Chapter 17
Biochar Production and Its Impact on Sustainable Agriculture

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Abstract Biochar is a fine-grained, carbon-rich and porous organic derivative derived through pyrolytic combustion of biomass. Its use in agriculture since Amazonian *terra preta* civilization signifies its potential benefits in sustainable crop production and environmental remediation. It supports plant growth and yields through favourable soil physicochemical properties, enhanced water holding capacity, nutrient availability, heavy metal remediation and disease and pest suppression. It sequesters atmospheric carbon dioxide, pacifies the pace of global warming and contributes to quenching adverse effects of climate change in the long run. In this direction, large-scale biochar application in the agricultural production system is a holistic approach for socio-economic and ecological sustainability. Research results on biochar application, though miraculous, are mostly laboratory or greenhouse-based as the popularization of its wider field application in the agriculture sector is constrained by a higher rate of application incurring a high cost of production. This problem can be addressed through low-cost biochar generation from the locally available biowastes.

Keywords Biochar synthesis · Pyrolysis · Reclamation · Sustainable agriculture

17.1 Introduction

Healthy soil leads to a productive, profitable and sustainable agriculture production system (White and Barberchek 2017). Rhizospheric aeration, moisture, temperature, nutrients and microbial population are influenced by soil type and its physicochemical characteristics. However, continuous cropping over years depletes many essential plant nutrients from the soil that need to be replenished through judicious nutrient

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management. Furthermore, excessive application of synthetic pesticides, hormones, probiotics and chemical fertilizers have perilous effects on the soil environment that ends up with pesticide resistance and pest resurgence (Wu et al. 2012). Intensive cropping and use of chemical fertilizers deteriorate the soil health and reduce crop yield (Rawat et al. 2017). Continuous cropping without manuring exhausts soil carbon pool that influences soil biota. Heavy metal accumulation, particularly nearby opencast mines need to be remediated for sustainable cropping and maintaining soil biodiversity (Rawat et al. 2017).

It is high time to feed the ever-growing population without degrading the environment. Selection of any soil ameliorant for land reclamation must be based on its compatibility, cost and availability. Hence, due care must be taken to maintain the soil carbon pool to facilitate soil biodiversity, natural cycles and to sequester atmospheric carbon. Among many options of soil fertility restoration and carbon sequestration, biochar application has been a well-proven, widely accepted and age-old practice dating back to Amazonian civilization (Lahori et al. 2017). Biochar is “a fine-grained, carbon-rich, and porous organic derivative derived through anaerobic thermo-chemical combustion of biomass” (Amonette and Joseph 2009). Pyrolytic burning of biomass produces oil and gas as co-products in addition to biochar depending on the substrate type and processing conditions (Gaunt and Rondon 2006).

17.2 History of Biochar Production and Use

As mentioned earlier, biochar production and application trail to the era of a fire-fallow system of cultivation during the Neolithic revolution when nomadic hunters and gatherers domesticated certain plants and animals for leading a settled life and getting more nutrition per unit area. These ancient nomads were clearing up the forests and grasslands, and burning biomass just before the rainiest part of the year to enrich the soil with valuable plant nutrients and to eliminate weeds and control the disease-pest infestation. However, after three to five years of cropping, the nomads were abandoning the land in search of new locations due to reduced soil fertility, and the resurgence of diseases, pests and weeds. After a gap of a few years, they were again returning to the same land on recovery. This cyclic process of burning and assorting is known as slash-burn or shifting cultivation. In India, it is known as *jhoom* or *jhum* cultivation (Singh 2018). As of 2004, an estimated area of 200 to 500 million hectares across the world was under this system of cultivation. As the slash and burn system of cultivation is not sustainable and scalable for the larger human population, an alternative system such as the *inga* alley cropping or slash and char system (Biederman 2012) with significantly less environmental repercussion had evolved (Elkan 2004).

17.2.1 Slash and Burn System Versus Slash and Char System

The slash and burn system of farming had evolved during the Neolithic era to expand crop area for feeding the growing human population by clearing thick vegetation. The burning of biomass was yielding ashes, that provided essential plant nutrients, but at the cost of devastating environmental pollution (Raison et al. 2009) by producing many toxic gases that polluted air in the near vicinity. The wood ash thus produced, being light in weight, was also getting washed away through natural drainage exposing the land to accelerated weathering and soil erosion. In long run, that eventually affected farming and large-scale ranching.

To mitigate the negative effects of burning, people started charring residues instead of burning after cutting. This alternate system of farming, known as the 'slash and char system', had tremendous environmental benefits over the slash and burn system as it significantly reduced toxic gases and improved the bio-physicochemical properties of soil. Slash and burn system with 1–3 years of cropping followed by 20 years of the fallow period could be sustainable but not practicable under growing food demands (Steiner et al. 2008).

In the slash and char system, biochar is produced which can be buried in the soil after mixing with biomass such as agricultural residues, manure and food waste for conditioning or *terra preta*. Terra preta is the most fertile black-coloured soil on the planet found in the Amazon basin, popularly known as Amazonian dark earth or Indian black earth (*Terra Preta de Indio*). It is known to regenerate on its own. It sequesters considerable quantities of atmospheric CO_2 into the soil as safe, stable but active form in contrast to the slash and burn system that increases carbon footprint opposite to it. Near about 50% of the carbon remains in stable form and remains active over hundreds of years (Lehmann et al. 2006).

17.2.2 Biochar in Traditional Agriculture

Charcoal, the precursor of biochar has been in use since the Paleolithic and Neolithic eras of slash and burn (Chen et al. 2019). Carbon dating of the charcoal paintings on the walls of the caves across the globe uncovers the story of charcoal use even more than 30,000 years ago (Zorich 2011). The International Biochar Initiative (IBI) defined biochar or pyrogenic carbon as "the solid material produced through thermochemical conversion of biomass in an oxygen-deprived environment". It is popular both in ancient and modern civilizations. The application of biochar in the ancient era is evident from the *Terra preta* in the Amazonian basin of South America (Glaser et al. 2001) for more than 2500 years (USBI News 2021a). Such a meaningful piece of ancient agricultural heritage was unveiled in 1966 by Wim Sombroek, a Dutch soil scientist who located a rich self-regenerating soil in the Amazon basin of Brazil (Wayne 2012). The nutrient and organic matter content of this Amazonian dark soil were extremely high (Harder 2006; Marris 2006; Tenenbaum 2009). Its chemical analyses indicated the presence of burned wood, crop and bone residues of animals and fishes (Sombroek et al. 2002). The productivity of *terra preta* is four times greater than the soil from similar parent material (Wayne 2012). Bruno Glaser of the University of Bayreuth in his article "the *Terra preta* phenomenon: a model for sustainable agriculture in the humid tropics" has estimated around 250 tons of carbon in *terra preta* compared to the maximum of 100 tons in unimproved soils from the same area (Glaser et al. 2001). The land size varied from 20 ha (Smith 1980; Zech et al. 1990; McCann et al. 2001) to 350 ha (Smith 1999) patches covering 50,000 ha in the central Amazonian region. Still today, 10% of the Amazonian basin is under terra preta soil (USBI News 2021a).

