Chapter 9
Soil Health Management Through Low Cost Biochar Technology

Shaon Kumar Das and Goutam Kumar Ghosh

Abstract The utilization of biochar as an amendment to improve soil health and the environment has been a catalyst for the recent global enthusiasm for advancing biochar production technology and its management. Biochar is simply carbon rich charcoal-like substance which is created by heating biomass (organic matter) in limited oxygen condition, through a process known as pyrolysis. Locally available weed biomass which is not economically important and caused crop loss can be used as an important source of biomass for preparation of biochar. Biochar is able to ameliorate soil acidity as well as it is also able to increase the soil fertility. Biochar reduces leaching of soil nutrients, increases soil structure and pH, reduces dependency on artificial fertilizers, enhances nutrient availability for plants, increases water quality of runoff, reduces toxicity of aluminum to plant roots and microbiota and thus reducing the need for lime, reduces bioavailability of heavy metals, thus works as bioremediation and decreases N_2O and CH_4 emissions from soils, thus further reducing GHG emissions. Employment of biochar as a specialized soil amendment provides a practical approach to address the anticipated problems in the agronomic and environmental sectors. Incorporating huge quantity of biochar into soils provides numerous agricultural benefits, which this special paper examines. But, there is no concrete compilation yet how to apply biochar at farm level. This paper discusses on several factors related to biochar that need to be considered for maximising the soil amelioration and soil quality benefits from the use of biochar.

Keywords Amendment · Biochar · Charcoal · GHG emissions · Soil nutrients

S. K. Das (✉)
ICAR-National Organic farming Research Institute, Gangtok, India

G. K. Ghosh
Palli-Siksha Bhavan, Visva-Bharati, Sriniketan, West Bengal, India

J. S. Singh, C. Singh (eds.), *Biochar Applications in Agriculture and Environment Management*, https://doi.org/10.1007/978-3-030-40997-5_9

9.1 Introduction

Biochar is carbon rich charcoal-like substance which is created by heating biomass (organic matter) in a limited oxygen conditions, a process known as pyrolysis. Biochar application in soil has received a growing interest as a sustainable technology to improve highly weathered or degraded soils (Das et al. 2014a, b). It guarantees a long term benefit for soil fertility and productivity. It can enhance plant growth by improving soil physical characteristics (i.e., bulk density, water holding capacity, infiltration, porosity), soil chemical characteristics (i.e., pH, nutrient retention, nutrient availability), and soil biological properties (*i.e.,* microbial biomass carbon), all contributing to an increased crop productivity. The major quality of biochar that makes it attractive as a soil amendment is its highly porous structure which is responsible for improved water retention and increased soil surface area (Das and Avasthe 2015).

9.2 Benefit of Biochar

The major benefits of biochar are impressive because it reduces leaching of soil nutrients, increases soil pH and thus reducing the need for lime, enhances nutrient availability for plants, reduces toxicity of aluminium to plant roots, increases water quality of runoff, reduces dependency on fertilisers, reduces bioavailability of heavy metals and thus works as bioremediation, decreases N_2O and CH_4 emissions from soils, thus further reducing GHG emissions (Mate et al. 2015).

9.2.1 Nutrient Value

Biochar is able to improve soil fertility as well as productivity directly and indirectly as:

(a) *Indirect:* The indirect responses due to biochar application were attributed to either nutrient savings (in term of fertilizers) or improved fertilizer-use efficiency. Biochar being high C/N ratio can immobilize nitrogen which sometimes results in reduced N availability for short duration. This is the ability of biochar to retain applied fertilizer against leaching which results increase in fertilizer use efficiency (Gryze et al. 2010).
(b) *Direct:* Biochar itself contains some amount of nutrients which is available directly to plants. Positive yield responses as a result of biochar application to soils have been reported for a wide range of crops and plants in different parts of the world by improving soil quality (Tiwari et al. 2019a, b; Singh et al. 2019; Kour et al. 2019) with consequent improvement in the efficiency of fertilizer use. From an agronomic perspective it is suggested that biochar could improve

soil health by improving nutrient retention, particularly in coarsely textured soils (Das et al. 2014a, b).

