar (Kong et al. 2014; Kumar et al. 2018; Mukherjee et al. 2011; Lu et al. 2012; Li et al. 2017). Biochar can transfer soluble metals forms to insoluble one by binding it to organic matter, oxides, carbonates and can fixed in soil (Xiao et al. 2018). It can also stabilize heavy metals through reduction. Choppala et al. (2015) reported efficiency of chicken manure biochar and black carbon for reducing Cr(VI) (extremely toxic and highly mobile) to Cr(III) (generally nontoxic) and subsequent immobilization in soils. Pyrolysis temperature of biochar plays an important role in removal efficiency of metal by biochar. Wang et al. (2018) reported better removal efficiency of higher temperature pyrolyzed biochar for Hg than biochar pyrolized at lower temperature. Contrastingly, Cao et al. (2009) reported dairy manure biochar pyrolyzed at 200 °C have better potential to remove Pb from soil than the same biochar pyrolyzed at 350 °C. Skjemstad et al. (2002) and Cheng et al. (2006) documented effectiveness of bamboo biochar to adsorb Cu, Ni, Hg and Cr from both water and soil, and Cd only in contaminated soil. While cotton stalk biochar can reduce Cd bioavailability in polluted soil through adsorption or co-precipitation (Zhou et al. (2008). Salt affected soil can also be remediated to a larger extend with addition of biochar, that reduce salt stress and enhanced plant growth and improve soil nutrients which in turn will counteract the adverse effect of Na (Kim et al. 2016; Wakeel 2013). Cao et al. (2011) and Jones et al. (2011a) reported reduction (66–97%) of pesticides such as atrazine, simazine, carbaryl and ethion, when biochar was applied to soil. Zhelezova et al. (2017) reported absorption of two herbicides, glyphosate (N-(phosphonomethyl)-glycine) and diuron (3-(3,4-dichlorophenyl)-1,1-dimethylurea) by biochar. They also noted a decrease of adsorption by aged biochar comparison with freshly prepared biochar. Similarly, Martin et al. (2012) also found reduction (47%) of sorption by aged biochars for herbicide diuron. However, Trigo et al. (2014) found that, in some cases, biochar could serve for at least 2 years as effective sorbent of herbicides (indaziflam and fluoroethyldiaminotriazin). Polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) in water and soils can also be removed by incorporation of biochar (Wang et al. 2013a; Beesley et al. 2010). Apart from persistent organic pollutant (POPs) such as PAHs, PCBs, PCDD (polychlorinated dibenzo-p-dioxins) and DFs (dibenzofurans), some emerging organic pollutants such as phthalate acid esters (dibutyl phthalate and di(2-ethylhexyl) phthalate), pharmaceutical and personal care products (PPCPs, trimethoprim and triclosan), naturally released estrogenic steroid hormone and its metabolites (estradiol and estrone) are becoming threat to the soil quality (WHO 2010; Petrović et al. 2001).

Biochar has been reported to be very effective in the uptake of a variety of organic chemicals including fungicides, pesticides, PAHs, and emerging contaminants such as steroid hormones (Beesley et al. 2010; Kookana et al. 2011; Song et al. 2012; Sarmah et al. 2010). Qin et al. (2013) also found significantly higher removal efficiency of contaminants with rice straw biochar on petroleum-contaminated soil than that of the unrestored soils. Molecular diameter of contaminants determines the strength of biochar sorption. Small molecules can penetrate to the micro and mesopores of biochar, while larger molecules tend to adsorb on the biochar surface, that may block pores (Nguyen et al. 2007).

Thus, biochar can improve the physicochemical properties of degraded land and immobilize both organic and inorganic pollutants, based on feedstocks, production methods, application rates, soil types and age of biochars (Obia et al. 2016). Despite the immense benefits of biochar, it can also be harmful if it contains PAHs, chlorinated hydrocarbon, dioxin and heavy metals derived from carbonization temperature and feedstock chosen (Chagger et al. 1998; Brown et al. 2006; Singh et al. 2010b). Therefore, to remediate polluted soil by applying biochar emphasis should be given in selection of proper feedstock and pyrolysis condition.

Removal of contaminants from water is most commonly done by chemical precipitation employing hydroxide, sulfide, phosphate and carbonate (Sharma and Bhattacharya 2017). But it creates problem when the sludge produced during chemical precipitation need to dispose. Biochar is a low cost sorbent for contaminants and pathogens, can absorb hydrocarbons, dyes, phenolics, pesticides, PAHs, antibiotics, inorganic metal ions. Potentiality of biochar as water purifier has been studied by many researchers (Klasson et al. 2013; Tong et al. 2011). Biochars obtained from straw and bamboo were reported to remove dyes from wastewater (Xu et al. 2011b; Yang et al. 2014), that were stable to light, oxidizing agents and aerobic digestion during conventional waste treatment. Xu et al. 2011b also documented efficiency of biochar derived from canola straw, peanut straw, soybean straw, and rice hulls to remove methyl violet from water.

## 11.3 Factors Influencing the Efficacy of Biochar

A range of process conditions like the feedstock composition, temperature and heating rate during pyrolysis can be optimized to obtain diverse amounts and properties of biochars. The physiochemical properties of biochars contribute to their function as a tool for environmental management (Lehmann and Joseph 2009).

