Chapter 7
Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation

Dipak Kumar Gupta, Chandan Kumar Gupta,
Rachana Dubey, Ram Kishor Fagodiya, Gulshan Sharma,
Keerthika A., M. B. Noor Mohamed, Rahul Dev, and A. K. Shukla,

Abstract Global warming and associated climate change are becoming a threat to almost all the ecosystems on the earth. According to the intergovernmental panel on climate change (IPCC) special report 2019, the global mean surface (land and ocean) temperature has been increased by 0.87 °C while mean of land surface air temperature has increased by 1.53 °C since 1850–2015. Climate change is affecting food security and human life due to warming, changing precipitation patterns, and the greater frequency of some extreme events. The main cause of global warming is the continuous increase in the atmospheric concentration of greenhouse gases (GHGs) like CO_2, CH_4, N_2O and fluorinated gases due to several anthropogenic activities. Therefore, reducing the increasing concentration of GHG is necessary to slow down global warming and climate change. Among several options of greenhouse mitigation, application of biochar into the soil is gaining popularity due to several advantages over other options. Biochar is a highly stable form of carbon derived from pyrolysis of biomass at relatively low temperatures. Application of biochar into the soil has been reported to provide multiple benefits like increase in

---

D. K. Gupta (✉) · Keerthika A. · M. B. Noor Mohamed · A. K. Shukla
ICAR-Central Arid Zone Research Institute, Regional Research Station,
Pali Marwar, Rajasthan, India
e-mail: deepak.gupta@icar.gov.in

C. K. Gupta
Department of Agro-meteorology and Environmental Science, Birsa Agricultural University,
Ranchi, Jharkhand, India

R. Dubey
ICAR-Research Complex for Eastern Region, Patna, Bihar, India

R. K. Fagodiya
Division of Irrigation and Drainage Engineering, CSSRI, Karnal, Haryana, India

G. Sharma
ICAR-National Bureau of Soil Survey and Land Use Planning, Regional Center,
Jorhat, Assam, India

R. Dev
ICAR-Vivekananda Parvatiya Krishi Anusandhan Sansthan, Almora, Uttarakhand, India

J. S. Singh, C. Singh (eds.), *Biochar Applications in Agriculture and Environment Management*, https://doi.org/10.1007/978-3-030-40997-5_7

crop yield, nutrient and water use efficiency and several environmental benefits. Recalcitrant nature, relatively higher carbon content and easily available feedstock make biochar a highly sustainable and quick option for carbon sequestration into the soil. Biochar application into the soil not only helps in carbon sequestration but also provides a better option for managing agricultural residues. The application of biochar has also reported for reducing a considerable amount of methane and nitrous oxide emission from the agricultural field due to its priming effect on the soil. Biochar yield, physical properties, and carbon content varies with the type of feedstock and pyrolysis condition. Therefore, the rate of carbon sequestration and mitigation of greenhouse gas is also highly variable, however, the biochar application ultimately leads to a positive contribution towards climate change mitigation. However, most of the reported benefits are confined to laboratory and field trial at institute level, widespread adoption of biochar on farmer's field is still lacking. In the present chapter, all the aspects of biochar towards carbon sequestration and greenhouse mitigation have been well discussed.

Keywords Carbon sequestration · Climate change mitigation · Greenhouse gas · Global warming · Crop residue

7.1 Introduction

The global mean surface (land and ocean) temperature has been increased by 0.87 °C (0.75 °C–0.99 °C) while mean land surface air temperature has increased by 1.53 °C (1.38 °C–1.68 °C) since 1850 to 2015 (IPCC 2019). Global warming is resulting in changes in the global climate system and almost all the natural and human systems in many countries. According to the intergovernmental panel on climate change (IPCC) special report 2019, global warming has resulted in an increased frequency, intensity and duration of heat-related events; change in precipitation patterns and greater frequency of some extreme events in most land regions. Yields of some crops (e.g., maize and wheat) in many lower-latitude regions are being affected negatively by observed climate changes. The main cause of global warming is a continuous increase in the atmospheric concentration of greenhouse gases (GHG) like CO_2, CH_4, N_2O and fluorinated gases (F-gases: hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride) due to several anthropogenic activities. The total GHG emission has increased from 27 Gt CO_2 eq/year in 1970 to 49 Gt CO_2 eq/year in 2010 (IPCC2014a, b). Out of these greenhouse gases, CO_2 is a major greenhouse gas responsible for about 72% of global warming followed by CH_4 (20%), N_2O (5%) and F-gases (3%) (Fig. 7.1).

Despite several climate change mitigation measures, annual GHG emission is increasing on an average rate of 2.2% (1.0 Gt CO_2 equivalent) per year from 2000

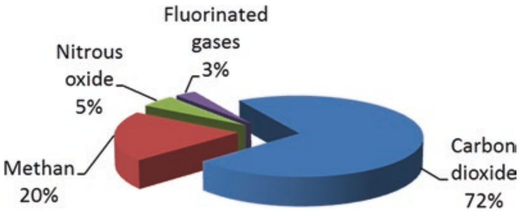

Fig. 7.1 The contribution of greenhouse gases in total global warming (IPCC 2014a, b)

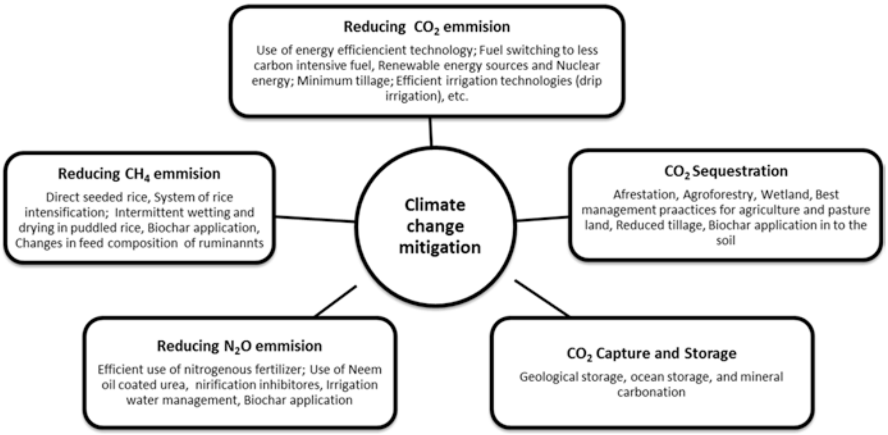

Fig. 7.2 Strategies for climate change mitigation

to 2010 compared to 1.3% (0.4 Gt CO_2 equivalent) per year from 1970 to 2000 (IPCC 2014a, b). It is expected that future emission of GHG will cause warming and long-lasting changes in all components of the climate system. Limiting total human-induced warming to less than 2 °C relative to the period 1861–1880 is necessary to stop the devastating effect of climate change. Without any additional mitigation, the global mean surface temperature has been predicted to increase between 3.7 °C and 4.8 °C in 2100 as compared to pre-industrial levels. Limiting warming to less than 2 °C would require to keep cumulative CO_2 emissions since 1870 to remain below about 2900 Gt CO_2 (IPCC 2014a, b). However, about 1900 Gt CO_2 had already been emitted up to 2011. Therefore, reduction in the atmospheric concentration of GHG is an urgent global need to arrest global warming and climate change.

Global warming can be reduced by the simultaneous effort of reducing CO_2, CH_4, N_2O, and F-gases emission at the source and capturing already emitted atmospheric CO_2 and storing in the long-lived pool. Therefore, identifying technologies that reduce anthropogenic GHG emission at the source as well as technologies that capture and store already emitted GHG become necessary to mitigate climate change. Several suggested strategies for the mitigation of climate change have been depicted in Fig. 7.2.