9.2.2 How Can Biochar Help Farmer

Using locally available materials for making biochar could provides an unique opportunity to improve soil fertility for longer period of time to the farmers. Biochar should apply along with other inputs like compost, manure or biopesticides at the same rate every year to realize actual benefits. Application rates of these organic inputs can be reduced when nutrients are combined with biochar because biochar itself contain some nutrient (Major et al. 2009). During conversion of organic residues into biochar farmers can also receive an energy yield by capturing energy given off in the biochar production process. In hilly and desert areas soil loss, weathering and degradation occur at unprecedented rates which causes imbalance in ecosystem properties. Biochar can play a major role in organic agriculture for sustainable soil management by improving existing best management practices, not only to decrease nutrient loss through leaching by percolating water but also to improve soil productivity (Jeffery et al. 2015).

9.2.3 Biochar and Water Availability

Biochar addition in soil increases water holding capacity and plant available water in sandy soils. In dry areas where water quantity and quality is extremely variable, it would contribute a significant benefit. Biochar has a high surface area with increased micro pores and improves the water holding properties of porus sandy soils. Therefore, biochar application for soil water benefits is maximized in sandy soils (Das et al. 2012a, b). Thus, there are enormous benefits of biochar in cropping areas where cost of water is very high such as dry areas.

9.2.4 Effect on Soil pH

Soil pH is an important factor for plant growth because nutrient availability in soils depends on soil pH. Most of the macronutrients are available in neutral soils. In order to neutralize acidic soils, farmers apply thousands of tons of lime to farm soils at great expense. Biochar have an effect on soil pH (Rodríguez-Vila et al. 2014) It can react similarly as agricultural lime do (by increasing soil pH). If a soil has a low cation exchange capacity, it is not able to retain nutrients and the nutrients are often washed out leaching. Biochar in its pores having large surface area develops some negative charges and thus provides more negatively charged sites for cations to be retained when added to soil (Steinbeiss et al. 2009)

9.2.5 Effect on Soil Physical Properties

Biochar application improved the saturated hydraulic conductivity of the top soil and xylem sap flow of the rice plant. It increases water holding capacity in sandy soil. Peanut hull biochar have ability to reduce moisture stress in sandy soil. It improves soil physical condition for earthworm populations. Application of 6.6 metric tons cassia biochar/ha is enough to initiate C-accumulation, which reflect in an increase in organic matter and a net reduction in soil bulk density (Das 2014a, b).

9.2.6 Effect on Soil Chemical Properties

Biochar contribute some quantity of nutrients in soil through the negative charges that develops on its surfaces. This negative charge can easily buffer acidity in the soil (as does organic matter). Due to its high alkalinity nature it has been demonstrated to reduce aluminium toxicity in acid soils. Application of biochar to acidic soils can avoid significant amounts of direct and indirect costs by avoiding GHG emissions (Hammes and Schmidt 2009). Application of biochar in soil increase soil pH, EC, CEC and decrease exchangeable acidity.

9.2.7 Effect of Biochar on Soil Biology

Biochar is able to enhance soil microbial biomass carbon and carbon mineralization. It stimulates the activity of a variety of agriculturally important soil microorganisms and can greatly affect the microbiological properties of soils. The pores in biochar provide a suitable habitat for many microorganisms by protecting them from predation and drying while providing many of their diverse carbon (C), energy and mineral nutrient needs. The intrinsic properties of biochar and its ability to form complex with different soil type, can have an impact on soil-plant-microbe interactions (Hass et al. 2012). Thus, modifications in the soil microbial community can subsequently influence changes in nutrient cycling and crop growth in biochar-amended soil. Biochar application increase Co adsorption which lead to increase local nutrient concentrations for microbial community species and enhanced water retention Dehydrogenase activity and microbial biomass carbon are enhanced due to biochar application in soils (Das and Mukherjee 2012).