The porous structure of biochar facilitates nutrient accumulation, growth of beneficial microorganisms and helps in the slow release of nutrients in available form and a balanced ratio supporting vigorous plant growth (Shindo 1991; Cheng et al. 2008). The black carbon in charcoal exists in soil for over 1000 years or longer. This black soil from anthropogenic activity in the Amazonian basin of dense rainforest could be attributed to the sustenance of a large human population for thousands of years before it was exposed to the outer world by Christopher Columbus in 1498 (Petersen et al. 2001; Lehmann 2009).

China and India have a strong history of biochar production and application. Conversion of crop residues into biochar instead of burning in-situ has been an age-old practice in China, mostly in the southern region of the country (Yan et al. 2019). The use of charcoal in agriculture in the Himalayan hills of the Indian subcontinent is a traditional practice. People gather biomass in forests and fields, cover them under mud-coat and set fire to get biochar on subsequent cooling. *Terra preta* like soils have been identified in Peru, Ecuador, Benin and Liberia in West Africa also (USBI News 2021a). Archaeologists have claimed the fall of Mesopotamia civilization due to climate change leading to drought and depletion of soil carbon (Codur et al. 2017).

In some ancient civilizations, the production of biochar was not the only requirement. Rather, they were more acquainted with the liquid product recovery. Traces of wood-tar and pyroligneous acids on the embalmed body of the dead are widely observed in the remains of ancient Egyptian societies (Emrich 1985; Day et al. 2012). Macedonians obtained wood oil from burning biochar in pits (Klark and Rule 1925). Evidence dating 6000 years back shows the use of wood tar to attach arrowhead with the spear shaft (Klark and Rule 1925; Emrich 1985). However, few such practices of charcoal making in many developing countries are not completely anoxic and thus unhealthy for the environment but are better than open burning of residues (USBI News 2021b).

17.3 Benefits of Biochar Use

Pyrolysis of natural vegetation or farm residues generates biofuel without competition with crop production. Controlled burning of biomass with limited or no oxygen produces syngas and wood oil in addition to the biochar, while open burning generates greenhouse gases (GHGs) and deteriorates the environment. Biochar on incorporation into the soil enhances natural processes, improves soil physicochemical properties, promotes beneficial microbial growth (Ajema 2018) and facilitates plant growth, protects against moisture stress (Bera et al. 2018), induces disease-pest tolerance, provides anchorage, sequesters atmospheric CO_2 (Cornet and Escadafal 2009), reduces soil erosion (Jien and Wang 2013), remediates (Cheng et al. 2020) and rejuvenates the soil.

17.4 Procedure for Synthesis of Biochar

The carbonization of wood for heating or making biochar is as old as human civilization itself (Brown 1917; Emrich 1985). Although different methods of biochar making were employed by ancient civilizations, all of them were to generate heat without any intent to harness the released volatile gases during the combustion process releasing toxic gases and fumes into the surrounding environment. However, in some civilizations, wood tar was collected for embalming dead or inserting arrowheads.

The simple process of thermal decomposition of biomass for biochar production involves either pyrolysis or gasification. Pyrolysis is the temperature-mediated systematic chemical decomposition of organic substrates in an oxygen starved atmosphere without combustion (Demirbas 2004). The gasification system produces smaller quantities of biochar (10–20%) but the larger volume of syngas (80%) on direct heating at >700 °C or more (Nartey and Zhao 2014; Biochar International 2021). In pyrolysis kilns, retorts and other specialized equipment are used to bake the biomass at <600 °C in absence of oxygen. Pyrolytic gases, often called syngas, are allowed to escape or combusted to make the process self-sustaining (International Biochar Institute 2021). Broadly, two systems of pyrolysis are used today, viz. fast pyrolysis and slow pyrolysis. Fast pyrolysis produces 75% oils and 10–20% char while slow pyrolysis produces one-third each of oils, char and gases (Nartey and Zhao 2014; Biochar International 2021). Pyrolysis occurs in three basic steps: In the initial step, moisture and some volatiles are lost; in the middle step, organic residues are transformed into volatile gasses and biochar, and finally, chemical rearrangement of the biochar occurs slowly (Demirbas 2004).

17.4.1 Stages of Pyrolysis

Biomass constitutes five main components: water, cellulose, hemicelluloses, minerals (ash), and lignin at varying proportions depending on the biomass source. Seasoned wood contains 12–19% moisture and freshly cut crops or wood contain 40–80% water on a weight basis. On heating, most of the water escapes at 100 °C and biomass starts breaking down above 150 °C. At this temperature, biomass softens and chemically bound water is released with carbon dioxide (CO_2) and volatile organic compounds (VOCs). On ‘torrefaction’, means further heating into the range of 200–250 °C, chemical bonds start breaking. Acetic acid, methanol and other oxygenated volatile compounds along with carbon monoxide and CO_2 are released from cellulose and hemicelluloses. Torrefied biomass (e.g. boiler fuel) is brittle, easy to grind with less energy, resistant to microbial decomposition and water uptake. The liquid condensate, known as ‘wood vinegar’, ‘smoke water’ or ‘pyrolignous acid’, can be used as a fungicide, plant growth promoter, compost stimulant and to improve the effectiveness of biochar (International Biochar Institute 2021). The torrefaction process is endothermic—external heat is required for increasing the temperature of dry biomass. When the temperature reaches 250–300 °C, the thermal decomposition of biomass becomes more extreme with the release of a combustible mixture of H_2, CH_2, other hydrocarbons, CO, CO_2 and tars. At this stage, pyrolysis becomes exothermic with the release of heat due to break-up of large polymers of biomass and release of structural oxygen to support self-sustained combustion thereby increasing the temperature up to 400 °C till oxygen gets depleted completely leaving carbon-rich charcoal-like residues. As heat is released and lost outside the system, external heat is required for any further pyrolytic processes. At the end of this exothermic pyrolysis stage, the maximum yield is obtained but stable carbon is yet to be attained. The ash content, VOCs and fixed carbon of wood biochar may be around 1.5–5%, 25–35% and 60–70%, respectively (Biochar International 2021). The biochar at the end of the exothermic stage still contains a significant amount of VOCs. More heating is needed to enhance the fixed carbon content, surface area and porosity from the remaining VOCs. To elevate the fixed carbon content to 80–85% and reduce the VOCs below 12%, the biochar is heated further to a temperature range of 550–800 °C depending on the substrate and particle size (Biochar International 2021). At this stage, the biochar yield is 25–30% of the oven-dry weight of the feedstock.