Among these, strategies that led to carbon sequestration in the soil as well as reduce CH_4 and N_2O emission should be considered as one of the most potent

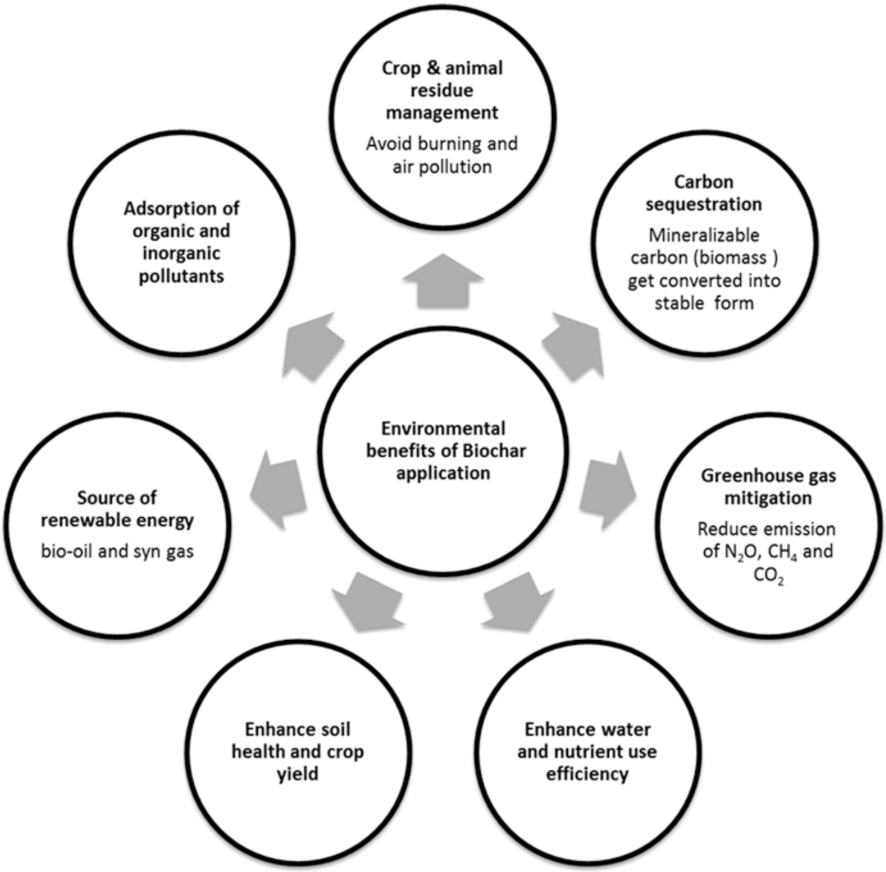

Fig. 7.3 Environmental benefits of biochar application in to the soil

options. The conventional methods like agroforestry, afforestation and soil management are being promoted for soil carbon sequestration. However, increasing the levels of soil organic carbon by conventional agricultural management can take many years (Denman et al. 2007). Recently, interest has grown to sequester atmospheric carbon into biochar followed by its application to the soil. Soil application of biochar is being frequently reported as a potential option for climate change mitigation through carbon sequestration and other agricultural and environmental benefits. Application of biochar into the soil not only sequester carbon but also reduce emission of N_2O and CH_4 from soil, provide suitable option for management of agricultural and forestry wastes, enhancement of soil sustainability, reduction in fertilizer requirements, production of renewable energy and several other environmental benefits (Waters et al. 2011; Lehmann and Joseph 2009; Jeffery et al. 2011; Wang et al. 2016; Majumder et al. 2019). The reported potential benefits of biochar in environmental management have been depicted in Fig. 7.3. Therefore, the present chapter will discuss the role of biochar in carbon sequestration and greenhouse gas mitigation.

7.2 Carbon Dioxide and its Impact on Global Warming

Among different greenhouse gases responsible for global warming, CO_2 has the least global warming potential. Therefore, the global warming potential of other GHGs is determined with respect to CO_2. It means CO_2 absorbs less heat per molecule than the other greenhouse gases like methane and nitrous oxide. However, higher atmospheric concentration and a long life cycle in the atmosphere make CO_2 the most responsible GHG for global warming. It contributes about 72% of the total global warming induced by anthropogenic activities (IPCC 2014a, b). Before the industrial revolution (the mid-1700s), the global average atmospheric concentration of CO_2 was about 280 ppm and it has reached 407.4 ± 0.1 ppm in 2018 (Dlugokencky et al. 2019). The major sectors responsible for CO_2 emission are fossil fuel combustion and industrial processes. CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010 (IPCC 2014a, b). Therefore, rising atmospheric CO_2 concentration can be reduced by two processes (a) reducing emission by using energy-efficient technology; switching to renewable energy like biodiesel, ethanol, wind energy, solar power, reduced tillage, and efficient irrigation system and (b) capturing and storing emitted CO_2 into the long-lived pool.

7.3 Role of Biochar in Carbon Sequestration

Plant assimilates CO_2 by the process of photosynthesis and stores it into the above and below-ground biomass as well as supply liters to the soil for soil organic carbon buildup. This process of CO_2 assimilation and storage by the plant into the long-lived reservoir of plant biomass and soil organic carbon is known as carbon sequestration. However, the duration of C-storage in biomass is highly variable. It varied from a few years in the annual crop to 5–60 years in the agroforestry system and a few hundred years in the forests. Soil organic carbon buildup by natural process is very slow and also prone to lose under intensive tillage practices and soil erosion. Therefore, land-use systems which lead to a large amount of carbon assimilation within a relatively short period and it's storage for long period are suitable options for reducing the concentration of atmospheric CO_2 and mitigating global warming and climate change.

Among different options of soil carbon sequestration, biochar application to soil is being considered as the most promising option for long term storage of carbon sequestered in biomass. It is reported that natural biochar sink in Australia is sequestering about 21 million tons of carbon dioxide annually (Graetz and Skjemstad

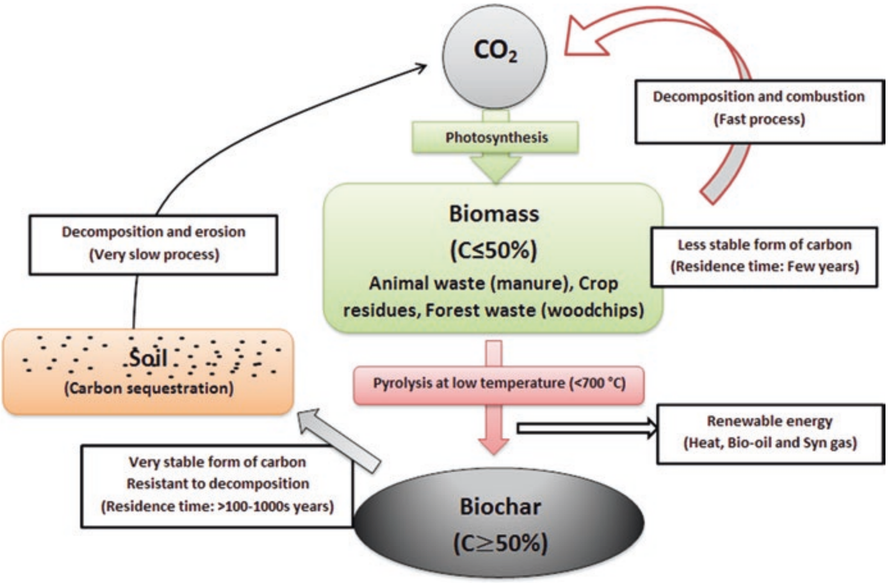

Fig. 7.4 Process of carbon sequestration by biochar

2003). Preliminary calculations suggests that if 2.5% of the world's agricultural land produces biochar (ideally from wastes) for application into topsoil then atmospheric CO_2 levels might be reduced to pre-AD 1752 level by 2050 (Jacquot 2008). According to Lehmann et al. 2006, globally, up to 12% of all anthropogenic land-use change emissions can be offset annually if slash-and-burn agriculture is replaced by slash-and-char systems. Further, it has been also suggested that, if other greenhouse gas emissions from soils after application of biochar are not elevated, and if emissions associated with production and transport of biochar and/or its feedstocks do not off-set the sequestered C, then the overall greenhouse effect will be abated by application of biochar into the soil (Roberts et al. 2010). This high potential of biochar for carbon sequestration is being advocated mainly due to its high carbon content and very stable form. The overall mechanism of carbon sequestration by biochar can be understood in Fig. 7.4.

The mechanism responsible for the higher potential of long term carbon storage by biochar application into the soil can be grouped in following properties of biochar

(i) Biochar is a stable and rich form of carbon
(ii) It leads to a relatively higher rate of carbon sequestration
(iii) It leads to agricultural and forestry waste management

7.3.1 Biochar: A Stable and Rich Form of Carbon

There are two intrinsic properties of biochar that make it a very potential option for long term carbon sequestration in the soil. First is, its stability i.e. resistance to biotic and abiotic decay into the soil and second is relatively higher carbon content as compared to biomass. The estimated C-residence time of biochar in the soils has been reported to range between hundreds to thousands of years (Liang et al. 2008; Kuzyakov et al. 2009; Major et al. 2010; Zimmerman 2010). Wang et al. (2016) through a meta-analysis of 24 studies reported 108 days and 556 years mean residence time of labile and recalcitrant biochar resulting in only a small part of biochar bioavailable and remaining 97% contribute directly to long-term C sequestration in soil. The initial rate of biochar decomposition is relatively faster and gets decreased with time. The median rate of biochar decomposition in this meta-analysis was found to be 0.0046% day^{-1}. The initial fast rate of decomposition is mainly due to the decomposition of the labile condensed fraction of biochar. This initial fast rate of decomposition disappears after 2 years and maintained at a very low level over prolonged periods (Kuzyakov et al. 2014; Fang et al. 2014).

