Chapter 5
Biochars and Its Implications on Soil Health and Crop Productivity in Semi-Arid Environment

P. Kannan, D. Krishnaveni, and S. Ponmani

Abstract Land degradation and climate change are important associated processes necessitating appropriate management options to solve alarming food security threats in developing nations. Biochar produced from plant matter and applied to the soil has become increasingly recognized to address multiple contemporary concerns, such as agricultural productivity and contaminated ecosystem amelioration, primarily by removing carbon dioxide from the atmosphere and improving soil health. Biochar is an anaerobic pyrolysis product derived from organic material, resistant to easy degradation and stored carbon in the long-term in the terrestrial ecosystem and capable of reducing greenhouse emission from soil to the atmosphere. Further, it has the potential to adsorb and degrade heavy metals accumulated in the industrial and contaminant sites. The different source of biochars and graded levels of application has positive and negative effects on crop yield under different soil types. Most of the results in biochar are a greenhouse and laboratory-based experiment and lack of field experimental evidence in the semiarid environment. In this chapter need for biochar production, characterization, soil health changes, environmental clean-up potential, and crop yield dynamics under changing climate and research on biochar in the near future will be focused on sustainable crop and environmental management.

Keywords Biochar · Waste management · Soil health · Environment

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J. S. Singh, C. Singh (eds.), *Biochar Applications in Agriculture and Environment Management*, https://doi.org/10.1007/978-3-030-40997-5_5

5.1 Introduction

Global environmental change, including land degradation, loss of biodiversity, changes in hydrology and changes in climate patterns resulting from enhanced anthropogenic emission of greenhouse gases, will have serious consequences for world food security, particularly affecting the more vulnerable socio-economic sectors (Ericksen et al. 2009; Lal 2010). The World Bank suggests that at least a doubling of cereal yields and a 75% increase in meat production by 2030 are required to maintain the current level of nutrition globally (Fresco 2009). To significantly increase food production, when large areas of agricultural lands will be adversely affected by climate change or converted into forestry for C sinks may not be possible unless new technologies and sustainable practices are rapidly adopted (Singh and Singh 2019; Singh et al. 2019a, b; Vimal and Singh 2019). Biochar is a charred by-product of biomass pyrolysis produced from biological wastes, crop residues, animal poultry manure, or any type of organic waste material. Pyrolysis is the chemical breakdown of a substance under extremely high temperatures in the absence of oxygen. Biochar application has been promoted in agricultural practice that creates a win-win situation by improving soil quality and enhancing agricultural sustainability concomitant with mitigating GHG emissions. Recently biochar application got momentum because its capability of carbon sequestration, reducing soil compaction, improves soil physical condition and nutrient uptake from the soil.

The application of biochar to agricultural soils may play a crucial role in global climate change mitigation through the reduction of greenhouse gas production and the sequestering of atmospheric carbon in soils (Gaunt and Cowie 2009; McCarl et al. 2009; McHenry 2009). The agronomic benefits of biochar in soils could assist in the adaptation of agriculture to meet rising demands for food and fibre. Furthermore, improving soil health with biochar applications may increase the resilience of agricultural systems and enable the continuation of farming on marginal lands (Chan et al. 2007; Steiner et al. 2008)

Application of biochar to soil has been shown to have many advantages including enhanced soil health characteristics, reduced metal contamination risks and consequently increased plant growth (Namgay et al. 2010; Reichenauer et al. 2009) as well as reduced greenhouse gas emissions from soil (Singh et al. 2010a, b; Van Zwieten et al. 2009; Yanai et al. 2007). The competing and often conflicting demands of land use primarily stem from growing populations requiring housing and food, coupled with community desires for greater allocation of land to ecological reserves and the increasing production of energy crops to displace greenhouse gas-emitting fossil fuels (Koomen et al. 2005; Simon and Wiegmann 2009). In addition to the challenge of a changing climate, the increasing claim for this scarce land-use resource will force the necessity for greater productivity from less land, meaning farmers will need to undertake activities that result in significant yield increases (Singh et al. 2017a, b, c; Vimal et al. 2018; Kumar et al. 2018; Singh 2019). Land managers from more developed countries historically had greater access to technological innovations and training, thereby improving the productivity of agricultural systems compared with those from developing countries (Singh 2013; Singh 2014; Singh 2015; Singh 2016; Singh Boudh 2016; Kumar et al. 2017; Kumar and Singh 2017; Tiwari and Singh 2017). With the escalating effects of climate change, technological adaptation will become increasingly vital to sustainably augment production systems globally (Bryan et al. 2009).

Recently, biochar has attracted much attention due to its promising role in many environmental management issues. Biochar can be mainly used as a large-scale soil amendment a wide range of agricultural applications including chemical contaminants, soil fertilization as well as carbon sequestration. It improves soil quality by increasing soil pH, moisture-holding capacity, attracting more beneficial fungi and microbes as well as improving cation exchange capacity (Laird 2008). The presence of many functional groups such as carboxylic, alcohol, and hydroxyl on the biochar surface makes an opportunity to form complexes between these groups and heavy metal ions (Woolf 2008). Due to the specific surface area and high sorption capacity in regard to heavy metals ions, the biochar could be used as an effective adsorbent of these contaminants (Matthews 2008). Being a renewable resource and due to its economic and environmental benefits, biochar is a promising resource for environmental technology used for water contaminants treatment. Most studies have reported that biochar showed excellent ability to remove contaminants such as heavy metals, organic pollutants and other pollutants from aqueous solutions. Meanwhile, several biochars exhibit comparable or even better adsorption capacity than commercially activated carbon (Zhang et al. 2013; Yang et al. 2014). Therefore, it is very imperative to emphasize the importance of biochar production, characterization and various applications of biochar in this book chapter.

5.2 Biochar and Its Characteristics

5.2.1 Biochar

Biochar is a carbonaceous material produced from organic waste through thermochemical decomposition under different temperatures in the presence of little/no oxygen by the process of pyrolysis and used for soil conditioning, carbon conservation and greenhouse abatement (Kannan et al. 2016).