Once the temperature goes above 600 °C, the addition of small quantities of steam and air can trigger up the temperature up to 700–800 °C which results in activation and gasification processes. Air and steam can activate the surface of biochar at high temperature and release more VOCs. Activation increases the surface area, porosity and CEC by adding acidic functional groups but at the cost of lowering the yield. If an excess of air and/or steam is added to the process then a relatively clean gas is produced that can be used for generation of electricity but the yield of biochar is reduced below 20% and the ash content increases significantly (Biochar International 2021).

17.4.2 Preprocessing of Feedstock

Preconditioning of the feedstock can alter the rate of pyrolysis and final properties of biochar. Pretreatment with phosphoric acid increases functional groups, reduces the pH of biochar and produces slow-release phosphatic fertilizer. Pretreatment with iron salts produces magnetic biochar that can remove heavy metals from water. Alkali (potassium hydroxide) pretreatment softens biomass and breaks-down lingo-cellulosic compounds. Mixing of clay, ferrous sulphate and rock phosphate with biomass slows down the rate of pyrolysis, captures nitrogen and increases the concentration of nutrient-rich nanoparticles (Biochar International 2021).

17.4.3 Post-processing of Biochar

Post-processing of biochar can alter its properties. Phosphoric acid can be treated to make slow-release phosphatic fertilizer, reduce pH and enhance functional groups. Urine is added to increase nitrogen content and alkali is added to increase pH and potassium content. Rock phosphate, dolomite, gypsum, iron oxides, lime are added to rectify soil constraints. Urea and diammonium phosphate (DAP) is added to biochar for making complex fertilizers (Mohiuddin et al. 2006).

17.4.4 Effect of Residential Time

The largest specific surface area (155.77 $m^2 g^{-1}$), a higher carbon content (67.45%) and a lower ash content (15.38%), and higher carboxylic and phenolic-hydroxyl group (1.74 and 0.86 mol kg^{-1}) were obtained in biochar from *Robinia pseudoacacia* biowaste with zero residential time (the gap between burning char falling on ground and cooling by the sprinkling of cold water). However, a longer exposure time (5.30 min) resulted in lower values of above parameters (Xiao et al. 2020).

17.5 Methods of Preparation

Biochar can be prepared in small quantities at the individual household level (Whitman and Lehmann 2009) and in large quantities in big industries (Amonette and Joseph 2009). A specific requirement driven procedure is adopted for the synthesis of biochar and other by-products (Srinivasarao et al. 2013). Various pyrolysis technologies are available for traditional and commercial production of biochar and other fractions.

The global biochar market in 2018 was US$1.3 billion while the demand was 395.3 kilotons in that year, which is expected to get doubled by 2025. Increased demand for organic food so also its application in waste treatment and water purification in emerging economies like India and China, are likely to trigger the biochar requirement in near future. Environment friendliness, cheaper cost and multifarious applicability render it indispensable to reorient government policies for wider market expansion (Grand View Research 2018). To popularize biochar among the farmers, low-cost biochar production technology with the least negative environmental impact needs to be developed at the community as well as individual farm-family level. A few traditional, as well as modern biochar making methods are discussed hereunder.

17.5.1 Heap Method

The heap or mound method of charcoal making is an oldest practice in many parts of the world where a heap or mound or pyramid-like structure is made up of dried wood, crop residues, weeds, sawdust, rice husks, etc. The heap is then covered with grasses, available agriculture waste or coir and moist earth to prevent the free flow of oxygen during burning (Fig. 17.1). Vents are opened at the top to downward to allow free out flow of the combustion gas and to facilitate uniform charring. The fire is set at the bottom hole or top hole of the heap which subsequently engulfs the entire heap within an hour or several days depending on the type and volume of substrates. The quantity of smoke during burning depends on the substrate type, oxygen supply and moisture content of the feedstock. When smoke production stops, the holes are plugged with mud for the final conditioning of the biochar. After several days of cooling, the earth cover is removed and water is sprinkled to wash away ash. Earth-mound kilns with adjustable chimneys at the top that regulate diameter and height controlling oxygen flow are the most advanced among earth kilns (Emrich 1985). This method is the cheapest, easiest, simplest, quickest and most popular way of making biochar.

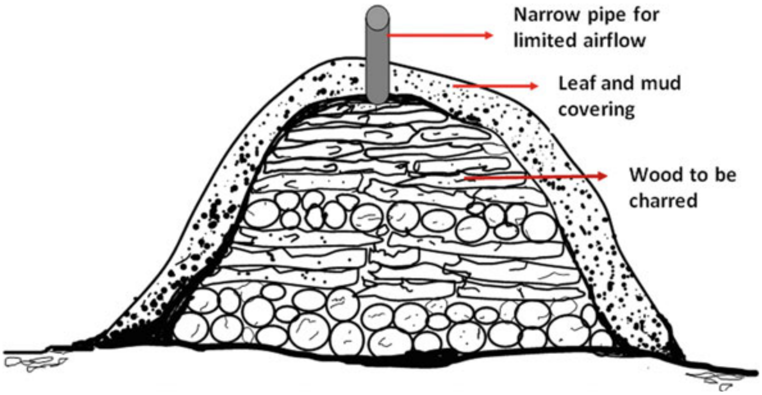


Fig. 17.1 Schematic diagram of the *heap* method of biochar making

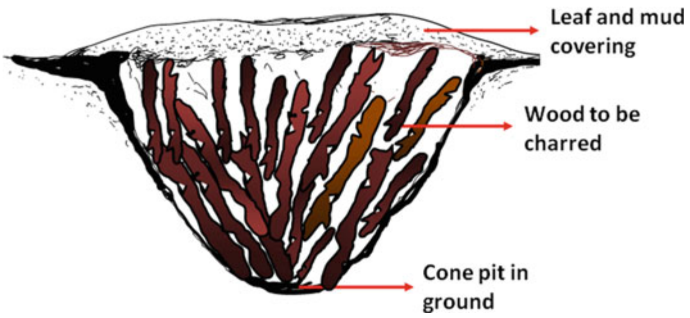


Fig. 17.2 Schematic diagram of *cone-pit* method of biochar making

17.5.2 Cone-Pit Method

Cone-pit method is also another traditional practice of producing charcoal. A pit of desired diameter and depth is dug in well-drained upland depending on the volume of the biomass (Fig. 17.2). A dried feedstock is put in it up to the ground level or below that at a time or in a phased manner after ignition of the fire. After completion of partial combustion, the pit is covered with fresh grasses or leaves followed by sealing with mud to restrict the inflow of oxygen into the pit. On cooling, the pit is opened and biochar is removed for further use in agricultural land or other purposes.