9.3 Application of Biochar in Soil

There are different methods for application of biochar in soil like broadcasting, deep banding, band application, spot placement, etc. However, method of biochar application in soil mainly depends on farming system, labour and available machinery. Generally farmers apply biochar in their own field by hand only. But due to prolonged contact with airborne biochar particulates, it is not viable on large-scale considering human health. Broadcasting application needs large amount to cover whole field. Suitable method of application deposits biochar directly into the rhizosphere, and may be viable for perennial cropping systems, and previously established crops. (Jefferym et al. 2011). Deep banding of biochar has been successfully implemented in several wheat fields in Western Australia. Mixing of biochar with composts, manures and other organic input may reduce odours, colour and improve nutrient performance over time due to slower leaching rates (Table 9.1). Mixtures may be applied for uniform topsoil mixing without incorporation (Das and Mukherjee 2011).

9.3.1 Application Rates

Application of biochar in soils is based on its properties like agricultural value from enhanced soils nutrient retention and water holding capacity, carbon sequestration and reduced GHG emissions. There is no specific rate of application of biochar in soil. It depends on many factors including type of biomass used, the types and proportions of various nutrients (N, P, etc.), the degree of metal contamination in the biomass, and also climatic and topographic factors of the land (Jones et al. 2012). It was found that rates between 5–10 t/ha (0.5–1 kg/m^2) have often been found better. Due to variability in biochar materials, nature of crop and soils, farmer should always consider testing several rates of biochar application on a small scale before setting out to apply it on large areas. Even low rates of biochar application can

Table 9.1 Effect of biochar on different soil properties

Factor	Impact
Bulk density	Soil dependent
Soil moisture retention	Upto 25% increase
Liming agent	1 point pH increase
Cation exchange capacity	50% increase
Nutrient use efficiency	10–20% increase
Crop productivity	30–100% increase
CH4 emission	90% decrease
N2O emission	50% decrease
Biological nitrogen fixation	50% increase
Mycorrhizal fungi	30% increase

significantly increase crop productivity assuming if the biochar is rich in nutrients. Biochar application rates sometimes also depend on the amount of dangerous metals present in the original biomass (Das and Mukherjee 2014).

9.4 Soil Health Management

Biochar can act as a soil conditioner by improving soil physical, chemical and biological properties. Benefits from biochar application rates can be maximized only if the soil is rich in nitrogen or if the crops are nitrogen-fixing legumes. Researcher found that application of biochar to soils in a legume-based (e.g. peanut and maize) rotational cropping system, clovers and lucernes is more beneficial. Significant changes in soil quality, including increase in pH, organic carbon and exchangeable cations were observed at higher rates of biochar application, i.e. > 50 t/ha. When mixed with organic matter, biochar can result in enhanced retention of soil water as a result of its pore structure which contributes to nutrient retention because of its ability to trap nutrient rich water within the pores. Biochar is able strongly to adsorb phosphate, even though it is an anion (Knowles et al. 2011). It is reported that the higher BNF with biochar additions is due to greater Mo and B availability. These properties make biochar a unique substance, retaining exchangeable and plant available nutrients in the soil, and offering the possibility of decreasing environmental pollution by nutrients and improving crop yields. Thus, biochar application could provide a new technology for both soil fertility and crop productivity improvement, with potential positive and quantifiable environmental benefits (Kookana 2010).

9.5 Land Restoration/Reclamation

Biochar have received considerable attention in recent years as soil amendment for both sequestering heavy metal contaminants and releasing essential nutrients like sulphur. Biochar are porous with a polar and aromatic surface (Das et al. 2015). They have a high surface to volume ratio and a strong affinity to non-polar substances such as polycyclic aromatic hydrocarbons (PAHs), dioxins, PBDEs, furans (PCDD/Fs), and PCBs. Through the intervention of biochar, groundwater could be protected from the hydrophobic herbicide, insecticide and fungicide. Biochar applications have the potential to absorb pollution by adsorbing ammonia to reduce ammonia volatilization in agricultural soils (Laird et al. 2010)