5.2.2 Pyrolysis

The chemical breakdown of a substance under high temperatures in the absence of oxygen is called as pyrolysis (Fig. 5.1).

Organic chemical transformation in pyrolysis (Fig. 5.2).

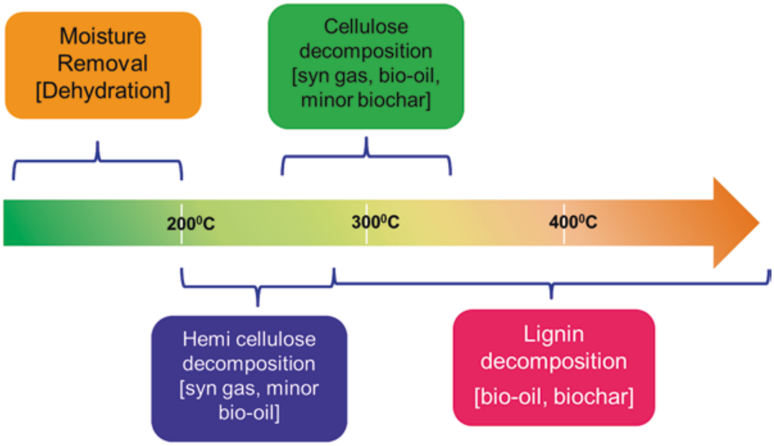


Fig. 5.1 Pyrolysis temperature and conversion nature of proximate components of plant

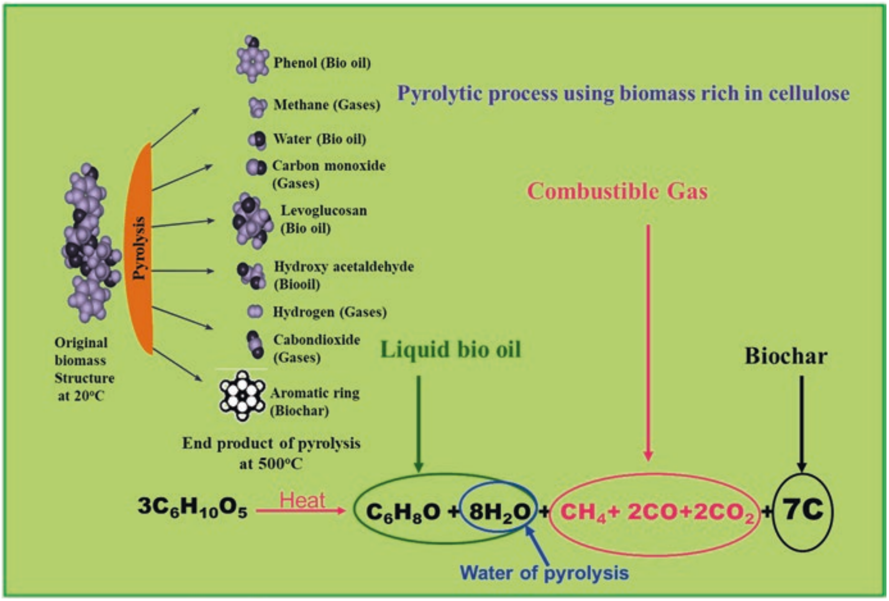


Fig. 5.2 Chemical transformation process of proximate components of the plant into biochar

5.2.3 *Biochar Production*

Biochar can be produced by thermochemical decomposition of biomass at temperatures of 200–900 °C in the presence of little or no oxygen, which is commonly known as pyrolysis (Demirbas and Gonenc 2002). Pyrolysis is generally divided into fast, intermediate, and slow depending on the residence time and temperature.

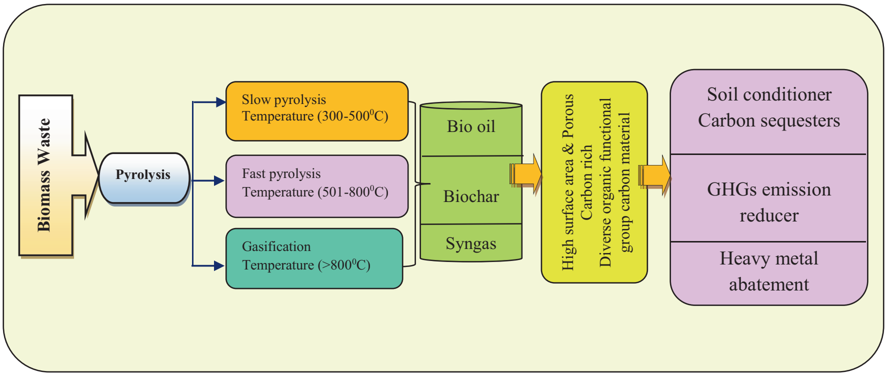


Fig. 5.3 Biomass conversion, properties and application potential

Table 5.1 Effect of pyrolysis method, temperature and residence time on the end product

Process	Temperature (°C)	Residence time	Products		
			Liquid (bio-oil) (%)	Solid (biochar) (%)	Gas (syngas) (%)
Fast pyrolysis	300–1000	Short (<2 s)	75	12	13
Intermediate pyrolysis	500	Moderate (10–20 s)	50	25	25
Slow pyrolysis	100–1000	Long (5–30 min)	30	35	35
Gasification	>800	Moderate (10–20 s)	5	10	85

Fast pyrolysis with a very short residence time (<2 s) is often used to produce bio-oil from biomass yielding about 75% bio-oil (Mohan et al. 2006). Slow and intermediate pyrolysis processes with a residence time of a few minutes to several hours or even days are generally favored for biochar production (25–35%) (Brown 2009). Gasification is different from the general pyrolysis process. For gasification, the biomass is converting into gases rich in carbon monoxide and hydrogen by reacting the biomass at high temperature (>700 °C) in a controlled oxygen environment and/or steam. The resulting gas mixture is known as synthetic gas or syngas (Mohan et al. 2006) (Fig. 5.3 and Table 5.1).