The primary reason for the higher stability of biochars in soils is their chemical recalcitrance i.e. resistant to microbial decomposition (Liang et al. 2008) which is due to the presence of aromatic structures. An increase in the aromaticity of organic matter leads to a more recalcitrant nature of the organic matter. Biochar is produced by the process of pyrolysis of biomass in an oxygen-limited environment at relatively low temperatures. During pyrolysis, the biomass undergoes devolatilization and the solid portion gets enriched in carbon. The H and O are preferably removed over C and the H/C and O/C ratios tend to decrease as biomass undergoes its transformation into biochar. This process results in very low H/C and O/C ratios in biochar as compared to the original biomass feedstock (Nsamba et al. 2015). The ratio of H/C and O/C is an indicator of the degree of aromaticity, carbonization, maturation and the stability of biochar (Lehmann and Joseph 2009). According to Krull et al. (2009), decreasing the H/C ratio in biochars indicates an increasing aromatic structure in the biochar. As pyrolysis temperature increases, the turbostratic layering inside of biochar increases in orderliness, the mass percentage of the fused aromatic C thereby increases, the produced biochar is thus often low in easily degradable C but high in recalcitrant C (Nguyen et al. 2010). The value of H/C ratios greater than 0.7 indicates a low biochar quality and pyrolysis deficiencies and the value of the O/C ratio greater than 0.4 indicates lower biochar stability (EBC 2012). The International Biochar Initiative (IBI) recommends a maximum value of 0.7 for the molar H/C ratio (Nsamba et al. 2015, Mary et al. 2016) to distinguish biochar from biomass that has not been or only somewhat thermo-chemically altered.

On the weight basis, biochar contains a high percentage of carbon as compared to original feedstock, however, it varied with the type of feedstock and pyrolysis condition. The carbon content has been reported to vary 29–50% in rice straw derived biochar and 70–85% in apple and oak tree branch at pyrolysis temperature ranging from 400–800 °C (Jindo et al. 2014). Billa et al. (2019) reported 57.59%

carbon in rice husk derived biochar to 93.38% in Cassava residue derived biochar at the standard procedure for Biochar production. Lee et al. (2013) reported more than 84% carbon in biochar obtained from Bagasse, Cocopeat, Paddy straw, Palm kernel shell, Wood stem and Wood bark at constant pyrolysis temperature of 500 °C. Windeatt et al. (2014) reported 90.6, 88.6, 54.5, 93.9, 75.3, 83.2, 71.8 and 82.6% carbon in biochar obtained from Palm shell, Sugarcane bagasse, Rice husk, Coconut shell, Wheat straw, Cotton stalk, Olive pomace, and Coconut fiber. Purakayastha et al. (2015) reported 66% carbon in maize biochar, followed by 64% in pearl millet biochar, 64% in wheat biochar and 60% in rice biochar.

Charcol is also mineralized in soil otherwise the earth's surface would be converted into charcoal within a period of time. Shneour (1966) successful oxidized artificial graphitic 14C to $14CO_2$ in the presence of soils with high microbial activity. Thermodynamically, the abiotic oxidation of elemental C to CO_2 is a strongly exothermic reaction ($\Delta H = -94{,}052$ kJ). However, under environmental conditions, this process is extremely slow (Shneour 1966). Therefore, biochar is much more stable than uncharred organic matter i.e. biomass, and that this difference is the relevant measure for its ability to prevent carbon from being returned rapidly to the atmosphere.

7.3.2 Carbon Storage Potential of Biochar

Biochar is a rich source and a very stable form of carbon obtained from the pyrolysis of biomass. Biochar production itself do not sequester carbon from the atmosphere, however, it leads to the transformation of carbon sequestered in biomass into more stable form i.e. biochar as well as helps in enhancing soil organic carbon sequestration. It has been reported that conversion of biomass carbon to biochar leads to storage of about 50% of the initial carbon compared to the low amounts of carbon retained after burning (3%) and biological decomposition (less than 10–20% after 5–10 years) (Lehmann et al. 2006). Windeatt et al. (2014) reported 21.3–32.5% carbon retained in biochar obtained from pyrolysis of Palm shell, Sugarcane bagasse, Rice husk, Coconut shell, Wheat straw, Cotton stalk, Olive pomace and Coconut fiber at 600 °C. The balance of carbon stored in the biochar, as the mass fraction of the carbon remaining in biochar from the original feedstock carbon, was between 45% for olive pomace and 57% for coconut fiber. The average value of carbon stored from the original feedstock carbon was 51%. Therefore, the biochar itself represents a carbon stock that once added to soil tends to persist for a long time. Further, biochar additions can also interact with the native organic matter already present in soils, and either stimulate or reduce the rate of decomposition of the native soil organic matter (Paustian et al. 2019). Zhang et al. (2018) reported a 76.29% increase in SOC after 5 years of wheat straw biochar application in the soil at the rate of 40 t/ha. Both positive and negative effects on native soil organic matter decomposition following biochar addition have been reported (Song et al. 2016;

Wang et al. 2016), but in most cases, these effects on the long-term soil C balance are small (Wang et al. 2016).

However, the net amount of carbon available for storage depends upon the percentage of biochar obtained from the original feedstock and carbon content of biochar. The carbon sequestration potential of the biochars, which is a measure of the amount of the original feedstock carbon that would be retained in biochar for long time periods upon addition to soil, is generally calculated by the following equation (Windeatt et al. 2014).

$$CSB(\%) = \frac{\mathrm{M} \times \mathrm{Ch} \times C_{Ch} \times R_{50}}{\left(\mathrm{M} \times C_F\right)}$$

where, CSB is carbon sequestration potential of biochar (%), M is the mass of feedstock (g), Ch is the yield of biochar (%), C_{Ch} is the carbon content of the biochar, R_{50} is the recalcitrance index and C_{F} is the carbon content of the feedstock.

$$R_{50X} = \frac{T_{50x}}{T_{50\,graphite}}$$

where $\mathrm{T}_{50\mathrm{x}}$ and $\mathrm{T}_{50\ \mathrm{graphite}}$ are the temperatures at which 50% of the biochar and graphite are oxidised respectively.

During pyrolysis both mass and carbon content of biomass feedstock decreases due to loss of volatile compounds. The biochar yield and carbon content have an inverse relation with the temperature of pyrolysis. With the increase in pyrolysis temperature, the biochar yield decreases while carbon content increases (Singh et al. 2017a, b, c; Singh et al. 2018; Tiwari et al. 2018; Jindo et al. 2014; Zhang et al. 2017). Increased heating temperature results in higher concentrations of fixed C, total C and stable-C in biochar, as well as higher heating value due to the increased release of volatile compounds (Crombie and Masek 2015). Further, chemical composition and carbon content of feedstock varied and therefore of biochar. It has been reported that biochar carbon content and biochar yield increase with the increase in lignin content of the feedstock (Sun et al. 2017). Biomass feedstock's with relatively high ash contents produced relatively low fixed carbon biochars, which was attributed to the high ash content inhibiting the formation of aromatic carbon forms (Enders et al. 2012; Sun et al. 2017). The lowest carbon content was seen in rice husk biochar which has the highest ash content, conversely, the highest carbon content was seen in the coconut shell biochar which has the lowest ash content.