17.5.3 Drum Method

The drum method of biochar making is popular in areas where the transportation of biomass is cheaper *than in-situ* construction of kilns. Portable and handy metallic drums are easy to operate requiring less maintenance (Srinivasarao et al. 2013). Usually, cylindrical metal oil drums of about 200 L with both sides intact or of varying sizes depending on the volume of substrate capacity and are preferred for this purpose (Fig. 17.3). A square or round-shaped hole of 12–16 cm diameter or side length is made at the centre of the top lid to allow combustion syngas to escape through a chimney fitted to it. At the bottom of the drum, holes measuring about 4 cm^2 each are made covering 20% of the bottom area for uniform air flow from below. The pyrolytic temperature and quality of biochar depend on the inlet air volume and thus indirectly on the vent area at the bottom and side of the drum, if at all done in some designs. The entire drum is placed on 3–4 bricks to facilitate free airflow from the bottom. After putting feedstock systematically inside the drum, the fire is set by pouring some petroleum oil or using polythene pieces at the top or side-hole. Once the biomass catches fire, it is allowed to burn for about 15 min for partial combustion and then the top lid is covered. Initially, sooty smoke with luminous

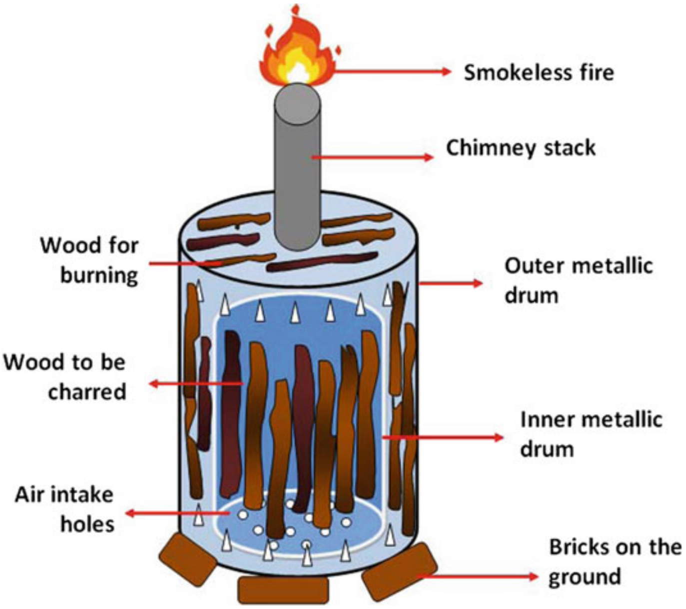


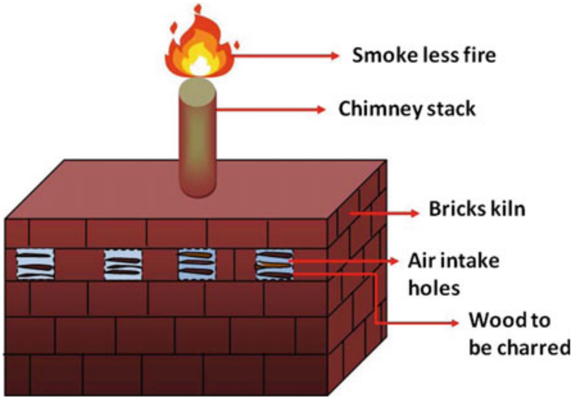
Fig. 17.3 Schematic diagram of *drum* method of biochar making

flame comes out of the chimney and subsequently bluish smokeless flame (non-luminous) come indicating completion of the heating phase of biochar making. The drum is then brought down from the top of bricks and placed on a muddy surface to prevent further entry of air. The top lid is also sealed by using mud to prevent airflow. After a few hours of cooling, the biochar is ready for direct use or grinding. The Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, India has developed a biochar kiln for the community as well as the individual level (Venkatesh et al. 2016).

17.5.4 Brick Kilns

Brick kilns are constructed at the place of origin of huge quantities of biomass. The size and quality of the kiln depend on the volume of feedstock and its expected longevity. Earthen bricks are mostly used but cemented bricks or fire bricks are also used in some designs. Earthen bricks are brittle and may break down if not specially baked and plastered thoroughly. Broken bricks allow free inflow of air resulting in vigorous burning and more ash production. Mud or cement mortar is used to plaster the bricks arranged in cylindrical or cubical shape (Fig. 17.4).

Fig. 17.4 Schematic diagram of *brick kiln* method of biochar making



A simple biochar kiln, known as ‘Holy Mother Biochar Kiln’, has been made by the Sarada Matt (Holy Mother) at Almora, Uttarakhand, India by using clay mud-plaster and earthen bricks. Biomass is added continuously during combustion and the primary air vent at the bottom is kept open till biomass is added. Then further biomass addition is stopped and the primary vent is closed when the biomass reaches just below the secondary air vents. Thereafter, water is sprinkled over it to drop down its temperature and the biochar is collected and stored on drying.

17.5.5 Biochar Stoves

Biochar stoves are still widely used by more than two billion people across the globe, particularly in the developing and underdeveloped energy-starved countries to cook food or heat their homes with by burning wood, dried dung, crop residues or coal. Such inefficient traditional heating practices cause air pollution that can exacerbate global warming and bring health issues such as cardiac arrest and respiratory congestions. The UN Environment Programme (UNEP) has identified the Atmospheric Brown Clouds (ABCs) as a major contributing factor in climate change (UNEP 2008) resulting mostly from a forest fire and inefficient anthropogenic biomass combustion. Inefficient combustion of biomass produces black particles (soot) that absorb sunlight and heat up the air mass while suspended white particles reflect back the incident solar radiation. Black carbon significantly contributes to global warming, next only to CO_2 (Ramanathan and Carmichael 2008). Even non-biochar making cookstoves emit huge volume of black carbon. Black carbon from rocket stove equals to that of from an open fire (MacCarty et al. 2008). However, modern science-based technologies sequester carbon very efficiently through production of heat along with biochar without much gas release. Gasifier stoves such as Top-Lit Updraft Gasifier (TLUD) (Fig. 17.5) and the Anila stove are reported to have very low black carbon emissions. Four basic stratified zones viz. raw biomass, flaming pyrolysis, gas and