5.2.4 Conversion Efficiency

Conversion of woody biomass to biochar has shown an average recovery of 54% of the initial carbon in the biochar (Lehmann et al. 2003). But our study reported 32–67% recovery from different biomass and these variations mainly attributed to the nature of feedstock used and thickness of the feedstock. The conversion

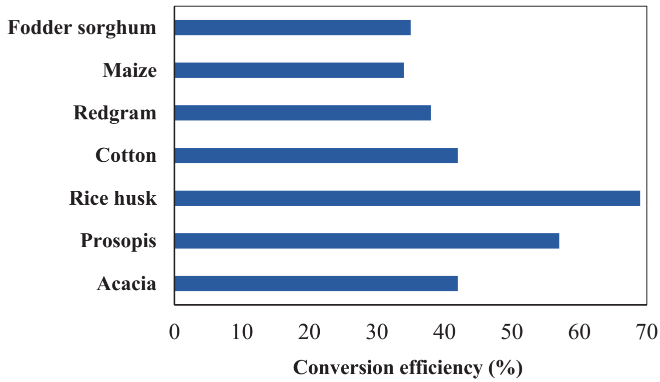


Fig. 5.4 The conversion efficiency of different agricultural waste into biochar

efficiency of different agricultural wastes was given in Fig. 5.4. The crop wastes of 500 kg were converted into its biochar respective under the anaerobic condition at 300–400 °C by slow pyrolysis process using slow pyrolysis unit (Kannan et al. 2016)

Biochar is a fine-grained and porous substance, similar in its appearance to charcoal produced by natural burning. It is produced by the combustion of biomass under oxygen-limited conditions (International Biochar Initiative 2008). As a soil amendment, biochar creates a recalcitrant soil carbon pool that is carbon-negative, serving as a net withdrawal of atmospheric carbon dioxide stored in highly recalcitrant soil carbon stocks (Lehmann and Joseph 2009).

Biochar is the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment. Due to its highly aromatic structure, biochar is chemically and biologically more stable compared with the organic matter from which it was made. It has been proposed as a technology to play a useful role in building soil health and mitigating climate change. Properties of biochar vary widely, depending on the biomass source used and the conditions of production of biochar (Lehmann and Joseph 2009).

The pH of the biochar produced from different agricultural feedstocks ranged from 7.9 to 11.2 which are of alkaline range. Among the various feedstocks used, fodder sorghum stalk biochar (11.2) and prosopis biochar (10.8) are high in alkaline nature. Rice husk biochar registered a low level of salinity (0.22 dS/m) whereas the other feedstocks biochar (0.58–2.1 dS/m) are likely to develop a moderate level of salinity. Among the various agricultural feedstocks, redgram and maize stalk biochar registered the highest organic carbon content of 76 g/kg followed by cotton biochar 69 g/kg (Table 5.2).

The nutrient composition of biochars varied with the source of feedstocks. The total N varied from 0.43 to 2.06%. The biochar produced from maize stalk registered the highest total N of 2.06% and a total P of 0.84% and fodder sorghum recorded a maximum total K of 2.7%. The lowest total N of 0.31% was in cotton stalk biochar and the lowest total P of 0.23% and total K of 0.20% were recorded in the rice husk biochar.

Table 5.2 Chemical properties of Biochar (Kannan et al. 2016)

Biochar	pH	EC (dS/m)	OC (g/kg)	Total (C %)	Total (N %)	Total (P %)	Total (K %)
Prosopis	9.4–10.8	0.83–1.25	25–32	62–89	0.70–1.23	0.05–0.26	0.2–0.5
Rice husk	7.9–8.1	0.22–0.52	34–57	57–64	0.63–1.78	0.07–0.23	0.1–0.2
Maize	8.9–10.0	0.65–1.09	21–76	56–71	0.43–2.06	0.08–0.84	0.3–0.8
Cotton	8.8–10.2	0.58–0.85	17–69	54–85	0.31–0.67	0.15–0.39	1.1–1.4
Redgram	8.4–10.3	0.63–1.0	24–76	61–75	0.53–1.65	0.18–0.46	0.8–2.5
Fodder sorghum	9.5–11.2	1.2–2.1	8–15	51–54	0.32–1.02	0.16–0.24	1.1–2.7
Acacia	8.9–9.8	0.55–0.90	45–57	65–72	0.60–1.54	0.22–0.65	1.1–1.7

5.3 Implications of Biochar on Soil Health

The presence of biochar in the soil has a significant effect on the physical nature of the system, affecting the texture, depth, porosity, structure, and consistency, particle-size distribution, surface area, pore size distribution, and packing. Also, biochar affects the physical properties of soil, physical properties that may subsequently have a direct effect on plant growth. Since the availability and penetration depth of water and air into the root zone is determined mainly by the physical compositions of the soil horizons and physical makeup (Lehmann and Rondon 2006; Chan et al. 2008). The presence of biochar will directly influence the response of soil to water, its aggregation, permeability, and swelling-shrinking dynamics, in addition to its capacity to hold cations and its reaction to ambient-temperature variations (Brady and Weil 2008). Biochar also changes the physical nature of soil, causing a net increase in the total soil-specific surface area and improves the soil structure and aeration. Compositional proportions vary according to feedstock materials, pyrolysis conditions, processing temperatures adopted, heating rates and pressures (Fig. 5.5).

As a consequence of improved soil physical properties (structure, surface area, porosity, bulk density, and water holding capacity), plant water availability, nutrient retention capacity, root penetration, and aeration do increase (Chia et al. 2015). Sandy soils amended with biochar have higher water holding capacities than do loamy and clay soils, while increased soil aeration is mainly observed in fine-textured soils (Mukherjee et al. 2014).