9.6 Heavy Metal Sorption

The use of biochar to remove contaminants such as organic contaminants or metals is a relatively novel and promising technology. Biochar made from bagasse and other agricultural residues is effective alternative, low-cost environmental sorbents of lead or other heavy metals. Several studies have reported the effective removal of lead by biochar sorbents. Like many other traditional sorbents, the high affinity for lead and other metal ion species bound by biochar may be controlled by other mechanisms as well, including complexation, chelation, and ion exchange. Application of maize stalk biochar is useful to ameliorate chromium (Cr) polluted soils and reduce the amount of carbon produced due to biomass burning (Rajkovich et al. 2012)

9.7 Pathogen and Biochar Interaction

Researchers have reported both increased root colonization and stimulated mycorrhizal fungus spore germination in response to biochar application probably due to improved soil physicochemical properties through enhanced nutrient availability. The efficacy of biochar is dependent on saprophytic fungal activity, which, through their extracellular enzymatic activity and hyphal growth/penetration, can violate the integrity of the material. Citrus wood biochar @1% (w/w) in sandy soil was found to be effective against *Leveillula taurica* (powdery mildew) and *Botrytis cinerea* (grey mold) in pepper and tomato and also in mite *Polyphagotarsonemus latus* in pepper (Das 2014a, b). Beside this, tolerance of asparagus seedlings to *Fusarium oxysporum* is also enhanced by biochar.

9.8 Cattle Feedlot Biochar

Potential sources of organic materials for biochar production include urban green wastes, forestry and crop processing residues as well as animal manures. Biochar made from cattle feedlot manure is an effective soil amendment for improving the productivity in acid soil. This biochar contain high mineral P content which remained as plant available for long period (≥3 years). The increase in P availability led to enhanced P uptake which results in an increase in N uptake and N use efficiency. Manure-based feedstocks tend to have lower carbon content, and higher nutrient/mineral content compared to wood based biochar. Biochar from urban green waste have no harmful effect on pasture productivity (Mohan et al. 2014) Biochar has the capacity to increase soil C accumulation rates in acidic pasture systems. Green waste biochar enhance soil C accumulation at a faster rate than farm manure biochar.

9.9 Crop Production

Biochar applications to soils have shown positive responses for net primary crop production, grain yield and dry matter. Application of wheat straw biochar along with NPK significantly increase the yield of maize in Inceptisol than either crop residue incorporation (CRI) or crop residue burning (CRB). Higher agronomic nitrogen use efficiency was recorded with application of biochar. The combined application of biochar along with organic/inorganic fertilizer has the potential to increase crop productivity, thus providing additional incomes, and may reduce the quantity of inorganic fertilizer use and importation (Kimetu and Lehmann 2010). The impact of biochar application is seen most in highly degraded acidic or nutrient depleted soils. Low biochar application in soil has shown marked impact on various plant species, whereas higher rates seemed to inhibit plant growth. So, moderate additions of biochar are usually beneficial.

9.10 Effect on Upland Rice

Biochar improve saturated hydraulic conductivity of the top soil and the xylem sap flow in upland rice plant. Researchers found that it increased higher grain yields at sites with low P availability and improved the response to N and NP chemical fertilizer treatments (Lehmann et al. 2009). It also reduced leaf SPAD values, possibly through a reduction of the availability of soil nitrogen, indicating that biochar without additional N fertilizer application could reduce grain yields in soils with a low indigenous N supply.

9.11 Effect on Nodulation and Nitrogenise Activity

Biochar addition increase root nodule number, localised N_2 fixation per nodule, nitrogenise activity in legumes, mycorrhizal colonisation and plant-growth promoting organisms in the rhizosphere. Increased nodulation following biochar application could increase sustainable N input into agro ecosystems. Biochar applications also increase nitrogen fixation rates. Increased micronutrient availability (e.g. Mo and B), together with the liming effect on soil pH following biochar application has been proposed as the mechanisms for increased biological N_2 fixation of pot grown beans (Sohi et al. 2010). Symbiotic association between biochar and mycorrhizal association showed that biochar could influence mycorrhizal abundance. Rice biochar showed greater microbial activities than other biochar because of its higher liability (Gaskin et al. 2008).