Table 7.1 Rotation period of major agroforestry trees species in India

S.N.	Tree species	Family	Rotation (Years)	Uses
1.	*Acacia mangium*	Fabaceae	6–20	Pulpwood and timber
2.	*Acacia nilotica*	Fabaceae	30–40	Timber and gum Arabic
3.	*Ailanthus excelsa*	Simaroubaceae	5–20	Matchwood and leaf fodder
4.	*Alnus nepalensis*	Betulaceae	25–30	Timber
5.	*Neolamarckia cadamba*	Rubiaceae	5–10	Pulpwood and timber
6.	*Albizia lebbeck*	Mimosaceae	10–20	Timber
7.	*Casuarina equisetifolia*	Casuarinaceae	4–6	Pulp and paper, boles
8.	*Dalbergia sissoo*	Papilionaceae	10–60	Timber and fodder
9.	*Eucalyptus tereticornis*	Myrtaceae	4–8	Pulp and paper, plywood
10	*Gmelina arborea*	Verbenaceae	4–12	Timber and firewood
11.	*Hardwickia binata*	Fabaceae	20–30	Timber and fodder
12.	*Leucaena leucocephala*	Leguminosae	3–4	Pulp and paper, poles, fodder
13.	*Melia dubia*	Meliaceae	5–15	Plywood
14.	*Millettia pinnata*	Leguminosae	50–60	Oil from seed kernals (biodiesel)
15.	*Populus deltoides*	Salicaceae	6–8	Pulpwood and paper, plywood
16.	*Prosopis cineraria*	Leguminosae	5–30	Timber and fodder
17.	*Salix alba.*	Salicaceae	15–20	Pulpwood, match splints and timber
18.	*Tectona grandis*	Verbenaceae	20–60	Timber
19.	*Terminalia arjuna*	Combretaceae	10–20	Plywood, timber and bark

7.3.3 A Relatively Faster Rate of Carbon Sequestration

The carbon sequestration in biomass and soil by natural process takes a long time. Gupta et al. (2019) reported that sequestration of about 31.6 Mg C ha^{-1} in biomass and 3.32 Mg C ha^{-1} in soil by *Hardwickia binata* based silvopasture system took 30 years. Measured rates of soil C sequestration through the adoption of recommended management practices have been reported to range from 0.05 to 1.0 Mg C ha^{-1} year^{-1}(Lal 2004). In India carbon sequestration potential of agroforestry systems has been estimated between 0.25–19.14 Mg C ha^{-1} year^{-1} in biomass and 0.003 to 3.98 Mg C ha^{-1} year^{-1} in soil (Dhyani et al. 2016). The period of biomass carbon sequestration by agroforestry depends on harvesting rotation. The harvesting period of different agroforestry tree species generally ranged from 5–60 years depending on their use (Chaturvedi et al. 2017) (Table 7.1). It means the agroforestry system stores carbon for 5–60 years and after harvesting of the tree, the stored biomass carbon gradually released to the atmosphere. However, the length of the C-locking period also depends on their use like timber, fuelwood and paper, and pulp. As compared to these systems, the application of biochar can lead to a faster rate of sequestration in the soil.

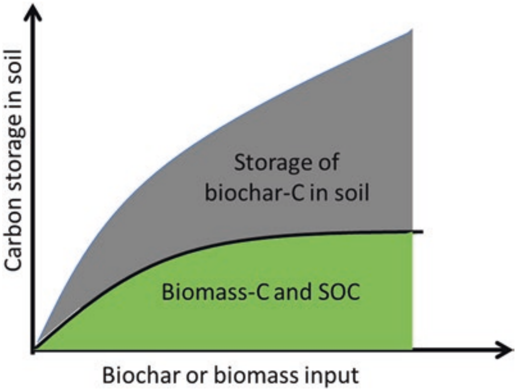

Fig. 7.5 Soil carbon storage after application of biochar and biomass in to the soil. (Modified from Wang et al. 2016)

Most of the study advocates use of agricultural, animal and forest residue as feedstock for the production of biochar. These feedstocks are annually available in large amount and their conversion into biochar takes a relatively short period of time depending upon the capacity of the kiln to produce biomass. After conversion to biochar, they are directly applied to the soil. Application rates of 10, 25, 50 and 100 t ha^{-1} were all found to significantly increase crop productivity when compared to controls, which received no biochar addition (Jeffery et al. 2011). The greatest positive effects were seen in biochar application rates of 100 t ha^{-1} (39%) (Jeffery et al. 2011). Biochar carbon is a natural constituent of many soils and soil function is not generally impaired (and maybe enhanced) with the addition of large quantities (e.g., 100 t/ha or more) of biochar. Thus biochar application to the soil can lead to storage of about 10–100 Mg C ha^{-1} in the form of biochar carbon within 2 years. However, the rate of biochar based carbon sequestration further varies with the frequency of biochar application into the soil. As compared to other biological system, each quantity of biochar applied to soil gets continuously accumulated over time with very little loss or decay (Fig. 7.5). Due to its recalcitrance to decomposition in soil, single applications of biochar can provide beneficial effects over several growing seasons in the field (Steiner et al. 2007; Major et al. 2010).

7.3.4 *Easily Available Feedstock for Biochar Production*

The feedstock suggested for biochar production should be sustainably available. Therefore unused agricultural crop residues are suggested as feedstock for biochar production. The commonly reported feedstock used for biochar production are rice straw, wheat straw, rice husk, coconut husk, coconut shell, cotton stalk, olive pomace, palm shell, rice husk, sugarcane bagasse, corn stover, cassava, corncob, coffee husk, groundnut husk, sawdust, poultry litter, paper pulp, wood chips, green waste, wood, peanut hull, pine chip (Jeffery et al. 2011; Windeatt et al. 2014; Billa et al. 2019). The world and Asian countries produced a large amount of crop residue annually thus provide sufficient feedstock for biochar production. In 2013, 5 billion tons of agricultural residues were produced worldwide out of which 47% was produced by Asia followed by America (29%), Europe (16%), Africa (6%) and Oceania (2%) (Cherubin et al. 2018). Most of this biomass is either burnt or discarded and some amount is used as animal feed, manure production, fuel, and soil incorporation.

India produced about 620 million ton crop residue in 2008–2009 out of which about 15.9% residue was burnt on the farm. Rice straw contributed 40% of the total residue burnt followed by wheat straw (22%) and sugarcane trash (20%) (Jain et al. 2014). In India, the disposal of such a large amount of crop residues is a major challenge. To clear the field rapidly and inexpensively and allow tillage practices to proceed unimpeded by residual crop material, the crop residues are burned in situ. Burning of crop residue eventually leads to unlocking of biomass sequestered CO_2 into the atmosphere as well as resource wastage and atmospheric pollution. Burning of crop residues emitted 8.57 Mt. of CO, 141.15 Mt. of CO_2, 0.037 Mt. of SOx, 0.23 Mt. of NOx, 0.12 Mt. of NH_3 and 1.21 Mt. of particulate matter in 2008–2009 (Jain et al. 2014). The burning of rice straw in Punjab and Haryana causes severe air pollution into adjoining states like Delhi. The efficient utilization of agricultural residue is very important for sustainable agricultural production.

Production of biochar from these resources thus provides a sustainable option for efficient management of crop residue, animal waste, forest by-products vis a vis improvement of soil fertility, carbon sequestration and crop growth. Modern biomass pyrolysis technologies can use agricultural and forestry wastes (such as forest residues, mill residues, field crop residues or urban waste to sequester around 30 kg of carbon for each GJ of energy produced (Lehmann et al. 2006). If available crop and forest biomass are converted into biochar at the rate of 35% recovery and product with 70% carbon then about 1402 million tone biochar can be produced per year worldwide. Similarly in India 113.3 million tons of biochar can be produced from crop residue and 250 million tons from wood residue per year (Table 7.2).

Table 7.2 Available crop residue and potential of biochar production (million ton/ha/year)

Biomass	Residue production	Biochar yield (35% recovery)	Biochar carbon content (70%)
World			
Cereals	3607.6	1443.0	1010.1
Legumes	382.1	152.8	107.0
Oil crops	275.2	110.1	77.1
Sugar crop	625.6	250.2	175.2
Tubers	119.6	47.8	33.5
Total residue	5010.1	2004.0	**1402.8**
India			
Crop residues	463.3	162.2	**113.5**
Wood residues	1019.8	356.9	**249.9**

Note: Value of crop residue production has been adopted from Cherubin et al. (2018) and Venkatesh et al. (2018)

7.4 Factors Affecting Role of Biochar in Carbon Sequestration and Greenhouse Gas Mitigation

7.4.1 Biochar Yield and Carbon Content in Biochar

The amount of carbon sequestered in the soil through biochar depends upon biochar and carbon content in the biochar. Both of these are highly variable and depend upon the type of feedstock and pyrolysis condition (Tiwari et al. 2019a, b; Singh et al. 2019; Kour et al. 2019). Therefore, optimum pyrolysis condition that leads to higher biochar yield and carbon content will ensure the higher potential for carbon sequestration.

7.4.2 Rate and Frequency of Application

The soil carbon stored in the form of biochar is directly proportional to the amount and frequency of biochar applied to the soil. The higher the rate of biochar application, the higher the amount of carbon will be stored in the form of biochar in the soil. Further frequency of application i.e. annually or biannually or another time interval that finally leads to the accumulation of biochar in the soil is the main factor. Therefore the optimum rate of application and frequency which has a positive impact on crop yield and environment is necessary to determine.