The application of biochar increases microbial activity and biomass and changes the microbial community composition and abundance. However (Tiwari et al. 2019a; Tiwari et al. 2019b; Singh et al. 2019; Kour et al. 2019), the beneficial effect of biochar on the soil environment depends on the type of biochar, application rate, soil type and plant response (Lehmann et al. 2011). The bacterial community in soils of cotton that have continuously been cropped for 2 years, 6 years, 11 years

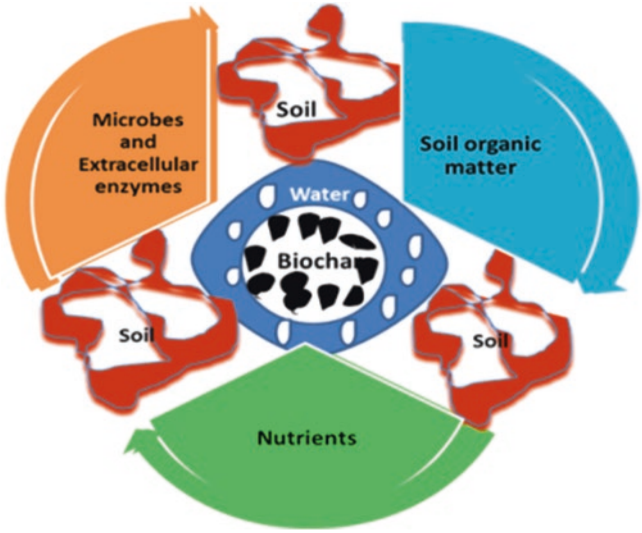


Fig. 5.5 Schematic diagram of biochar and soil interaction. Biochar adsorbs microbes, inorganic nutrients, and soil organic matter

and 14 years and treated with biochar (B0, 0 t/ha; B1, 12.5 t/ha and B2, 20 t/ha) was investigated using next-generation sequencing. The relative abundance of Sphingomonas and Pseudomonas in the biochar-treated soils was significantly higher than that in the soil without biochar treatment.

The results suggest that the biochar application has a significant impact on the soil bacterial community, which may improve the microbial diversity of continuous cropping systems in cotton soils (Han et al. 2017).

Application of biochar could influence the mycorrhizal fungi functioning with the following mechanisms by: (i) modifying physicochemical characteristics of the soil, (ii) indirectly influencing the mycorrhizae by affecting soil microbes in the surroundings, (iii) interfering with plant–fungus signaling and allelochemical detoxification on biochar, and (iv) the provision of refugia from fungal grazers. The porous structure of biochar enhances the habitat of mycorrhizal fungi and other soil microbiota, which improved the soil quality (Warnock et al. 2007).

Biochar may increase the cation and anion exchange capacity of the soil (Singh et al. 2010a, b; Liang et al. 2006) improving the soil properties through raising in pH, increases in total N and P, encouraging greater root development and decreasing available aluminum(Cheng et al. 2006; Chan et al. 2008). Moreover, biochar holds the capability to reduce the effects of drought by raising soil moisture content, therefore decreasing nutrient leaching and soil erosion (Lorenz et al. 2007). Higher water bioavailability and moisture retention are thought to be an important factor for achieving superior yields in biochar-amended soil. Conversely, the biochar surface contain numerous chemically reactive groups, such as OH, COOH, and ketones that provide enormous potential for the adsorption of toxic chemicals, such as aluminum

(Al) and manganese (Mn) in acid soils, and arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb) in heavy metal-contaminated soils (Berek et al. 2011; Uchimiya et al. 2010). In landfill sites, biochar particle size increases the soil porosity and promotes the airflow through the landfill cover and increased oxygen diffusion within the landfill cover, which leads to potentially higher levels of microbial degradation (Yaghoubi and Reddy 2011). There is a significant interest in the application of biochar to soils that have gained, significant interest due to the multifold benefits of biochar such as nutrients retention and water-holding capacity and it also promoting plant growth (Quayle 2010; De Gryze et al. 2010). It has been found that biochar can: (a) decrease soil tensile strength, (b)increase improve soil structure and pH, (c) improve fertilizer use efficiency, (d) decrease aluminum toxicity to plant roots and microbiota, and (e) improves soil conditions for earthworm populations. Furthermore, biochar reduces the leaching of soil nutrients, which enhance the availability of nutrients for plants and reduces the bioavailability of heavy metals (Lehmann et al. 2003).

Biochar produced at low-temperatures (300 or 400 °C) is acidic whereas at high temperatures (700 °C) it is alkaline in nature. This is an important finding as the agricultural use of biochar can have a two-fold application. If the soil intended for biochar application is acidic in nature, then the biochars produced at 700 °C or higher temperatures can be used to neutralize the soil and improve soil fertility. Alternatively, biochars formed at lower temperatures might be suitable for alkaline soils to correct for alkalinity problems. It also serves as a valuable soil amendment by supplying plant nutrients with carbon sequestration (Hossain et al. 2011). Biochar is a potential tool for improving the quality, agronomic value of soil, and minimize the harmful effects of heavy metals present in the soil. The multi-fold benefits of biochar application in the soil are listed below for easy understanding of the reader. The application of grass derived biochar and oak-derived biochar in unburned increased the bacterial population (118.7 ± 121.0 and 87.7 ± 4.4 CFUs are per gram of soil, respectively) as compared to control (31.8 ± 1.4 CFUs are per gram of soil) application of biochar (Khodadad et al. 2011).