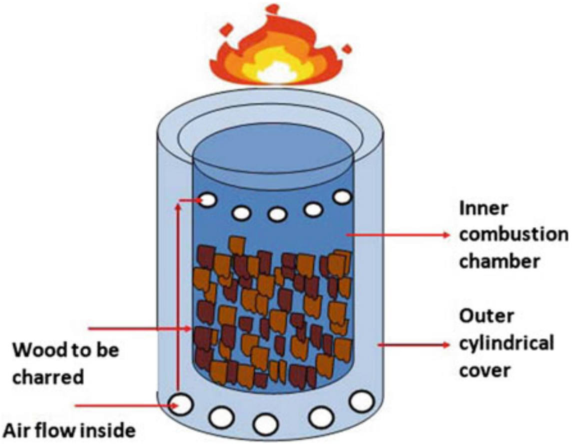


Fig. 17.5 Schematic diagram of top-lit updraft gassifier (TLUD)

charcoal combustion are found in TLUD (Anderson and Reed 2004). If removed and quenched properly at right time then charcoal can also be obtained. During this process, the biomass is kept between two concentric cylindrical plates and a fire is ignited at the centre to pyrolyze the fuel in between the concentric rings. The gases from pyrolyzing fuel come out of the centre and they burn there to generate heat for cooking whereas the biomass becomes char (Srinivasarao et al. 2013). The modern *Anila stove* has been designed by U. N. Ravikumar of the Centre for Appropriate Rural Technology (CART) to take advantage of the huge biomass available in rural areas mostly in developing and underdeveloped countries and to minimize in-house air pollution that comes during cooking. The *Anila stove* works on the principle of top-lit updraft gasification. Hardwood fuel is lit at the top which burns downward and simultaneously combusts the released syngas. The stove is made from stainless steel and ordinarily weighs around 10 kg (Iliffe 2009). The IBI (Reddy 2011) has designed a fan-propelled biochar cooking stove that circulates air and liberates energy from the biomass for cooking and produces biochar in lesser quantity at the end of the process.

Three different pyrolysis reactors viz. kiln, retort and converter have been described by Emrich (1985) depending on the technology, size, purpose and the type of feedstock in use. In traditional biochar making process *kilns* are used solely to generate biochar. *Retorts* or reactors pyrolyzepile wood-log over 30 cm (length) × 18 cm (diameter) (Emrich 1985) whereas *converters* carbonize small biomass fragments like chipped or pelletized wood.

17.6 Economic Feasibility of Biochar Production

Application advantages of biochar for carbon sequestration, soil amendment, and bioremediation of heavy metals and organic pollutants are widely accepted however its large-scale use has been constrained by its high cost of production (Xiao et al. 2020). Slow pyrolysis of corn stover resulted in a higher yield of char (40% by weight) but with the lower gas release, while fast pyrolysis maximized bio-oil with lower biochar and gas yields as co-products (Brown et al. 2010). Anaerobic production of biochar from *Robinia pseudoacacia* biowaste demonstrated a low-cost of \$20 t^{-1} (Xiao et al. 2020). As estimated in 2015, slow pyrolysis of corn stover was not profitable at offset value of biochar of \$20 t^{-1} as feedstock cost was \$83 t^{-1} in the USA while the fast pyrolysis resulted in 15% internal rate of return (IRR) as gasoline from bio-oil could value \$2.96 per gallon gasoline-equivalent. By 2030, the carbon offset value of biochar is expected to rise to \$60 t^{-1} and the gasoline price per gallon is presumed to reach \$3.70 that could benefit investors with an IRR of 26% (Brown et al. 2010). A stochastic analysis of biochar production in Canada from spruce trees by slow pyrolysis mobile unit estimated fixed and variable cost of \$505.14 and \$499.13 t^{-1}. Its soil application @ 10 t ha^{-1} of carbon was reported to have increased the beet root yield from 2.9 to 11.4 t ha^{-1} with the maximum net profit of \$11,288 ha^{-1} (Keske et al. 2019).

17.7 Effects of Biochar on Agriculture

17.7.1 Geomechanical Properties

Favourable soil tilth and an increase in root penetrability promote crop growth and yield (Jiang 2019). Although the literature on the biochar effects on soil tilth are rarely traceable but its ameliorative bio-physicochemical properties significantly improve soil tilth and tillage efficacy. Hseu et al. (2014) in a simulated rainfall experiment on biochar amendment in the degraded mudstone soil have observed increased macropores and reduced soil strength that invariably improved soil quality and physical properties for tilth. According to Snyder et al. (2009), reduced tillage requirements and residue retention due to biochar application significantly reduced GHG emission irrespective of the type of cultivation. Experiments conducted by Tim Crews (Cox 2013) in the Land Institute at Kansas revealed the importance of the 2000 year of the old practice of retaining soil nutrients that improves soil tilth too. Positive influence of biochar on soil tilth and soil aggregate stability has also been corroborated by Elad et al. (2010, 2011), Matt (2015), Yuniwati (2018) and Planet (2020).

Biochar can enhance the shear strength of clays and cyclic resistance of sand but can desaturate soil separates (Pardo et al. 2018). Sokolowska et al. (2020) in their experiment with wood waste and sunflower stick biochar experienced reduced tensile strength in all types of soils under test. Another experiment by Sadasivam and Reddy (2015) revealed a dramatic increase in cohesive strength of moist soil by almost thrice and an increase in shear strength of soil by incorporation of biochar at 10% (w/w) indicating induced stability to landfill covers. The above results were also corroborated by Reddy et al. (2015) with results showing positive relation between biochar amendments and geotechnical properties like hydraulic conductivity and shear strength of soil while compressibility had reverse relation. Looking at the paucity of information on the impact of biochar amendment on geomechanical properties, Renee (2019) has advocated for further intensive research for its effective geoenvironmental engineering applications.

17.7.2 Nutrient Dynamics

The role of biochar on nutrient dynamics in soil has already been touched upon earlier in this chapter. However, attempts are made in this section to review the research findings on the differential response of plants to varying levels of biochar applications only. Sukartono et al. (2011) have reported an increase in nutrient uptake in maize crop with the application of biochar. Olszyk et al. (2020) in their experiment reported variation in concentration of Ca, K, Mn, Mg, Zn and Fe in carrot taproot and lettuce leaf depending on the biochar type. The Ca, Mg and Zn were the most influenced and the concentration of K increased in the taproot system of carrot. The addition of corn stover biochar increased the uptake of macronutrients both in presence and absence of chemical fertilizers but switch-grass biochar had no effect on macronutrient uptake and pinewood biochar reduced the uptake (Chintala et al. 2013). The importance of P and K for the increase in crop productivity was revealed by Karer et al. (2013a) in an experiment on barley that resulted in reduced N uptake while P and K uptake improved with the biochar addition. In corn, omission of biochar from integrated chemical fertilizer application had at par effects on N, P and K uptake rates. However, the reduction in yield was severe under deficient N supply (Karer et al. 2013a). The uptake of nutrients in rice as studied by Ali et al. (2015) indicated a positive response of biochar on Ca, K, Mg, Cu and Mn uptake over control while the uptake of Zn, N and crude silica did not differ significantly. Moreover, the uptake of Fe was higher under normal fertilization than biochar supplementation in rice soil (Ali et al. 2015). In chickpea, application of maize stover biochar prepared by batch-wise hydrothermal carbonization (210 °C) had recorded better uptake of N, P, K and Mg than the biochar produced at 600 °C (Dilfuza et al. 2019). The utilization of biochar not only increased the growth of calendula (*Calendula officinalis* L.) but also increased the acquisition of macro and microelements from the soil (Karimi et al. 2020). A comparative report on the changes in chemical properties under biochar and cattle manure amendment in maize crop has been depicted at Table 17.1 for better understanding (Sukartono et al. 2011).