9.12 Carbon Sequestration

In order to considerably increase long-term C sequestration, biomass has to be converted to a relatively non-degradable form, such as biochar. The biochar is highly resistant to microbial activity, considerably augmenting the recalcitrant fraction of SOC and decreasing emissions of CO_2 from soil. In addition, biochar application was reported to decrease emissions of CH_4, and N_2O from soils. Despite the recalcitrant nature of biochar, about 40% of the total biomass-C of the feedstock is lost during the pyrolysis process, and an additional 10% is mineralized over a few months after biochar application in soil. Nevertheless, the remaining 50% of the total C is relatively stable. The degree of stability of the biochar-C depends on its specifications. While C in biochar produced by high temperature pyrolysis is either recalcitrant or degradable at an extremely slow rate, some of the C in biochar produced under low temperatures is biodegradable. In addition, compared with fallow soils, application of biochar increases rates of CO_2 emissions from the amended soil. This response may be explained by several factors, such as lower bulk density, improved aeration, and higher pH, providing a favorable habitat for soil microorganisms (Novak et al. 2009).

Considering an application rate of between 10 and 100 Mg biochar per hectare and that biochar's C concentration is between 50% and 78%, and assuming a total area of 1411Mha cropland around the world, then the global capacity for storing biochar-C under this landuse is between 7 and 110 Pg. Annual net emissions of carbon dioxide, methane and nitrous oxide could be reduced by a maximum of 1.8 Pg CO_2–C equivalent (CO_2–Ce) per year (12% of current anthropogenic CO_2–Ce emissions), and total net emissions over the course of a century by 130 Pg CO_2–Ce, by utilizing the maximum sustainable technical potential of biochar to mitigate climate change, without endangering food security, habitat or soil conservation. When the use of the process of biochar sequesters more carbon than it emitted, it is carbon negative. Biochar holds 50% of the carbon biomass and it sequesters that carbon for centuries when applied into the soil, removing the CO_2 from the active cycle and thus reduce overall amount of atmospheric CO_2. Plant growth is also enhanced by this process as it absorbs more CO_2 from atmosphere. Overall, these benefits make the biochar process carbon negative as long as biomass production is managed sustainably. Biochar system also needs to be taken into account, *viz.*, emissions resulting from biomass growth, collection, pyrolysis, spreading and transport, to consider it a truly carbon negative. Due to its capability to actively reduce the atmospheric concentrations of greenhouse gases, biochar technology may be considered as geoengineering solution. It may also be considered as a long wave geoengineering option for climate change mitigation as it plays a role into the removal of CO_2 from the atmosphere and enhances the level of long wave radiation leaving from the planet. A biochar system is a carbon sink, where agricultural crops are grown and is subsequently pyrolysed to produce biochar, which is then applied to soil (Novak et al. 2009). In carbon cycle, plants remove CO_2 from atmosphere via photosynthesis and convert it into biomass. But all of that carbon (99%) is returned to atmosphere as CO_2 when plants die and decay, or immediately if biomass is burned as a renewable substitute for fossil fuels. In biochar cycle, half (50%) of that carbon is removed and sequestered as biochar and the rest half (50%) is converted to renewable energy co-products before being returned to the atmosphere. A more efficient way to increase and maintain a high soil organic matter content would be to apply more stable C products such as biochar. Future political agreements may make it profitable for farmers to add biochar to soil. Large amounts of carbon in biochar may be sequestered in the soil for long periods estimated to be hundreds to thousands of years. Terra preta soils suggest that biochar can have carbon storage permanence in soil for many hundreds to thousands of years. Biochar mineralizes in soils in a little fraction and remains in a very stable form which provides it the potential to be a major carbon sink. About 12% of the total anthropogenic carbon emissions by land use change (0.21 Pg C) can be offset annually in soil, if the slash-and-burn system is replaced by the slash-and-char system. Compared with other terrestrial sequestration strategies, such as afforestation or re-forestation, carbon sequestration in biochar increases its storage time. The principal mechanisms operating in soils through which biochar entering the soil is stabilized and increase its residence time in soil are due to formation of interactions between mineral surfaces, intrinsic recalcitrance and spatial separation of decomposers and substrate (Githinji 2013).