5.4 Implications of Biochar on Crop Growth and Yield

A combination of higher biochar application rates along with NPK fertilizer increased crop yield on tropical Amazonian soils (Steiner et al. 2007) and semi-arid soils in Australia. Biochar application in low pH soil (<5.2) under steep slope enhanced the carrots and beans yields over the control (Rondon et al. 2004). According to the Lehmann and corkers, increasing yields with increasing biochar applications up to 140 Mg C ha^{-1} on highly weathered soils in the humid tropics (Lehmann et al. 2006). This was not true for all crops however they found that biomass growth of beans increased with biochar applications up to 60 Mg C ha^{-1} but fell to the same value as for control plots when biochar application was increased to

90 Mg C ha^{-1} (Rondon et al. 2004). Crops respond positively to bio-char additions up to 50 Mg C ha^{-1} and may show growth reductions at a very high application rate (Lehmann 2007). Application of redgram stalks biochar @ 5 t ha^{-1} increased the dry matter production 24% and groundnut pod yield 29% in acidic red soil under rain-fed situation (Kannan et al. 2016). Application of biochar at the rate of 25 ha^{-1} in combination with FYM at the rate of 10 ha^{-1} and N at the rate of 30 kg ha^{-1} is recommended for improving mung bean growth and yield (Hussain et al. 2017). Biochar @ 10 t ha^{-1} increased above ground biomass by 23% and grain yield by 10% of durum wheat compared to control (Steiner et al. 2007).

Application of biochar prepared from wheat straw (1.9 ha^{-1}) along with recommended doses of NPK at 180:80:80 kg ha^{-1} significantly increased the yield of maize in Inceptisol of IARI farm and this treatment was superior to either crop residue incorporation or crop residue burning (Purakayastha 2010).

The production of plant biomass through photosynthesis removes CO_2 from the atmosphere, and therefore any increase in plant biomass due to biochar additions in soil systems will contribute to the mitigation of rapidly rising atmospheric CO_2 levels. Specifically, biochar increases plant nutrient availability and enhances the soil environment (CEC, soil pH, aeration), which in turn indirectly contributes to enhanced plant growth (Chan et. 2008; Steiner et al. 2007; Zackrisson et al. 1996). In a field trial (Cowpea and Rice) in Amazon basin Anthrosol soils with high carbon levels and Ferralsols with added wood biochar, significantly increased phosphorus, calcium, manganese and zinc availability, with a 38–45% increase in biomass of the two crops in the Anthrosol (Lehmann et al. 2003). The application of biochar doubled the crop yield in maize under degraded cropping soils and the improvement could be explained by biochar nutrient availability and other soil properties improvement (Kimetu et al. 2008). Biochars generally appear to increase nutrient availability through increased ion retention in soils (Liang et al. 2006) and therefore potentially enhance plant yields. Biochar applications produced from manures may directly contribute high levels of nutrients to soils. Field experimental results reported that the application of 10, 25 and 50 t/ha of poultry manure biochar enhanced the yield of radish (Chan et al. 2008)

Lin et al. (2015) observed yield increases of 11% in soybean grain yield and of 28% in wheat grain yield following maize stalk biochar application to coastal saline soil. Genesio et al. (2015) reported an even greater grape yield increase (66%) in the same field after applying biochar from orchard prunings. On the other hand, Schmidt et al. (2014) reported neither a grape yield nor quality effect after wood BC was applied to Swiss vineyard soils during a 4-year field trial. The application of biochar @ 100 Mg dry weight ha^{-1}, which increases the yield were 1.17 and 0.43 Mg ha^{-1} for maize and soybean, respectively (Katterer et al. 2019). Berihun et al. (2017) reported that the Application of *Lantana* biochar @ 18 t ha^{-1} increased the grain yield of maize (528 kg ha^{-1}) than compared to control (134 kg ha^{-1}) (Table 5.3).

Table 5.3 Effective of different rate of biochar application on crop yield under different soil type

Crops	Soil type	Biochar rate (t/ha)	Fertilizer rate (kg/ha)	Yield / biomass increase over control (%)	Additional information
Wheat	Ferrosol	10	1.25 g nutricote per 250 g soil (nutricote contain 15.2% N. 4.7% P, and 8.9% K)	+250	A similar response was observed for the biomass yield of Soya bean and radish. Calcarosol amended with fertilizer and biochar however gave varied crop responses (Van Zwieten et al. 2010)
Radish	Alfisol	100	N (100)	+266 (biomass)	In the absence of nitrogen fertilizer application of Biochar did not increase the dry matter production of radish even at a higher rate(100 t/ha) (Chan et al. 2008)
Rice	Inceptisol	30	Nil	+294	Sole effect of biochar (Noguera et al. 2010)
	Oxisol	88	Nil	+800	Interaction effect of earthworm and biochar
	Oxisol	88	N (40), P (20), K (20)	−21	Interaction effect of earthworm and biochar
Maize	Oxisol	20	N (156–170), P (30–43), K (83–138)	+28 (1st year) +30 (2nd year) +140 (3rd year)	In the first year after biochar application. No significant effect on crop yield was observed (Major et al. 2010)
Rice	Ferralsol	11	N (30), P (35), K (50)	+29 (stover) +73(grain)	While charcoal addition alone did not affect Crop production, a synergistic effect occurred when both charcoal and inorganic fertilizer were applied (Steiner et al. 2008)
Groundnut	Alfisol	5	N (10), P (10) and K (45)	+29(pod yield)	Biochar addition mainly influence soil moisture retention and increase the soil pH, thereby enhance the nutrient availability in rainfed Alfisol (Kannan et al. 2016)

(continued)

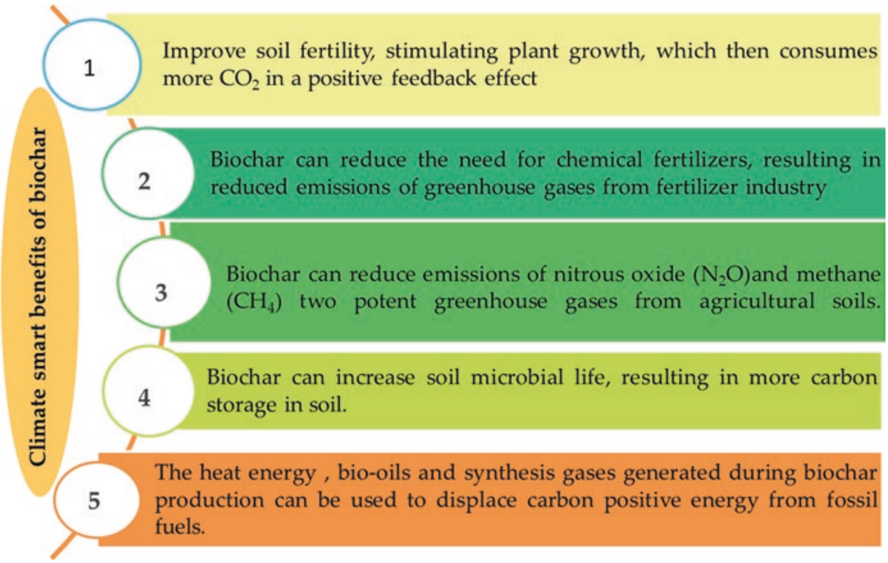
Table 5.3 (continued)