7.4.3 Methods of Application and Soil Management

Soil applied biochar is also subjected to loss mainly in three different ways: (1) by erosion from the surface, (2) by abiotic and (3) biotic degradation. Biotic and abiotic factors have a limited effect on biochar loss while erosion through water and wind may lead to loss of biochar from applied soil. Therefore methods of application that led to minimum loss will ensure a higher rate of carbon sequestration. Subsurface application has been suggested to minimize the loss of biochar and enhance its storage.

7.4.4 The Negative Effect of Biochar Application

Besides its potential agricultural benefits, biochar may contain inherent contaminants, either introduced by its feedstock (e.g., heavy metals), or co-produced during (improper) pyrolysis (e.g., polycyclic aromatic hydrocarbons) (Hilber et al. 2017). However, the link between biochar's inherent contaminants and toxicity to soil meso and macrofauna remains unclear, with data being often contradictory and influenced by feedstock and pyrolysis conditions.

7.4.5 Farmer Adoption

The ultimate user of biochar for soil application is farmers. Therefore, the rate of farmer adoption is one of the most influential factors for carbon sequestration in the soil through biochar. The latest development leads to a reduction in the production cost (−10 to 30 USD t^{-1}); however, the use of biochar in commercial agriculture remains scarce (Maroušek et al. 2019). While many beneficial reports on biochar trials exist in the scientific literature, laboratory and institute field trial, the practice of applying it to the soil in the commercial farm had just began, and no widely accepted guidelines currently exist (Majro et al. 2010). Further, biochar has not been officially advocated as a measure for carbon sequestration by any regulatory regime or program. Some of the organization like international biochar initiative is working on developing protocol and package and practices of biochar application in agricultural soil. Dickinson et al. (2015) reported that the net present value of biochar application to soils was positive in a sub-Saharan African context but negative in a Northwestern European context, due to a combination of greater production costs and more modest yield benefits in the latter scenario. Therefore, without an understanding of farmers' roles as the main stakeholders in the generation and use of this innovation, the use of biochar is unlikely to be effective.

7.5 Role of Biochar in Mitigation of Methane Emission

7.5.1 Methane Emission and Its Impact on Global Warming

Methane (CH_4) is the second potential greenhouse gas after CO_2 which contributes about 15% of total anthropogenically induced global warming and climate change. Its global warming potential is 28 times higher than CO_2. Its concentration in the atmosphere has increased from 715 ppb in the pre-industrial era to 1863 ppb in 2018. Since 2007–2015, its concentration is increasing at the rate of +6.9 ± 2.7 ppb $year^{-1}$. Therefore it can be said that the contribution of methane in climate change is increasing as compared to CO_2 (when its slowdown is seen in the last 3 years) (Saunois et al. 2016). Methane is produced under anaerobic conditions (submerged soil) through the anaerobic digestion of organic matter by the action of methanogenic bacteria (Fig. 7.6). Around 70–80% of methane emission is of biological origin and remaining from natural sources. Table 7.3 describes the source and sink of methane emission from soil. Natural sources like swamps, marshes, ocean, forest soil, termites, etc. cause 20–30% of methane emission, while around

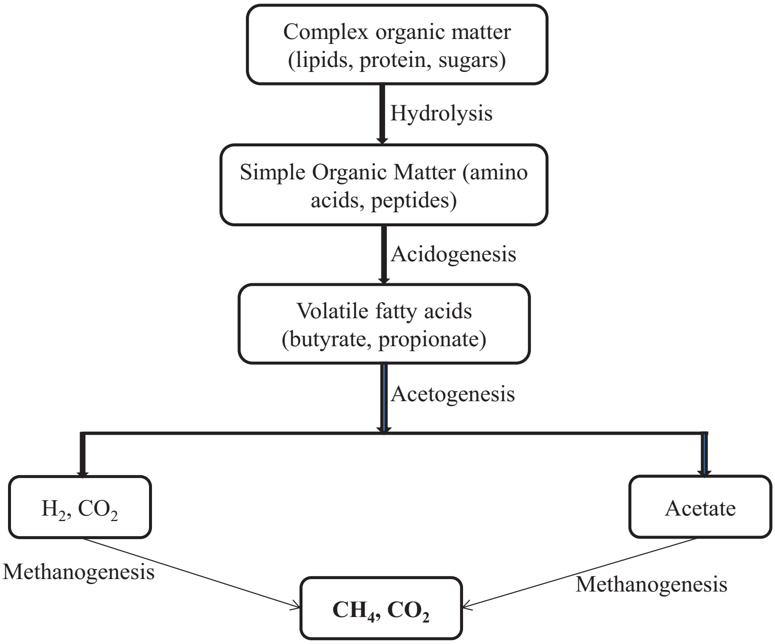

Fig. 7.6 Methanogenesis process of methane emission from soil

70–80% of emission is anthropogenic. Enteric fermentation from ruminants and conventional puddled rice cultivation practices contributes around 20–40% of its emission.

7.5.2 *Biochar and Methane Emission*

Many studies have shown that soil is responsible for around 15–30% of methane emission and most of the anthropogenic emission comes from paddy cultivation (12%) (Xiao et al. 2018; Malyan et al. 2016). Therefore most of the study has been done for the reduction of methane emission from the paddy field. There are several proposed options for reducing methane emission from paddy field. Some of the potential options are direct-seeded rice (Gupta et al. 2016a and 2016b), intermittent wetting and drying (Gupta et al. 2015), system of rice intensification; use of neem oil coated urea (NOCU) (Gupta et al. 2016a) and use of Azolla as biofertilizers (Malyan et al. 2019), etc. Recently it has been reported that soil application of biochar also offers great potential for the reduction of methane.

Aside from impacts on soil C storage, several studies suggest that biochar amendments may decrease soil CH_4 emissions, which would further contribute to greenhouse gas mitigation. Liu et al. (2011) tested the emission rate in rice soil with the incorporation of two biochar i.e. bamboo chips and straw char with control. A

Table 7.3 Sources and sink of methane emission from soil

Source	CH_4 emission (Tg/year)
Natural	
Wetland	127–202
Termite	21–132
Ocean	
Methane hydrates	
Manmade	
Coal mining	77–133
Landfills	
Animal waste	
Sewage	
Enteric fermentation	
Rice cultivation	115–243
Biomass burning	43–58
Others	15–53
SINK	
Atmospheric removal (tropospheric and stratospheric)	510–583
From soil	28–38

Source: Saunois et al. (2016)

reduction of 51.1% and 91.2% of methane in bamboo chips and straw char biochar was found compared to control plots. The reduction in methane emission was attributed to either inhibition of methanogenic bacteria or enhancement in methylotrophic bacteria. Similarly, amending the soil with rice husk biochar @ of 2 and 4% (weight biochar/weight soil) showed 45.2 and 54.9% reduction in methane emission compared to control (Pratiwi and Shinogi 2016). When soil amended with biochar and control (no biochar) were studied in elevated CO_2 and temperature conditions then result showed that cumulative methane emission was much lower with 112.2 mg kg^{-1} compared to 185.4 mg kg^{-1}dry weight soil per season in control (Han et al. 2016). The reduction of methane emission under biochar amended soil was attributed to enhanced methanotrophic activity (especially methanotrophic pmoA gene) which favors rhizospheric activity for methanotrophs. This result confirmed that applying rice straw biochar in soil not only reduces methane activity but at the same time enhances rice productivity (Han et al. 2016). Similarly, many studies show that the application of biochar results in reduced methane emission. Like Rondon et al. (2005) found reduced emission from *Brachiaria humidicola* and soybean plots treated with biochar @ 15 g kg^{-1} soil and 30 g kg^{-1} soil respectively. Similarly, in 2006, Rondon et al. found a reduction in methane emission in tropical soil with the application of wood-based biochar @ 20 t ha^{-1}. Therefore it can be said that methane emission rate varies with soil type, biochar physicochemical properties and agronomic management including water management practices (Zhang et al. 2010).