9.13 Carbon Credit

Application of higher amounts of biochar to soils may increase the carbon credit benefit to the farmers. Carbon added to the fields in the form of biochar could give farmers C credits that can be sold on a C credit market for additional income. Increasing the C sink in soil will help reduce the amounts of CO_2, CH^4, and N_2O.

9.14 Stability in Soil

Biochar is not a single material, and its characteristics vary depending upon from where and how it is made. Stability of biochar in soil is important in determining environmental benefits because stability determines how long carbon (C) applied to soil as biochar will remain sequestered in soil and contribute to mitigate climate change and how long biochar can provide benefits to soil and water quality (Singh et al. 2017a, b, c, 2018; Tiwari et al. 2018; Das and Mukherjee 2012). Most of the biochar commonly used by the farmer have a small labile (easily decomposed) fraction in addition to a much larger stable fraction. The mean residence time of this stable fraction is estimated to range from 100 to 1000 years.

9.15 Impact on Climate Change

Biochar technology is called as geoengineering solution that has potential to actively reduce the atmospheric concentrations of green house gases. As it results in the removal of CO2 from the atmosphere and increases level of long wave radiation leaving the planet, it is considered as a long wave geoengineering option for climate change mitigation. A biochar system, where agricultural crops are grown, and subsequently pyrolyzed to produce biochar, which is then applied to soil, is a carbon sink. This means CO2 from atmosphere is sequestered as carbohydrates in the growing plant and conversion of the plant biomass to biochar stabilizes this carbon (Keith et al. 2011). The stabilization of carbon in biochar delays its decomposition and ensures that carbon remains locked away from the atmosphere for hundreds to thousands of years. In addition, gases released in the process of creating biochar can be used to make bio fuels. If we want to tackle climate change challenges, we must emphasize the potential of soil to sequester carbon. Sustainable biochar can be used now to combat global warming by holding carbon in soil and by displacing fossil fuel use.

9.16 Safety Concerns

Application of large amounts of biochar to agricultural soils entails significant practical and technical barriers like safe production and use. This risk is similar to other dusts that can become combustible hazards, such as coal, plastics, some metals, foods, and woods. The dust of biochar can spontaneously combust and poses a minor risk when handled, stored, or transported in enclosed spaces (Renner 2007; Sohi et al. 2010; Liu et al. 2012; Nelissen et al. 2012). Some biochar contain toxic materials that are controlled by "permissible exposure limit" standards in many countries. The levels of these toxic materials in the biochar are highly dependent on both the biomass feedstock and its production. So, there is no straightforward permissible exposure limit available for biochar as yet (Ogawa and Okimori 2010).

9.17 Conclusions

Soil amendment with biochar has attracted a fair amount of research interest due to its abundant usage and wide potential, which includes enhancing crop production by improving soil fertility, decreasing greenhouse gas emissions and increasing soil carbon sequestration. Use of biochar in agricultural systems is one viable option that can improve the soil quality, increase carbon sequestration in soil, reduce farm waste. The initial outcomes reveal that biochar application helps in improving soil health and crop productivity. However, to promote the application of biochar as a soil amendment and also as a climate change abatement option, research, development and demonstration on biochar production and application is very vital.