Crops	Soil type	Biochar rate (t/ha)	Fertilizer rate (kg/ha)	Yield / biomass increase over control (%)	Additional information
Maize	HaplicLuvisol	20	Nil	+66 (Cob yield)	Maize grain yield did not significantly increase in the first year after the biochar application, but it increased at plots with the 20 t/ha of biochar over the control by 28, 30 and 140% in three following years (Vitkova et al. 2017).

5.5 Implications of Biochar on Climate Change

5.5.1 Biochar Effect on Carbon Sequestration

Carbon in biochar can persist in soils over a long time. Beyond the carbon sequestered in the internal structure, biochar incorporated in soils also offers numerous other potential climate benefits.



Carbon sequestration is a process in which carbon is captured and stored to prevent it from being emitted into the atmosphere (Duku et al. 2011). It is essential that the carbon is transferred to a passive carbon pool that is stable or inert, in order to decrease C emission to the atmosphere. Hence, biochar provides an easy route from the active carbon pool to the passive pool. Transferring, even a small amount of the carbon that cycles between the atmosphere and plants, to a much slower biochar cycle, would impact greatly on atmospheric CO_2 concentrations because of the annual uptake of CO_2 by plants from the atmosphere through photosynthesis is eight times greater than anthropogenic GHGs emissions. Biochar is biologically and chemically more stable than the original carbon form, due to its molecular structure and its origins.

It is difficult for the sequestered carbon to be released as CO_2, making this a good method for carbon sequestration (Shafie et al. 2012; Lehmann 2009). The diversion of even 1% of the net annual uptake of carbon by plants into biochar would mitigate almost 10% of current anthropogenic carbon emissions (Lehmann and Joseph 2009). It is assumed that 3 billion tonnes of biochar are produced annually. This, in turn, reduces approximately 3 billion tonnes of atmospheric carbon emissions if all of the biomass (60.6 billion tonnes) is regenerated in the form of biochar through pyrolysis (Fernandez-Lopez et al. 2015). An estimated 1 billion tonnes of carbon will be sequestered annually by 2030, which is a rationally conservative approximation of the potential of biochar (Shackley et al. 2009). The thermochemical conversion of biomass into biochar through pyrolysis increases the recalcitrance of the carbon that originated in the biomass. The addition of biochar of similar carbon content to soil leads to steady soil carbon levels, due to its stability in soil (Lehmann et al. 2006). The biochar acts as a carbon sink that remains in the soil for long periods of time, possessing high levels of resistance to chemical and biological degradation, in turn increasing terrestrial carbon stocks. It is estimated that 20% of the total carbon biomass can be captured by conversion into biochar (Lehmann 2007). The common consensus is that soil is a finite C sink at best; the application of biochar provides an opportunity for reducing C emissions and sequestering C for soil remediation (Freibauer et al. 2004; Lal 2004).

5.5.2 Biochar for the Reduction of GHG Emissions

In the carbon cycle, atmospheric CO_2 is fixed by photosynthetic organisms (e.g. plants) and then it is converted into biomass that is mixed with soil when these organisms die. The biomass in soil is mineralized and microbial respiration causes the evolution of CO_2 to the atmosphere. When biochar is applied to soil, its recalcitrant nature causes it to stay in the soil for long periods of time, thereby reducing GHG emissions. Pyrolysis products (bio-oil, syngas) are burned as fuel, releasing CO_2 into the atmosphere that will be utilized by plants, and ultimately converted into biomass again. The carbon cycle of biochar-production has some indirect GHG-emission sources as well. They conducted a life cycle assessment of pyrolysis and concluded that the operation and maintenance of the pyrolysis process contribute to 89% of its GCG emissions, while building works, equipment, and transportation contribute 7.2, 3.33, and 0.23%, respectively(Yang et al. 2016). Global warming potential of several biochars derived from agriculture, poultry litter, sewage sludge, cattle manure, and food waste was compared and reported negative values for almost all of the biochar cycles, averaging −0.9 kg CO_2eq/kg, indicating that more GHG is consumed than emitted (Alhashimi and Aktas 2017).

Apart from CO_2, methane (CH_4) and nitrous oxide (N_2O) emitted from soil have the potential to influence climate. Agriculture is a primary contributor to atmospheric GHGs. CH_4 is generated by soil microorganisms under anaerobic conditions through the methanogenesis. CH_4 is approximately 20 times more powerful than CO_2 in absorbing thermal radiation trapped in the Earth's troposphere, and this augments global warming. Methane emissions were close to zero when biochar was applied at a rate of 2% to the soil. Reduction in CH_4 emissions involves increased soil aeration that may lead to reductions in the frequency and extent of the anaerobic conditions under which methanogenesis occurs (Verheijen et al. 2010).