17.7.3 Disease Pest Infestation

Very few disease control methods are available to manage soil-borne pathogens whereas biochar has been successfully tested to fight against major diseases in fruit, vegetables, ornamental plants, trees, shrubs, etc. Elad et al. (2010) in their experiments with biochar amendments to the soil observed antagonistic effects against foliar fungal pathogens such as grey mould (*Botrytis cinerea*) and powdery mildew (*Leveillula taurica*) in pepper and tomato and to the broad mite pest (*Polyphagotarsonemus latus*) in pepper. In another experiment with biochar, they reported a shift in the bacterial community that could contribute to the resistance against bacterial wilt in tomato. The soil amendment with biochar altered microbial population and caused a shift towards beneficial microbial populations that promoted plant growth and induced resistance against soil-borne diseases (Lad et al. 2011). Graber et al. (2014) reported resistance of plants to pathogens in a U-shaped response curve depending on the dose of biochar, with a minimum disease outbreak at intermediate dose but severe effects at both the minimum and maximum doses. However, a relatively lower incidence of damping-off was seen in lower doses of biochar but at higher or moderate doses, the severity was similar to untreated control. Biochar has been affecting the progress of soil-borne diseases such as *Fusarium oxysporum* in asparagus (Elmer and Pignatello 2011), *Ralstonia solanaceaearum* in tomato (Nerome et al. 2005) and *Rhizoctonia solani* in cucumber (Jaiswal et al. 2014). Suppression of canker causing *Phytophthora* in woody plants was reported by Zwart and Kim (2012) under biochar addition to the soil.

17.7.4 Weed Dynamics

Study on weed dynamics is important, especially because, biochar can reduce the efficacy of herbicides. Many researchers have advocated for enhanced crop yield and ameliorative effects of biochar addition on bio-physicochemical properties of soil. Biochar has minimal effect on weed germination and emergence pattern as reported by Soni et al. (2015). Biochar mediated reduced germination and subsequent infestation of *Phelipanche aegyptiaca* (Egyptian broomrape), a weed in tomato has also been reported (Dilfuza et al. 2019). An increase in height and above-ground biomass of pig-weed and crabgrass was observed that might complicate the weed management strategy in biochar amended crop fields (Mitchell 2015). In a four year experiment with walnut shell biochar at 5 t ha^{-1}, 60–78% higher weed density was reported by Safaei et al. (2020) indicating more efficient utilization of macro and micronutrients by weeds compared with wheat and lentil crop. However, the reduced air-dry weight of weeds compared to the control plots in the rye crop grown with biochar has been reported in Poland (Kraska et al. 2016).

Preemergence herbicides are usually applied to the soil before the emergence of crop that might increase the adsorption of the applied herbicides by biochar thereby reducing efficacy. An experiment conducted by Soni et al. (2015) by incorporating biochar at 2 t ha^{-1} completely suppressed the herbicidal effects of atrazine and pendimethalin in corn crop due to the presence of organic carbon and higher surface area in biochar that resembled activated carbon thereby reducing the herbicidal efficacy (Soni et al. 2015). In another experiment, recommended dose of pendimethalin at 1 kg a.i. ha^{-1} along with biochar reduced grain yield of direct-seeded rice by 7.5% compared to pendimethalin without biochar. A higher dose of pendimethalin also reduced the biological yield of rice (Nath 2016). Hence, alternative weed management practices should be adopted for eradicating preemergence weeds in biochar amended soil (Sohi et al. 2010).

17.7.5 Water Use Efficiency

Biochar has the benefit of increasing water use efficiency (WUE) and water retention in soil (Monnie 2016; Dwibedi et al. 2022) at varying degrees depending on soil type, biochar characteristics and climatic parameters (Gao et al. 2020). Remarkable positive influence of biochar application on the WUE have also been observed by Benjamin et al. (2016), Lusiba et al. (2018) and Zhang et al. (2020). An experiment with corn cob biochar showed no remarkable effect on the water retention curve in sandy loam soil up to 20 t ha^{-1} but only at 80 t ha^{-1} the effect was significant (Monnie 2016). However, large application of biochar at 200 t ha^{-1} in sandy soil did not promote plant growth compared to 100 t ha^{-1} thereby fixing the upper limit of its beneficial effects (Kammann et al. 2011). This observation was corroborated by the result from low magnitude applications (1 and 2% of biochar in soil) that although slightly increased the water holding capacity but the effect was not sufficient to mitigate deficit moisture stress condition for which application with the higher rate was perhaps necessary (Afshar et al. 2016).

In the changing climatic scenario, it is imperative to develop a water balance agricultural method to improve resilience to climatic variability. A meta-analysis of observational data on biochar amendment revealed an increase in long-term evapotranspiration rates thereby increasing soil water retention capacity and water availability to crop (Benjamin et al. 2016). An increase in plant resistance to water stress (60% field capacity) was observed in biochar amended soil compared to the control (without biochar) (Aniqa et al. 2015). However, the negative effects of biochar on plant water availability are also cited by Fischer et al. (2019).

17.7.6 Crop Growth and Yield

Biochar has synergistic effects on crop growth and yield (Dwibedi et al. 2022). Its application in Chernozem soil significantly increased spinach (*Spinacia oleracea* L.) in terms of growth by 102 and 353% in spring and autumn, respectively (Zemanovai et al. 2017). In high drought-affected Chernozem soil, biochar application at 72 t ha^{-1} along with chemical N could increase barley crop yield by 10% compared to the control with N fertilizer but without biochar. However, reduction in maize and wheat grain yields by 46% and 70% at biochar application rate beyond 72 t ha^{-1} has been reported by Karer et al. (2013b). A single application of biochar at 20 t ha^{-1} to Colombian savanna soil increased maize yield by 28–140% compared to unamended control (Major et al. 2010). Perhaps the nutrient adsorptive capacity and antiallelopathic effects of biochar at 18 t ha^{-1} resulted in higher germination percentage, germination index and mean germination time of garden pea (*Pisum sativum* L.) seeds (Berihun et al. 2017) while biochar at 10 and 20 t ha^{-1} had positive influence on *Lepidium sativum* L. seed germination (Kraskal et al. 2016). Results of enhanced growth and yield parameters of bean (da Silva et al. 2017), wheat (Sial et al. 2019), maize (Zhu et al. 2015), rice (Muhammad et al. 2017), winter rye (Kraskal et al. 2016), sunflower (Qiang et al. 2020), and tomato (Yilangai et al. 2014) with positive effects on the plant height, root, shoot and grain dry mass, number of pods and/or grains due to application of biochar have also been reported. However, short-term application of biochar did not have any effect on grain yield or yield components of rice as reported by Yin et al. (2020). Rosenani et al. (2014) in their experiments with rice husk biochar reported higher biomass in *Amaranthus viridis* and *Ipomoea reptans* while no significant increase in yield was observed in sweet corn, except increase in total dry matter. The grain yield increase in cowpea with biochar amendment was irrespective of soil moisture regimes while the highest grain yield was reported under no-water deficit stress (Moosavi et al. 2020). However, significant interaction between biochar and maize productivity under limited water supply might prove a novel approach in enhancing yield as well as WUE (Faloye et al. 2019). Biochar amendment at 20 and 40 t ha^{-1} in rain fed region of North China although could significantly increase grain yield of maize by 23.9% and 25.3%, respectively with positive effects on root morphology and stalk biomass but its effects in the second year was not significant (Liu et al. 2020).