7.5.3 Factors Affecting Methane Emission from Biochar Applied Soil

Methane flux in the soil is affected by biochar in two ways (i) adsorption of methane on biochar surface (ii) enhanced methanotrophs activity via increased aeration (Jeffery et al. 2016). In the soil, methane is oxidized under aerobic conditions by the action of methanotrophs which takes methane as substrate and converts it into carbon dioxide and water. Additionally, many other things matter like soil physical and chemical properties, biomass type and process of biochar preparation (pyrolysis temperature) also affect the methane emission process. In general, adding biochar helps in enhancing soil fertility which increases methanogenic activity (Feng et al. 2012). The relation of biochar and methane emission is via methanotrophs group of microorganisms. Methanotrophs are gram-negative bacteria whose growth is stimulated through biochar application which ultimately acts as a sink for methane emission. Secondly, biochar increases the porosity of soil which allows new microbial hotspot to develop in this small porous structure where microbes retain methane for their metabolic activity and hence decrease methane emission (Feng et al. 2012). Several biochars and soil factors affect methane emission from soil. Some of them are discussed below:

(i) Water Management: Biochar when added in the puddled field under saturated condition increases methane sink or reduces source emission which means either methanotrophic process enhances or methanogenesis reduced. In the rice field, methane emission is mostly via three ways i.e. diffusion, ebullition, and plant-mediated transport. Plant mediated transport through aerenchyma is the major pathway. The application of biochar increases methane oxidation at anoxic/oxic surface of the plant. Contrary to this, in upland soils where the oxic environment persists, the application of biochar can enhance methane emission as they will provide more substrate for methanogens. Thus the application of biochar in flooded soil is more beneficial than its application in non-flooded soil in reducing methane emission and overall carbon footprint (Jeffery et al. 2016).

(ii) pH: Methane production or oxidation is microbe mediated process where both methanogens and methanotrophs work under a certain optimum conducive environment. Optimum pH for both is 6–8. Most of the biochar is basic ($pH > 7$) in nature which provides a liming effect to the soil. As methanotrophs are more sensitive to aluminium toxicity at lower pH, hence increasing pH via biochar applications helps in enhancing their activity and thus more methane gets sunk (Jeffery et al. 2011).

(iii) Pyrolysis temperature: Biochar produced via high pyrolysis temperature has a higher methane sink due to reduced H: Corganic ratio. Less H: Corganic ratio means more aromaticity. Additionally, it was found that higher temperature pyrolyzed biochar have lesser labile compounds on their surface which provide less area for microbial methanogens for reduction and thus less methane emission (Bruun et al. 2011).

(iv) Feedstocks: In general feedstock composition does not show much difference in methane flux except for biochar produced from sewage sludge. Biochar made from sewage sludge showed enhanced methane sink especially on acidic soil (Cayuela et al. 2014).

(v) Branauer, Emmett, and Teller (BET) surface area: pyrolysis temperature and BET surface area of biochar are positively linked. This indicates that in these types of biochar adsorption of produced methane on its surface occurs which reduces its emission (Jeffery et al. 2016).

7.6 Role of Biochar in Mitigation of Nitrous Oxide Emission

7.6.1 Nitrous Oxide Emission and Its Impact on Global Warming

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) with 114 years of atmospheric residence time and 265 times higher global warming potential (GWP) than that of CO_2 (IPCC 2014a, b). It contributes about 5% of the total human-induced global warming. The atmospheric concentration of N_2O has reached 350 ppb since the pre-industrial (1750) level (285 ppb). It has steadily increased at a rate of 0.73 ± 0.03 ppb year^{-1} over the last three decades and accounts for approximately 5% of the total greenhouse effect (IPCC 2014a, b). From 1961 to 2010 the global N_2O emission from agriculture has increased by about 3 times from 1.44 Tg to 4.25 Tg (Fagodiya et al. 2017). Besides this, it is also responsible for the destruction of the stratospheric ozone as once it transported to the stratosphere it releases the ozone depleting-chemicals through chlorine or nitrogen oxide catalyzed processes (Ravishankara et al. 2009). A doubling of atmospheric N_2O would cause a 10% decrease in the ozone layer that would increase ultraviolet radiation reaching the earth's surface by about 20%. Agriculture, fossil fuel combustion and industrial process, biomass burning, atmospheric deposition, and human sewage are the major anthropogenic sources of the N_2O emission (Fig. 7.7). Among the anthropogenic sources, agriculture is the largest source which accounted for 67% of total anthropogenic N_2O emission. Out of which 42% is direct emission from nitrogenous fertilizers and manure management; and 25% are indirect emissions from the runoff and leaching of fertilizers (IPCC 2013).

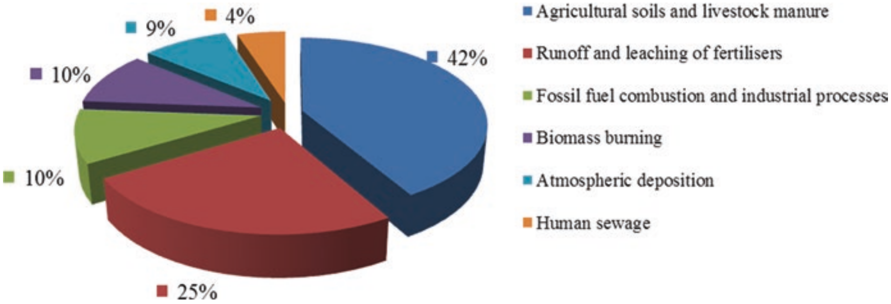

Fig. 7.7 Various sources of nitrous oxide emission

7.6.2 *Biochar and Nitrous Oxide Emission*

There are several proposed options for reducing N_2O emissions from soil. Some of the potential options are the use of nitrification inhibitors (NIs) and neem oil coated urea (NOCU) (Gupta et al. 2016a, b; Fagodiya et al. 2019) and use of Azolla as biofertilizers (Malyan et al. 2019). Besides increasing soil C storage and reducing CH_4 emissions, biochar application in soil has reported reducing N_2O emission which would further contribute to greenhouse gas mitigation. Recently it has been reported that soil application of biochar also offers great potential for the reduction of N_2O emission from soil mainly due to high porosity, pH, and specific surface area of biochar. Rondon et al. (2005) reported first time in a greenhouse experiment that after biochar application the N_2O emissions were decreased by 50–80%. Since then, biochar gets popularity as a potential option for N_2O mitigation from agricultural soils and since then several studies have been conducted using biochar. Some of these studies are synthesized in Table 7.4. A recent meta-analysis of publication from various field and laboratory study by Borchard et al. (2019) has reported the 38% average reduction of N_2O emissions while Verhoeven et al. (2017) has reported average reductions of 9–12% while an earlier global assessment (Cayuela et al. 2014) suggested greater average reductions of almost 50%, compared to none biochar amended soils.

There are several properties of biochar which are helpful in the reduction of N_2O emissions from agricultural soils. Some of these are porosity, pH, acidic and basic functional groups, specific surface area, and redox properties which are mainly varying with the type of feedstock used for biochar and pyrolysis conditions (Grutzmacher et al. 2018; Cayuela et al. 2014). Once biochar applied to soils, the interaction between the soil and biochar can alter the soil pH, oxygen level, and microbial composition and activity which turn into a reduction in N_2O emission (Edwards et al. 2018; Harter et al. 2014). Biochar application reduced the substrate concentration (NO_3^-, NH_4^+) for nitrification and denitrification reactions which

Table 7.4 Some results of reduction in N_2O emission after biochar application in to the soil

Biochar feedstock	Experimental condition	N_2O reduction	References
Sugarcane straw	Greenhouse pot with wheat crop	71%	
Meta data analysis	Meta-analysis of 88 publication	38%.	Borchard et al. (2019)
Bamboo	Acidic tea field	Biochar@ 0.5% =38% @2% = 61%.	Oo et al. (2018)
Wheat straw and swine manure	Greenhouse pot experiment with five vegetable crops	Wheat straw biochar 36.4–59.1% Swine manure biochar 37.0–49.5%	Fan et al. (2017)
Meta data analysis	Meta data analysis of 30 publication	54%	Cayuela et al. (2014)

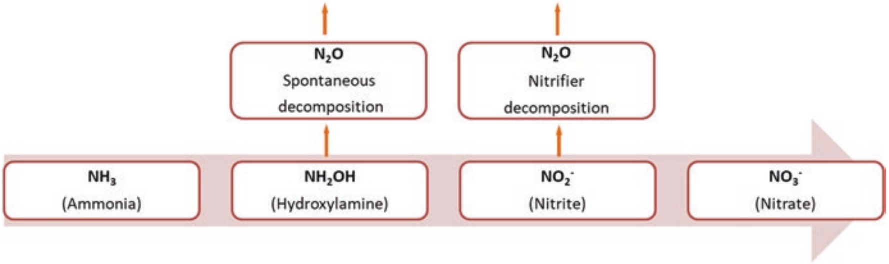

Fig. 7.8 Mechanism of N_2O emission from soil

limits the microbial activity and reduced N_2O emissions (Fig. 7.8) (Zheng et al. 2013). Besides this, it may enhance the soil pH and N_2O reductase concentration into the soils which lead to the final conversion of N_2O into N_2 and thereby reduced N_2O emission (Harter et al. 2014).