Another study showed that the biochar amendment significantly reduced total indirect CO_2 while increasing CH_4 emissions from paddy soil (Zhang et al. 2010). The CH_4 emission mainly depends on the physical and chemical properties of the biochar, soil type, soil microorganisms, water and fertilizer management (Van Zwieten et al. 2009). Nitrous oxide (N_2O) is produced by soil microorganisms through nitrification and denitrification. N_2O is 300 times more potent than CO_2 in absorbing thermal tropospheric radiation that enhances global warming. The production of N_2O is greatly affected by the presence of moisture in the soil, as higher moisture content (>70%) promotes the anaerobic conditions that favor denitrification, whereas lower moisture content (<50%) is strongly associated with nitrification. Around 8–23 times more N_2O is generated under conditions of high moisture content (80%) than at lower moisture content (40%) (Bruun et al. 2011). High soil moisture content, with 73–83% water-filled pore space (WFPS), promotes N_2O production, while this was not detected at the lower moisture content (64% WFPS). The addition of 10% biochar to soil (78% WFPS) reduced N_2O emissions by 89% (Yanai et al. 2007).

Biochar-induced reductions in N_2O are affected by the amount of biochar applied; higher application rates (20–60%) reduced N_2O by up to 74% while no reduction was observed at lower application rates (2–10%) (Spokas et al. 2009). Similarly, no reduction in N_2O emissions was found after addition of 4% biochar to soil. They observed that failed to find an immediate decline in N_2O emissions when soils were amended with low levels of biochar (10%) under 85% WFPS conditions, however, they observed a 73% reduction in N_2O over two subsequent rewetting cycles. Clearly, biochar under these circumstances, eventually exhibits improve sorption capacity (Yanai et al. 2007). Biochar soil amendment can affect nitrogen (N) transfer and soil N cycling processes that reduce N_2O emissions. Biochar aids in the biological immobilization of inorganic N that helps to retain N and decrease ammonia volatilization, as biochar contains low N concentrations and high C/N ratios. Biochar efficiently adsorbs NH_3 from the soil and acts as a buffer, thereby potentially decreasing ammonia volatilization from agricultural fields (Oya and Iu 2002). They found a reduced NO_3-N pool in biochar-amended soil plots and assumed that biochar particles enhanced the adsorption and uptake of NH_3. The impact of biochar on soil N_2O fluxes is variable and depends on factors such as soil type, soil water content, additional fertilizer application, biochar feedstock, and pyrolysis temperature. Moreover, biochar is an efficient adsorber of dissolved ammonium, nitrate, phosphate, and other ionic solutes, as well as hydrophobic organic pollutants in soil and water (Taghizadeh-Toosi et al. 2011).

5.6 Implications of Biochar on Environmental Clean-Up

Biochar can be an effective amendment for immobilizing heavy metals in contaminated soils but has variable effects depending on its chemical and physical properties and those of the treated soil. Meta-analysis results showed that across all studies, biochar addition to soils resulted in average decreases of 38, 39, 25 and 17%, respectively, in the accumulation of Cd, Pb, Cu and Zn in plant tissues. The effect of biochar on heavy metal concentrations in plants varied depending on soil properties, biochar type, plant species, and metal contaminants. The largest decreases in plant heavy metal concentrations occurred in coarse-textured soils amended with biochar. Biochar had a relatively small effect on plant tissue Pb concentrations, but a large effect on plant Cu concentrations when applied to alkaline soils. Plant uptake of Pb, Cu, and Zn was less in soils with higher organic carbon contents. Manure-derived biochar was the most effective for reducing Cd and Pb concentrations in plants as compared to biochars derived from other feedstocks. Biochar having a high pH and used at high application rates resulted in greater decreases in plant heavy metal uptake (Chen 2018).

The use of biochar for the removal of organic and heavy-metal contaminants from aqueous media is a relatively new and promising water and wastewater treatment technology. The presence of cellulose, hemicelluloses, lipids, sugars and proteins in agricultural residue feedstocks provides a variety of functional groups. These functional groups can be physically activated upon pyrolysis and by further steamer CO_2 treatment, to improve their ability to adsorb contaminants (Inyang et al. 2011).

The type and concentration of surface functional groups on biochar plays an important role in the adsorption capacity of the biochar. The carbon-structured matrix, the high degree of porosity, surface area, and a strong affinity for non-polar substances such as PAHs, dioxins, furans, and other compounds enable it to play a vital role as a surface sorbent for in controlling contaminants in the environment as a surface sorbent(Yu et al. 2009).

Biocharactsasasuper-sorbent for the removal of both organic and inorganic contaminants in soil and water. Considering the wide variety and availability of cheap feedstocks for biochar production, the use of biochar could be a cheaper remediation technology option for Pb adsorption than activated charcoal (Shang et al. 2012).

The surface of biochar can contain abundant and abundance of chemically reactive groups, (OH, COOH and ketones) that bestow biochar with an immense potential to adsorb heavy metals and toxic substances, such as aluminum (Al) and

Table 5.4 Effect of biochar application on the bioavailability of heavy metals in soils

Feedstock	Production temperature	Contaminant	Effect
Cotton stalks	450 °C	Cd	Reduction of the bioavailability of Cd in soil by adsorption or co-precipitation (Zhou et al. 2008)
Hardwood biochar	400 °C	As	Significant reduction of as in the foliage of *Miscanthus* (Hartley et al. 2009)
Eucalyptus	550 °C	As, Cd, Cu, Pb, Zn	A decrease in As, Cd, Cu, and Pb in maize shoots (Namgay et al. 2010)
Orchard prune residue	500 °C	Cd, Cr, Cu, Ni, Pb, Zn	Significant reduction of the bioavailable Cd, Pb, and Zn, with Cd showing the greatest reduction; an increase in the pH, CEC, and water-holding capacity (Fellet et al. 2011)
Chicken manure & green waste	550 °C	Cd, Cu, Pb	Significant reduction of Cd, Cu, and Pb accumulation by Indian mustard (Park et al. 2013)
Chicken manure	550 °C	Cr	Enhanced soil Cr (VI) reduction to Cr (III) (Choppala et al. 2012)
Sewage sludge	500 °C	Cu, Ni, Zn, Cd, Pb	Significant reduction in plant availability of the metals studied (Mendez et al. 2014)
Rice straw	300–400 °C	Cu, Pb, Cd	Significant reduction in concentrations of free Cu, Pb, and Cd in contaminated soils; identification of functional groups on biochar with high adsorption affinity to Cu (Jiang et al. 2012)
Quail litter	500 °C	Cd	Reduction of the concentration of Cd in the physic nut; greater reduction with the higher application rates (Suppadit et al. 2012)
Oakwood	400 °C	Pb	Bioavailability reduction by 75.8%; bio accessibility reduction by 12.5% (Ahmad et al. 2012)
Peanut shell & wheat straw	350–500 °C	Cd and Pb	5% PBC addition lowered Cd and Pb concentrations in grains by 22.9 and 12.2%, while WBC addition lowered them by 29.1 and 15.0%, respectively (Xu et al. 2017)