Application of biochar has also been influencing the cropping system as well (Dwibedi et al 2022). In rice–wheat system, Gupta et al. (2020) have reported higher grain yields for three consecutive years due to application of rice straw biochar and rice husk biochar at 5 t ha^{-1}. Significant positive correlation between N, P and K concentration in soil with total N, P and K in wheat indicated potential benefits of biochar application in supplementing plant nutrients in desired quantities (Gupta et al. 2020).

17.7.7 Climate Change

Carbon is an important basic constituent of all living organisms on this earth. Man is hunting for the traces of carbon in extraterrestrial bodies to explore any possible existence of life. On this earth, it cycles among the atmosphere, biosphere, hydrosphere and lithosphere in many forms. In the earth's atmosphere, carbon is present mostly as methane and carbon dioxide. The earth's largest carbon pool is found in the continental crusts and upper mantle, a large portion is present in form of sedimentary rocks. Oceanic carbon is the next largest stock, over 95% are present in inorganic dissolved carbon and only 5% (900 gigatons) of carbon (GtC) is available for exchange in the ocean surface (Kayler et al. 2017). The atmosphere contains only

839 GtC, a very small portion of total carbon but it plays a very significant role. Near about 19% of the carbon in earth's biosphere is stored in plants, and the rest remains in soil (FAO 2021). Soils contain 1325 GtC of top few feet and as much as 3000 GtC in total (Kayler et al., 2017). Oil and natural gases contain 270 and 260 GtC, respectively. Coal reserve accounts for 5000–8000 GtC and unconventional fossil fuels have whooping 15,000–40,000 GtC (Edmonds et al. 2004).

The concentration of CO_2 in the troposphere has elevated by 45%, from 280 ppm in 1750 to 415 ppm in 2019, due to the industrial revolution. The level of CO_2 has reached at this mark again after 3 million years, despite due absorption by various sinks involved in natural cycles. The earlier peak was natural and steady that had spread over many hundreds or even thousands of years allowing necessary adaption and adaptation by different species while the present rise is sudden and anthropogenic leading to mass extinctions of some life forms due to climate change.

Burning of fossil fuel, agricultural wastes and forest vegetation release fixed and structural carbons into the atmosphere elevating the CO_2 concentration of the atmosphere. Every year 30 GtC is fixed by crop plants, while on dying, it may return back to the atmosphere, resulting in little net change in soil carbon pool (Krounbi et al. 2019). Wildfires are estimated to add 8 billion tons of CO_2 every year for last 20 years and in 2017, the total CO_2 emission reached 32.5 billion tons as estimated by the International Energy Agency (Berwin 2018). In 2014, forest fires released 8.8 million tons of carbon compared to 104 million tons from all fires (Merzdorf 2019). Scientists have claimed that wildfires contribute less carbon than burning of fossil fuels, citing 15 years of carbon release from the wildfires in US at only 250 Gt as against fossil fuel contribution of 4800 GtC each year (Francovich 2019). However, their real worry began with the peatland fire in Indonesia in 1997–98 that released 3.7 billion tons of CO_2. Permafrost thaw due to global warming and climate change has increased the risks of uncontrolled fires in the northern peat that was previously not vulnerable to such hazard (Khadka 2018). Hence, issue of wildfires will be more challenging than mitigating the burning of fossil fuels in the future (Khadka 2018).

However, attempts to sequester significant amounts of free atmospheric carbon through afforestation and reforestation in forest fire affected areas are not successful in many cases due to global warming and related consequences. Restoration of the original wild biodiversity in such charred areas is quite difficult and time consuming. Many native species would be able to survive under changing climate due to mismatch with their physiological optima. Systematic planning and consistent efforts are required for altering the challenging and perilous effects of global warming and climate change.

Biochar can significantly smother climate change by reducing atmospheric GHG levels, and sequestering carbon dioxide. It can also increase productivity of marginal soils, reduce soil erodibility, recharge groundwater, reshapes soil biodiversity, regenerates natural vegetation and many more synergistic effects it can have in the line of sustainable agriculture and environment. Estimates reveal that application of biochar can reduce 12% of the global GHGs and doping of potassium can enhance carbon sequestration potential by 45% (Masek et al. 2019). Biochar in soil not only fixes atmospheric CO_2 but also ameliorates soil that facilitates plant growth. It induces dark colour in the topsoil, like *terra preta* of Amazon basin, which absorbs much incident solar radiation during daytime and reradiates it back as long-wave radiation during night thereby maintaining a steady range of diurnal temperature. Its presence in soil not only marginalizes diurnal air temperature but the soil temperature is maintained which protects vegetation against harmful effects of low temperature. Biochar is carbon negative and hence it can bring back the carbon from active cycle and sequester in an inactive native cycle that slows down the process of global warming and climate change (USBI News 2021b).

Studies on the application of biochar with poultry manure in maize (*Zea mays*) in rotation with soybean (*Glycine max*) in Canada showed a positive influence on carbon and nitrogen transformation in the soil–plant-atmosphere system (Mechler et al. 2018). In another experiment under soybean in Ohio, USA the cumulative N_2O emission over the growing period decreased by 92% in the biochar-amended soil compared to the control (without biochar) while the total cumulative CH_4 and CO_2 emissions did not get affected by any such amendment. Biochar amendment resulted in net soil carbon gain whereas humic acid and water treatment residual resulted in net soil carbon loss. However, all three amendments subsided the global warming potential (Mukherjee et al. 2014). A *meta*-analysis of Timmons et al. (2017) published papers with 552 paired comparisons conducted by He et al. (2017) indicated 22.14% increase in soil CO_2 fluxes, but 30.92% decrease in N_2O fluxes while CH_4 fluxes remained unaltered. However, under soil fertilization, the CO_2 fluxes were suppressed which implies that biochar is unlikely to stimulate CO_2 fluxes in the agriculture sector (He et al. 2017).