Feedstock materials and temperature duringpyrolysis mostly influence the nutrient content in biochar. Screening Electron Micrograph (SEM) images of biochar material shows its resemblance with the composition of feedstock materials. Loss of nutrient during production is affected by the pyrolytic temperature. The concentration of nutrients like nitrogen reduces with increasing rate of pyrolytic temperature while, the availability of phosphorus increases. This nutrient content finally affects pH and electrical conductivity of the produced bichar (Chan and Xu 2009; Singh et al. 2010b). Maximum biochar yield obtained from low operational temperatures and low heating rate (Kwapinski et al. 2010). With increasing operational temperature, biochar yield decreases but the concentration of carbon increases. Biochar produced at high temperature have a high surface and also highly aromatic in nature that results it chemically recalcitrant (Keiluweit et al. 2010; Chen et al. 2011). Therefore, biochar produced at low temperature are considered to be more reactive in soil which have a less condensed carbon structure contributing soil fertility (Singh and Cowie 2008; Steinbeiss et al. 2009).

Higher reactivity of the biochar surfaces with soil particles is partly attributed to the presence of a range of reactive functional groups. Surface area of biochar increases with increasing HTT (High Heating Temperature) until it reaches the temperature at which deformation occurs, resulting subsequent decrease in surface area. The fundamental physical changes that occur in biochar are all temperature dependent. Heating rate and pressure affect the physical mass transfer of volatiles evolving at the given temperature from the reacting particles. Lua et al. (2004) reported that with increasing pyrolytic temperature from 250 °C to 500 °C, the Brunauer–Emmett–Teller (BET) surface area of biochar also found to increase.

## 11.4 Constrains of Biochar Application

Research related to biochar and its application has developed with time and important key findings were found related to agriculture, forestry, and global environment. More research in this field is required as the benefits vary from soil to soil and various other parameters like feedstocks, production of biochar, etc. Vaccari et al. (2015) reported that the effect of biochar on agricultural productivity also depended on plant species. Therefore, a synergetic effort is required to understand the limitations in biochar applications and the problems related to its applications. In a study carried out by Anyanwu et al. (2018), it was reported that aged biochar has a negative effect on the growth of both earthwarm and fungi in soil ecosystem. Studies also found that the aged biochar also led to reduction in underground root biomass of *Oryza sativa* and *Solanum lycopersicum*. Biochars also found to reduce the soil thermal diffusivity. In addition, an increase in weed growth was found with higher rate of biochar application. Khorram et al. (2018) found 200% increase in weed growth with an application rate of 15 t $ha^{-1}$ of biochar. A delay in flowering of plant was also reported in some studies with addition of biochar.

In some cases, biochar also act as a soil contaminant due to the presence of some chemical compounds that may be form during the conversion processes. Studies are needed to see the presence of heavy metals and the plant-available organic compounds on the biochar surface. According to some researchers, these compounds may act as a fungicide or bactericide on the other hand; some others reported that they can serve as carbon source for some microbes (Painter 2001; Ogawa 1994). Also to understand the long term effect of biochar, a long term field study should be done on different soil types using biochars. Lack of long term studies on biochar application limits the actual scenario where various natural parameters are active. Moreover, the cost related to the feedstock preparation, biochar production, transportation and application is full of uncertainties that need to be clear.

There is also lack of a uniform system for the classification and governance regarding the commercialization of biochars for land and other applications. This will be helpful to the consumers in using biochar for various applications. The environmental agencies of different locations can play an active role regarding this issue. No standard biochar rate for application is available for specific type of soil regarding specific result. There is also lack of a decision support system for choosing a particular type and rate of biochar to fulfill a particular need. Mechanisms related to biochar-soil interaction are very complex and multiples assumptions have been made. In recent years, biochar is attracting a huge attention in the research field. The research outcome should be updated and make available for the benefit of people to apply on practical field.

## 11.5 Nano-biochar and Its Prospects

Biochar is gaining a huge attention in recent time from scientists, policymakers, farmers, and investors due to its properties that directly or indirectly helps humankind. Bulk biochar mostly applied for agronomic and environmental purposes. Recent studies found that generation of nano biochar (N-BC) from the physical degradation of bulk biochar (B-BC). Nano biochar is characterized by having a size smaller than 100 nm than the bulk biochar (Wang et al. 2013b; Chen et al. 2017). Due to its size, nano biochar have an excellent mobility both in soils and water and can act as a carrier particle for natural solutes and contaminants (Ahmad et al. 2014; Lian and Xing 2017). With increasing the application of biochar in soil, the degree of formation of nano biochar will increase. However, the knowledge on the formation of nano biochar particle is much limited. Some mechanisms that results in the formation of nano biochar are pore collapse and matrix fracturing during production of biochar and also weathering process in the environment. The carbon matrixes that can be easily fragmentized are readily mineralized through various chemical and microbial processes (Lin et al. 2012; Warnock et al. 2007). Degradation and conversion of nano biochar from the bulk biochar can be against longevity of biochar within soil systems. Due to its size particle and mobility, the toxic effects of nano biochar is considered more than the bulk biochar (Wang et al. 2016). Exposure of nano biochar may also trigger risks to organisms in waters and soils. It is considered that hetero aggregation formation can prevent the vertical transport of these nano biochar in soil ecosystem and therefore weaken its negative effect.

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