manganese (Mn) in acid soils, and arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni) and lead (Pb) in heavy metal contaminated soils (Singh et al. 2017a, b, c, d, e, 2018; Tiwari et al. 2018; Yuan et al. 2011). Due to the dissociation of oxygen-containing functional groups, biochars mostly carry net negative charges on their surfaces. So, it can be utilized as low-cost adsorbents for the removal of organic contaminants and heavy metal cations from water (Qiu et al. 2008). Several other researchers reported the efficiency of heavy metal removal using biochar with derived from rice husk (Liu and Zhang 2009), corn straw (Chen et al. 2011), peanut straw (Tong et al. 2011), olive pomace (Pellera et al. 2012) as well as oak wood and bark (Xue et al. 2012). Most of the heavy metals were adsorbed on the biochar surface using through inorganic constituents in the biochar (Table 5.4). Organic contaminants were either removed due to sorption or interaction with functional groups and surface charges.

Several studies report the removal of heavy metals including As(III, V) using iron-impregnated magnetic biochars (Wang et al. 2015), Cr(VI) using zinc and chitosan-modified biochars (Gan et al. 2015 and Huang et al. 2016), Pb (II), Cu(II), and Cd(II) using a $KMnO_4$-treated wood biochar (Wang et al. 2015), and Hg(II) using a graphene-treated biochar; Pb(II) and As(V) is the most studied of these heavy metals. Adsorption capacities for Pb (II) of 4.9–367.6 mg^{-1} were reported for a ZnS-biochar (Yan et al. 2015). Removal of phosphorus has also been reported in several studies using oxides of Ca, Mg, and Al-modified biochars (Liu et al. 2016). The use of catalytic and degradative nanoparticles, such as nanoscale zerovalent ions (Yan et al. 2015) and graphitic C_3N_4 have been reported to remove several organic chemicals. The use of nanocomposites is clearly a promising technology for the treatment of aqueous media, but it is in its infancy and requires a lot of further research, especially regarding the re-use, desorption, and disposal of these metal-attached nanocomposites.

5.7 Conclusions

Agricultural residues and municipal yard wastes can be a significant burden on the environment. Nutrients contained in the wastes may cause eutrophication of surface waters or pollution of groundwaters. Landfills of municipal green wastes may generate large quantities of greenhouse gases. But all these substances can be useful when managed properly. Biochar production is an intelligent way of recycling organics for soil amendment and reduces environmental pollution. Across the results of global biochar experiments clearly revealed that the application of different sources and quantity of biochar in different soil types showed positive improvement of soil health; positive, negative and no effect on greenhouse gas emission reduction. The better and poor crop growth and high and low yield response of biochar were noticed in different biochar experiments. Heavy metal abatement potential of biochar also varied among the biochar and heavy metals. The wider variation of biochar responses in the soil system mainly due to the feedstock types, pyrolysis method, and temperature. So prioritize and standardize the production technique, characterization and application of different sources biochars in different crops under varied soil types are very imperative to mitigate the vulnerability of climate change and sustain soil health in a different ecosystem (Fig. 5.6).

- The opportunities for carbon sequestration and the reduction of greenhouse gas emissions have not been explored in different ecosystems under field conditions, but they are potentially significant under changing climate.
- Further, it is to be studied in detail for promoting biochar as a greening approach to the environment as well as human health. Published data for the effect of biochar on trace gas emission is extremely limited under field conditions but has a potentially great impact on the net benefit of a biochar strategy.

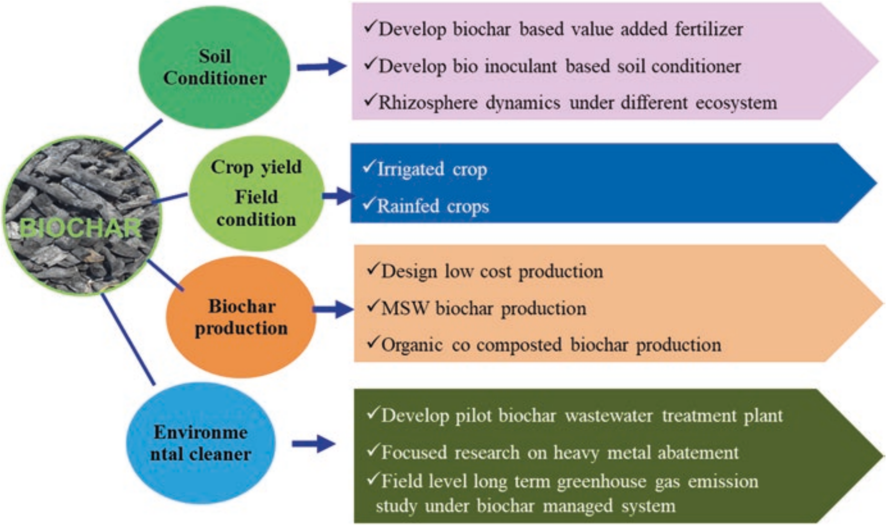


Fig. 5.6 Future Thrust Area in Biochar Research

- Good predictive models will be necessary for this to be reflected in future accounting for biochar projects.
- Municipal solid waste disposal through biochar production one of the viable options and it has to be studied in detail about production, characterization, and standardization for different crops.
- Long term effect of biochar application on soil health to be ascertained and its effect on crop yield to be studied in a long-term experiment under changing climate.

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