References

Das SK (2014a) Recent development and future of botanical pesticides in India. Popular Kheti 2:93–99

Das SK (2014b) Role of micronutrient in rice cultivation and management strategy in organic agriculture-A reappraisal. Agric Sci 5:765–769

Das SK, Avasthe RK (2015) Biochar as carbon negative in carbon credit under changing climate. Curr Sci 109:1223

Das SK, Mukherjee I (2011) Effect of light and pH on persistence of flubendiamide. Bull Environ Contam Toxicol 87:292–296

Das SK, Mukherjee I (2012) Effect of moisture and organic manure on persistence of flubendiamide in soil. Bull Environ Contam Toxicol 88:515–520

Das SK, Mukherjee I (2014) Influence of microbial community on degradation of flubendiamide in two Indian soils. Environ Monit Assess 186:3213–3219

Das SK, Mukherjee I, Flubendiamide (2012a) Transport through packed soil columns. Bull Environ Contam Toxicol 88:229–233

Das SK, Mukherjee I, Das SK (2012b) Dissipation of flubendiamide in/on okra [Abelmoschus esculenta (L.) Moench] fruits. Bull Environ Contam Toxicol 88:381–384

Das SK, Avasthe RK, Gopi R (2014a) Vermiwash: use in organic agriculture for improved crop production. Pop Kheti 2:45–46

Das SK, Avasthe RK, Singh R, Babu S (2014b) Biochar as carbon negative in carbon credit under changing climate. Curr Sci 107:1090–1091

Das SK, Mukherjee I, Kumar A (2015) Effect of soil type and organic manure on adsorption–desorption of flubendiamide. Environ Monit Assess 187:403. https://doi.org/10.1007/s10661-015-4623-2

Gaskin JW, Steiner C, Harris K, Das KC, Bibens B (2008) Effect of low-temperature pyrolysis conditions on biochar for agricultural use. Trans Am Soc Agric Eng 51:2061–2069

Githinji L (2013) Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. Arch Agron Soil Sci 60:457–470

Gryze DS, Cullen M, Durschinger L, Lehmann J, Bluhm D, Six J (2010) Evaluation of opportunities for generating carbon offsets from soil sequestration of biochar. In: An issues paper commissioned by the Climate Action Reserve, final version. http://www.terraglobalcapital.com/press/Soil_Sequestration_Biochar_Issue_Paper1.pdf

Hammes K, Schmidt WI (2009) Changes of biochar in soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 169–182

Hass A, Gonzalez JM, Lima IM, Godwin HW, Halvorson JJ, Boyer DG (2012) Chicken manure biochar as liming and nutrient source for acid Appalachian soil. J Environ Qual 41:1096–1106

Jeffery S, Martijn BT, Cornelissen G, Kuyper TW, Lehmann J, Mommer L, Sohi SP, Van De Voorde TFJ, Wardle DA, van Groenigen JW (2015) The way forward in biochar research: targeting trade-offs between the potential wins. GCB Bioenergy, 7:1–13

Jefferym S, Verheijen FGA, van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agron Ecosyst Environ 144:175–187

Jones DL, Rousk J, Edwards-Jones G, DeLuca TH, Murphy DV (2012) Biochar-mediated changes in soil quality and plant growth in a three year field trial. Soil Biol Biochem 45:113–124

Keith A, Singh B, Singh BP (2011) Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. Environ Sci Technol 45:9611–9618