17.8 Future Prospects and Constraints in Biochar Systems

The significance of biochar in environmental remediation and agricultural production systems is now an undoubted fact. However, its in-depth study on ISO-based life cycle assessments in various systems has not yet been well attended. The potential of biochar and biochar systems is manifold. It can be potentially linked to many sectors for green-growth, development and climate resilience. Decision tools based on local environmental, agricultural, social constraints and opportunities requirement need to be designed and validated to select befitting biochar system technologies (Scholz et al. 2014).

17.8.1 Scaling up from Pilot to Programme

Biochar systems are nascent technologies in-spite of their wide adoption by many older civilizations. As of now, many researchers have intensively studied various biophysicochemical properties of biochar synthesized from different feedstock, ranging from wastes to wood under varying pyrolytic conditions. However, most of them are either laboratory- or GHG-based experimentations lacking wider replicability in the farmers' fields to adjudge their effects extensively. A deeper insight into the economic benefits of the carbon trading of biochar systems overweighs the return from crop growth. So also, due to lack of applicable methodologies and legislative yardstick to regulate the targeted source of feedstock, the engagement of private sector is unlikely to exist in larger scale, at least in the present scenario in most developing countries. Therefore, it is high time for the institutions such as World Bank, International Finance Corporation, Global Environment Facility and many other international and national institutions to test-demonstrate various sustainable biochar production systems across the globe prioritizing the economically deprived but resource stuffiest countries.

17.8.2 Further Research Needs

The quantum of funds pumped towards research and demonstration has not yet reached at its desired level to scale up biochar systems comfortably. Among the areas of further research, effective targeting of the 'true wastes' that degrade the environment in absence of judicious and alternative uses is of prime importance now. Furthermore, development of low cost pyrolysis units befitting to the socioeconomically deprived countries is an area for future research. Critical assessment of biochar application process and their bio-physicochemical effects on the soil and crop yields also deserve deeper attention. Characterization of biochar and their bio-physicochemical properties, depending on feedstocks, pyrolysis temperature and duration, would allow better prediction of soil fertility, target crops and soil types to which these biochars could be allowed. The farmers may be directly involved or the knowledge will be made available through intermediary extension service systems, preferably in the developing countries first. Moreover, social aspects of biochar system related technologies need further attention as certain biochar systems would increase drudgery that in turn would discourage the farmers, and farm women in particular, in adopting them. As biochar systems at higher rate of application, in many instances, may not be financially sustainable for small and marginal farmers, small-scale experimental use in limited areas could remediate soil and enhance crop productivity in a time series perspective. As biochar systems aim at 'triple win promise' viz. energy, climate and soil but no such evidence satisfies universal conditions without considering local conditions (Scholz et al. 2014). Hence, long-term applied research at scale of implementation could essentially resolve this problem.

17.8.3 Constraints and Risks

While considering the feasibility of biochar production and management systems certain key questions need to be addressed. Firstly, will the biomass be honestly sourced from the true waste materials? While answering this question a comparative analysis with alternative waste disposal systems should be performed giving importance to the energy capture and nutrient-recycling unlike open burning and land filling. Further question of safe-feedstock use could be addressed through incorporation of non-toxic rural and agricultural wastes in biochar systems and deliberately avoiding the industrial and urban wastes. However, the risk of rampant deforestation and cleaning of natural vegetation can never be set aside under lucrative government incentives to popularize biochar systems. Next challenge could be sufficient availability of suitable feedstock locally and its economic feasibility in long run. Such a challenge could be sorted out by indicators like sustainable availability of feedstock on-farm and its potential use in high value crops in intensive cropping system. Furthermore, the risk of methane, carbon oxide and other toxic volatile fume release must be addressed meticulously to safeguard global environment. A site specific biochar application repository could scientifically address variable soil and crop requirements. The constraint of non-adoption of technology in post demonstration phase could be ascribed to drudgery and valuable alternate energy services.

17.9 Conclusion

Application of biochar is an ancient practice of soil conditioning and sustainable yield enhancement. It ameliorates and improves physicochemical properties of soils, facilitates nutrient availability and enhances plant growth and yield, rendering it most suitable for organic, dryland and conservation agriculture and land reclamation. Its lower production cost from locally available biowastes could lead-support resource poor small and marginal farmers as an intriguing option in crop production. Although research results on biochar application are alluring but most of them are laboratory or greenhouse-based, lacking wider adaptability in open field conditions. Even today, large knowledge gaps on persistence, bio-geochemical cycles, GHG regulations, microbial behaviour and metal retention period are still lacking that need to be addressed in full-scale outdoor trials. Crop specific tailored biochar dose recommendations based on biochar feedstocks, pyrolytic conditions and soil type need to be designed.

Table 17.1 Soil characteristics of sandy loam at Lombok, Indonesia after application of biochar and cattle manure under maize cropping system (Sukartono et al. 2011)

Organic amendments	pH		CEC (mg kg^{-1})		C (mg kg^{-1})		N (mg kg^{-1})		P (mg kg^{-1})		K (cmol kg^{-1})		Ca (cmol kg^{-1})		Mg (cmol kg^{-1})	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Cocconut shell biochar	6.49^{a}	6.46^{a}	15.04^{a}	15.15^{a}	1.15^{a}	1.13^{a}	0.12^{b}	0.14^{ab}	26.48^{a}	22.39^{ab}	0.75^{b}	0.78^{a}	2.44^{a}	2.54^{ab}	1.42^{b}	1.54^{b}
Cattle dung biochar	6.45^{a}	6.46^{a}	15.1^{a}	15.14^{a}	1.14^{a}	1.11^{a}	0.16^{a}	0.15a^{b}	26.24^{a}	21.67^{ab}	0.89^{a}	0.78^{a}	2.6^{b}	2.78^{b}	1.5^{a}	1.53^{b}
Cattle manure once	6.39^{b}	6.36^{b}	15.02^{a}	14.67^{ab}	0.9^{b}	0.94^{ab}	0.14^{ab}	0.13^{b}	25.66^{a}	20.95^{b}	0.76^{b}	0.71^{b}	2.38^{a}	2.15^{a}	1.4^{b}	1.45^{b}
Without amendment	6.29^{c}	6.32^{b}	13.34^{b}	13.4^{b}	0.87^{b}	0.89^{b}	0.11^{b}	0.13^{b}	23.59^{b}	14.44^{c}	0.7^{c}	0.7b	2.22 ^{c}	2.08^{a}	1.37^{b}	1.32^{c}
Before expt.*	5.97	–	12.99	–	0.85	–	0.12	–	24.41	–	0.57	–	2.34	–	0. 87	–

Mean with the same superscript letters within column do not differ significantly ($p = 0.05$); 1st and 2nd denote rainy season (2010–11) and dry season (2011) maize crops; * pre-treatment data

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