7.7 Conclusions

Biochar is a rich form of stable carbon and a suitable option for mitigating climate change through long term carbon storage and reduction in emission of GHG like N_2O and CH_4. Aside from carbon storage, biochar also provides a sustainable solution for managing the large volume of crop residue thus saving them from burning and air pollution. Production of renewable energy and heat during biochar production, increase in nutrient and water use efficiency after soil application further help in mitigating climate change through reduction in emission of CO_2 from fossil fuel combustion. However, yield, characteristics, and rate of biochar application significantly vary in the different study and it depends upon feedstock quality and pyrolysis temperature. Further, most of the reported studies are confined to laboratory or institute level field trial and adoption of biochar for application in agricultural soil by farmers is still lacking. There is a need to develop region and feedstock specific guidelines and policies for biochar production and application in the field to exploit potential benefits for enhancing soil quality and mitigating climate change.

References

Billa F, Angwafo TE, Ngome AF (2019) Agro-environmental characterization of biochar issued from crop wastes in the humid forest zone of Cameroon Samuel. Int J Recycl Org Waste Agric 8:1–13

Borchard N, Schirrmann M, Cayuela ML, Kammann C, Wrag-Mpnnig N, Estavillo JM, Novak J (2019) Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: a meta-analysis. Sci Total Environ 65:2354–2364

Bruun EW, Hauggaard-Nielsen H, Ibrahim N, Egsgaard H, Ambus P, Jensen PA, Dam-Johansen K (2011) Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass Bioenergy 35(3):1182–1189

Cayuela ML, Van Zwieten L, Singh BP, Jeffery S, Roig A, Sánchez-Monedero MA (2014) Biochar's role in mitigating soil nitrous oxide emissions: a review and meta-analysis. Agric Ecosyst Environ 191:5–16

Chaturvedi OP, Handa AK, Uthappa AR, Sridhar KB, Kumar N, Chavan SB, Rizvi J (2017) Promising agroforestry tree species in India. Jointly published by the Central Agroforestry Research Institute (CAFRI), Jhansi, and the South Asia Regional Programme (based in Delhi, India) of the World Agroforestry Centre, pp 1–190

Cherubin MR, Oliveira DMS, Feigl B et al (2018) Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: a review. Sci Agric 75(3):255–272

Crombie K, Mašek O (2015) Pyrolysis biochar systems, balance between bioenergy and carbon sequestration. GCB Bioenergy 7:349–361

Denman KL, Brasseur G, Chidthaisong A et al (2007) Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M et al (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge/New York

Dhyani SK, Ram A, Dev I (2016) Potential of agroforestry systems in carbon sequestration in India. Indian J Agric Sci 86:1103–1112

Dickinson D, Balduccio L, Buysse J, Ronsse F, Van Huylenbroeck G, Prins W (2015) Cost-benefit analysis of using biochar to improve cereals agriculture. GCB Bioenergy 7:850–864

Dlugokencky EJ, Hall BD, Montzka SA, Dutton G, Mühle J, Elkins JW (2019) Atmospheric composition [in *State of the Climate in 2018,* Chapter 2: Global Climate]. Bull Am Meteorol Soc 100(9):S48–S50

EBC (2012) European biochar certificate – guidelines for a sustainable production of biochar. European Biochar Foundation (EBC). Available at: http://www.european-biochar.org/en/download

Edwards JD, Pittelkow CM, Kent AD, Yang WH (2018) Dynamic biochar effects on soil nitrous oxide emissions and underlying microbial processes during the maize growing season. Soil Biol Biochem 122:81–90

Enders A, Hanley K, Whitman T, Joseph S, Lehmann J (2012) Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresour Technol 114:644–653

Fagodiya RK, Pathak H, Kumar A, Bhatia A, Niveta J (2017) Global temperature change potential of nitrogen use in agriculture: a 50-year assessment. Sci Rep 7:44928. https://doi.org/10.1038/srep44928

Fagodiya RK, Pathak H, Bhatia A, Jain N, Gupta DK, Kumar A, Malyan SK, Dubey R, Radhakrishanan S, Tomer R (2019) Nitrous oxide emission and mitigation from maize–wheat rotation in the upper Indo-Gangetic Plains. Carbon Manag 10(5):489–499

Fan C, Chen H, Li B, Xiong Z (2017) Biochar reduces yield-scaled emissions of reactive nitrogen gases from vegetable soils across China. Biogeosciences 14:2851–2863

Fang Y, Singh B, Singh BP, Krull E (2014) Biochar carbon stability in four contrasting soils. Eur J Soil Sci 65:60–71

Feng Y, Xu Y, Yu Y, Xie Z, Lin X (2012) Mechanisms of biochar decreasing methane emission from Chinese paddy soils. Soil Biol Biochem 46:80–88

Graetz RD, Skjemstad JO (2003) The charcoal sink of biomass burning on the Australian continent. CSIRO atmospheric research technical paper no. 64. CSIRO Atmospheric Research, Aspendale

Grutzmacher P, Puga AP, Bibar MPS, Coscione ARC, Packer AP, de Andrade CA (2018) Carbon stability and mitigation of fertilizer induced N_2O emissions in soil amended with biochar. Sci Total Environ 625:1459–1466

Gupta DK, Bhatia A, Kumar A, Chakrabarti B, Jain N, Pathak H (2015) Global warming potential of rice-wheat cropping system of the Indo-Gangetic Plains. Indian J Agric Sci 85(6):807–816

Gupta DK, Bhatia A, Kumar A, Das TK, Jain N, Chakrabarti B, Pathak H (2016a) Economic analysis of different greenhouse gas mitigation technologies in rice wheat cropping system of the Indo-Gangetic Plains. Curr Sci 110(5):867–874

Gupta DK, Bhatia A, Kumar A, Das TK, Jain N, Tomer R, Malyan S, Fagodiya RK, Dubey R, Pathak H (2016b) Mitigation of greenhouse gas emission from rice-wheat system of the Indo-Gangetic plains: through tillage, irrigation and fertilizer management. Agric Ecosyst Environ 230:1–9

Gupta DK, Bhatt RK, Keerthika A, Noor Mohamed MB, Shukla AK, Jangid BL (2019) Carbon sequestration potential of 30 years old Hardwickia binata Roxb based agroforestry system in hot semi-arid environment of India: an assessment of tree density impact. Curr Sci 116(10):112–116

Han X, Sun X, Wang C, Wu M, Dong D, Zhong T, Thies JE, Wu W (2016) Mitigating methane emission from paddy soil with rice-straw biochar amendment under projected climate change. Sci Rep 6:24731

Harter J, Krause HM, Schuettler S, Ruser R, Fromme M, Scholten T, Kappler A, Behrens S (2014) Linking N_2O emissions from biochar-amended soil to the structure and function of the N-cycling microbial community. ISME J 8:660–674

Hilber I, Bastos AC, Loureiro S, Soja G, Marsz A, Cornelissen G, Bucheli T (2017) The different faces of biochar: contamination risk versus remediation tool. J Environ Eng Landsc Manage 25(02):86–104

IPCC (2013) Climate change 2013: The physical science basis. In: Stocker TF, Qin D. Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge/New York, 1535 pp

IPCC (2014a) Climate change 2014: impacts, adaptation, and vulnerability working group II contribution to the fifth assessment report. Cambridge University Press, Cambridge/New York

IPCC (2014b) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, 151 pp

IPCC (2019) Summary for policymakers. In: Shukla PR, Skea J, Calvo Buendia E, et al (eds) Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (in press)

Jacquot J (2008) Can a kind of ancient charcoal put the brakes on global warming. Pop Mech. December 30, 2008

Jain N, Bhatia A, Pathak H (2014) Emission of air pollutants from crop residue burning in India. Aerosol Air Qual Res 14:422–430

Jeffery S, Verheijen FG, van der Velde M, Bastos AC (2011) A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric Ecosyst Environ 144(1):175–187

Jeffery S, Verheijen FG, Kammann C, Abalos D (2016) Biochar effects on methane emissions from soils: a meta-analysis. Soil Biol Biochem 101:251–258

Jindo K, Mizumoto H, Sawada Y, Sanchez-Monedero MA, Sonoki T et al (2014) Physical and chemical characterization of biochars derived from different agricultural residues. Biogeosciences 11:6613–6621