Kimetu JM, Lehmann J (2010) Stability and stabilisation of biochar and green manure in soil with different organic carbon contents. Aust J Soil Res 48:577–585
Knowles OA, Robinson BH, Contangelo A, Clucas L (2011) Biochar for the mitigation of nitrate leaching from soil amended with biosolids. Sci Total Environ 409:3206–3210
Kookana RS (2010) The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review. Soil Res 48:627–637
Kour D, Rana KL, Yadav N, Yadav AN, Rastegari AA, Singh C, Negi P, Singh K, Saxena AK (2019) Technologies for biofuel production: current development, challenges, and future prospects. In: Rastegari AA et al (eds) Prospects of renewable bioprocessing in future energy systems, Biofuel and biorefinery technologies, vol 10. Springer, Cham, pp 1–50
Laird DA, Fleming P, Davis DD, Horton R, Wang BQ, Karlen DL (2010) Impact of biochar amendments on the quality of a typical midwestern agricultural soil. Geoderma 158:443–449
Lehmann J, Czimczik C, Laird D, Sohi S (2009) Stability of biochar in the soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management. Earthscan, London, pp 183–206
Liu XY, Qu JJ, Li LQ, Zhang AF, Zheng JF, Zheng JW, Pan GX (2012) Can biochar amendment be an ecological engineering technology to depress N2O emission in rice paddies?—a cross site field experiment from south China. Ecol Eng 42:168–173
Major J, Steiner C, Downie A, Lehmann J (2009) Biochar effects on nutrient leaching. In: Lehmann J, Joseph S (eds) Biochar for environmental management. Science and Technology, Earthscan, London, pp 271–287
Mate CH, Mukherjee I, Das SK (2015) Persistence of spiromesifen in soil: influence of moisture, light, pH and organic amendment. Environ Monit Assess 187:7
Mohan D, Sarswat A, Ok YS, Pittman CU (2014) Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – a critical review. Bioresour Technol 160:191–202
Nelissen V, Rütting T, Huygens D, Staelens J, Ruysschaert G, Boeckx P (2012) Maize biochars accelerate short-term soil nitrogen dynamics in a loamy sand soil. Soil Biol Biochem 55:20–27
Novak JM, Busscher WJ, Laird DL, Ahmedna M, Watts DW, Niandu MAS (2009) Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci 174:105–112
Ogawa M, Okimori Y (2010) Pioneering works in biochar research, Japan. Aust Soil Res 48:489–500
Rajkovich S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol Fertil Soils 48:271–284
Renner R (2007) Rethinking biochar. Environ Sci Technol 41:5932–5933
Rodríguez-Vila A, Covelo EF, Forján R, Asensio V (2014) Phytoremediating a copper mine soil with *Brassica juncea* L., compost and biochar. Environ Sci Pollut Res 21:11293–11304
Singh C, Tiwari S, Boudh S, Singh JS (2017a) Biochar application in management of paddy crop production and methane mitigation. In: Singh JS, Seneviratne G (eds) Agro-environmental sustainability: vol-2: managing environmental pollution. Springer, Cham, pp 123–146
Singh C, Tiwari S, Singh JS (2017b) Impact of rice husk biochar on nitrogen mineralization and methanotrophs community dynamics in paddy soil. Int J Pure Appl Biosci 5(5):428–435
Singh C, Tiwari S, Singh JS (2017c) Application of biochar in soil fertility and environmental management: a review. Bull Environ Pharmacol Life Sci 6(12):07–14
Singh C, Tiwari S, Gupta VK, Singh JS (2018) The effect of rice husk biochar on soil nutrient status, microbial biomass and paddy productivity of nutrient poor agriculture soils. Catena 171:485–493
Singh C, Tiwari S, Singh JS (2019) Biochar: a sustainable tool in soil 2 pollutant bioremediation. In: Bharagava RN, Saxena G (eds) Bioremediation of industrial waste for environmental safety. Springer, pp 475–494
Sohi S, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Adv Agron 105:47–82

Steinbeiss S, Gleixner G, Antonietti M (2009) Effect of biochar amendment on soil carbon balance and soil microbial activity. Soil Biol Biochem 41:1301–1310
Tiwari S, Singh C, Singh JS (2018) Land use changes: a key ecological driver regulating methanotrophs abundance in upland soils. Energ Ecol Environ 3(6):355–371
Tiwari S, Singh C, Boudh S, Rai PK, Gupta VK, Singh JS (2019a) Land use change: a key ecological disturbance declines soil microbial biomass in dry tropical uplands. J Environ Manag 242:1–10
Tiwari S, Singh C, Singh JS (2019b) Wetlands: a major natural source responsible for methane emission. In: Upadhyay et al (eds) Restoration of wetland ecosystem: a trajectory towards a sustainable environment. Springer, Cham, pp 59–74