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 A et al (eds) Prospects of renewable bioprocessing in future energy systems, Biofuel and biorefinery technologies Vol 10. Springer, Cham, pp 1–50

Krull ES, Baldock JA, Skjemstad JO, Smernik RJ (2009) Characteristics of biochar: organo-chemical properties. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, Sterling/London, pp 53–66

Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X (2009) Black carbon decomposition and incorporation into soil microbial biomass estimated by C-14 labeling. Soil Biol Biochem 41(2):210–219

Kuzyakov Y, Bogomolova I, Glaser B (2014) Biochar stability in soil: decomposition during eight years and transformation as assessed by compound-specific 14C analysis. Soil Biol Biochem 70:229–236

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22

Lee Y, Park J, Ryu C, Gang KS, Yang W, Park YK, Jung J, Hyun S (2013) Comparison of biochar properties from biomass residues produced by slow pyrolysis at 500 C. Bioresour Technol 148:196–201

Lehmann J, Joseph S (2009) Biochar for environmental management: science and technology. Earthscan, London

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems. Mitig Adapt Strat Glob Chang 11:395–419

Liang B, Lehmann J, Solomon D, Sohi S, Thies JE, Skjemstad JO, FJ L˜a, Engelhard MH, Neves EG, Wirick S (2008) Stability of biomass-derived black carbon in soils. Geochim Cosmochim Acta 72:6096–6078

Liu Y, Yang M, Wu Y, Wang H, Chen Y, Wu W (2011) Reducing CH_4 and CO_2 emissions from waterlogged paddy soil with biochar. J Soils Sediments 11(6):930–939

Major J, Lehmann J, Rondon M, Goodale C (2010) Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Glob Chang Biol 16:1366–1379

Majumdera S, Neogia S, Duttaa T, Powelb MA, Banika P (2019) The impact of biochar on soil carbon sequestration: Meta-analytical approach to evaluating environmental and economic advantages. J Environ Manag 250:109466

Malyan SK, Bhatia A, Kumar A, Gupta DK, Singh R, Kumar SS, Tomer R, Kumar O, Jain N (2016) Methane production, oxidation and mitigation: a mechanistic understanding and comprehensive evaluation of influencing factors. Sci Total Environ 572:874–896

Malyan SK, Bhatia A, Kumar SS, Fagodiya RK, Pugazhendhi A, Duc PA (2019) Mitigation of greenhouse gas intensity by supplementing with Azolla and moderating the dose of nitrogen fertilizer. Biocatal Agric Biotechnol 20:101266. https://doi.org/10.1016/j.bcab.2019.101266

Maroušek J, Strunecký O, Stehel V (2019) Biochar farming: defining economically perspective applications. Clean Techn Environ Policy 21:1389. https://doi.org/10.1007/s10098-019-01728-7

Mary GS, Sugumaran P, Niveditha S et al (2016) Production, characterization and evaluation of biochar from pod (Pisum sativum), leaf (Brassica oleracea) and peel (Citrus sinensis) wastes. Int J Recy Org Waste Agric 5(1):43–53

Nguyen BT, Lehmann J, Hockaday WC, Joseph S, Masiello CA (2010) Temperature sensitivity of black carbon decomposition and oxidation. Environ Sci Technol 44:3324–3331

Nsamba HK, Hale SE, Cornelissen G, Bachmann RT (2015) Sustainable technologies for small-scale biochar production – a review. J Sustain Bioenergy Syst 5:10–31

Oo AZ, Sudo S, Akiyama H, Win KT, Shibata A, Yamamoto A, Sano T, Hirono Y (2018) Effect of dolomite and biochar addition on N_2O and CO_2 emissions from acidic tea field soil. PLoS One 13(2):e0192235. https://doi.org/10.1371/journal.pone.0192235

Paustian K, Larson E, Kent J, Marx E, Swan A (2019) Soil C sequestration as a biological negative emission strategy. Front Clim 1:8. https://doi.org/10.3389/fclim.2019.00008

Pratiwi EPA, Shinogi Y (2016) Rice husk biochar application to paddy soil and its effects on soil physical properties, plant growth, and methane emission. Paddy Water Environ 14(4):521–532

Purakayastha TJ, Kumari S, Pathak H (2015) Characterization, stability, and microbial effects of four biochars produced from crop residues. Geoderma 239–240:293–303

Ravishankara AR, Daniel JS, Portmann RW (2009) Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21^{st} century. Science 326(5949):123–125

Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2010) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833. https://doi.org/10.1021/es902266r

Rondon M, Ramirez JA, Lehmann J (2005) Greenhouse gas emissions decrease with charcoal additions to tropical soils. In: Proceedings of the 3rd USDA symposium on greenhouse gases and carbon sequestration, vol 208, Baltimore, USA

Saunois M, Jackson RB, Bousquet P, Poulter B, Canadell JG (2016) The growing role of methane in anthropogenic climate change. Environ Res Lett 11(12):12

Shneour EA (1966) Oxidation of graphitic carbon in certain soils. Science 151:991–992

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, Cham, pp 475–494

Song X, Pan G, Zhang C, Zhang L, Wang H (2016) Effects of biochar application on fluxes of three biogenic greenhouse gases: a meta-analysis. Ecosyst Health Sustain 2:e01202. https://doi.org/10.1002/ehs2.1202

Steiner C, Teixeira WG, Lehmann J, Nehls T, de Macedo JLV, Blum WEH, Zech W (2007) Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered central Amazonian upland soil. Plant Soil 291:275

Sun X, Shan R, Li X, Pan J, Liu X, Deng R, Song J (2017) Characterization of 60 types of Chinese biomass waste and resultant biochars in terms of their candidacy for soil application. GCB Bioenergy 9:1423–1435

Tiwari S, Singh C, Singh JS (2018) Land use changes: a key ecological driver regulating methanotrophs abundance in upland soils. Energy 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 AK et al (eds) Restoration of wetland ecosystem: a trajectory towards a sustainable environment. Springer, Cham, pp 59–74

Venkatesh G, Gopinath KA, Sammi Reddy K, Sanjeeva Reddy B, Prasad JVNS, Rajeshwar Rao G, Pratibha G, Srinivasarao Ch, Ravindra Chary G, Prabhakar M, Visha Kumari V, Shankar AK Venkateswarlu B (2018) Biochar production and its use in rainfed agriculture: experiences from CRIDA. CRIDA-NICRA Research Bulletin 02/2018. ICAR – Central Research Institute for Dryland Agriculture, Hyderabad, pp 50

Verhoeven E, Pereira E, Decock C, Suddick E, Angst T, Six J (2017) Toward a better assessment of biochar–nitrous oxide mitigation potential at the field scale. J Environ Qual 46:237. https://doi.org/10.2134/jeq2016.10.0396

Wang JY, Xiong ZQ, Kuzyakov Y (2016) Biochar stability in soil: metaanalysis of decomposition and priming effects. Glob Change Biol Bioenergy 8:512–523. https://doi.org/10.1111/gcbb.12266

Waters D, Van Zwieten L, Singh BP, Downie A, Cowie AL, Lehmann J (2011) Biochar in soil for climate change mitigation and adaptation. In: Singh B, Cowie A, Chan K (eds) Soil health and climate change. Soil biology, vol 29. Springer, Berlin/Heidelberg

Windeatt JH, Ross AB, Williams PT, Forster PM, Nahil MA, Singh S (2014) Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. J Environ Manag 146:189–197

Xiao Y, Yang S, Xu J, Ding J, Sun X, Jiang Z (2018) Effect of biochar amendment on methane emissions from paddy field under water-saving irrigation. Sustainability 10(5):1371

Zhang A, Cui L, Pan G, Li L, Hussain Q, Zhang X, Zheng J, Crowley D (2010) Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. Agric Ecosyst Environ 139(4):469–475

Zhang H, Chen C, Gray EM, Boyd SE (2017) Effect of feedstock and pyrolysis temperature on properties of biochar governing end use efficacy. Biomass Bioenergy 105:136–146

Zhang X, Chen C, Chen X, Tao P, Jin Z, Han Z (2018) Persistent effects of biochar on soil organic carbon mineralization and resistant carbon pool in upland red soil, China. Environ Earth Sci 77:177

Zheng H, Wang Z, Deng X, Herbert S, Xing B (2013) Impacts of adding biochar on nitrogen retention and bioavailability in agricultural soil. Geoderma 206:32–39

Zimmerman A (2010) Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). Environ Sci Technol 44:1295–1301