Review Paper

Comprehensive review on production and utilization of biochar

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Abstract

The on-farm burning of crop residues and biomass results in numerous environmental issues and affects human beings. Crop residues have considerable energy potential if utilized appropriately. Crop residues can be converted into biochar through thermo-chemical routes; conversion helps in the managing and handling of biomass. Biochar reactors usually operate at temperatures between 400 and 600 °C with fixed carbon contents ranging from 60 to 85%. The application of this biochar to soil improves the physiochemical characteristics of soil because biochar is rich in organic carbon content, which makes the soil more fertile and acts as a carbon sequestration agent over the long term. Biochar itself is considered a source nutrient and can alter the soil nutrient pools and availability. Biochar applied up to 10 cm depth of soil may decrease the denitrification potential and lower N_2O emission, greatly controlling leaching of mobile nutrients such as potassium, thus improving water use efficiency, nutrient availability and plant growth. Furthermore, it reduces the leaching of nitrogen into the groundwater and increases the water retention and cation-exchange capacity while moderating the soil's acidity, resulting in improved soil fertility. This article discusses different biochar production processes and various feedstocks and characteristics of biochar. The factors affecting biochar production and advantages of the utilization of biochar in soil are also reviewed.

Keywords Biomass · Biochar · Slow pyrolysis · Soil health · Greenhouse gas mitigation

1 Introduction

Biomass is referred to as an indirect source of solar energy and considered a source of stored energy. Biomass is a renewable organic material derived from plants and animals serving as sources of energy [1]. Improper disposal of biomass produced by the agricultural sector is a major challenge worldwide [2].

The demand for energy and food security is increasing as the world population grows. Energy is crucial for the development of the industrial, agricultural and transportation sectors of any country [3]. To meet the energy demand, fossil fuels are extensively used worldwide. Environmental and economic issues are continuously emphasizing the need to find eco-friendly renewable sources of energy [4, 5].

Mitigating greenhouse gas emissions and ensuring adequate global food supplies represent two of the last decade's most difficult challenges [6]. Although global food production has benefitted from chemical fertilizers, environmental problems have emerged as a result of their use [7]. Additionally, overuse of fertilizers can result in hardened soil, decreased soil fertility, polluted air and water, and the release of greenhouse gases. There is an urgent need to find an alternative to chemical fertilizers that, ideally, can be sourced in abundant amounts, promotes global food production, enhances CO_2 capture, and does not affect soil health or damage the environment [8]. To sustain agricultural productivity, it is crucial to maintain adequate levels of organic matter in the soil to preserve its physical, chemical and biological integrity. Biochar, a pyrogenic black carbon, may play an important

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role in improving soil health, resulting in higher crop yield and absorbing atmospheric carbon dioxide [9]. Ji et al. [10] reported that biochar is the most auspicious straw management measure and provides the highest carbon abatement rate and economic profit.

Biochar is produced by heating biomass at high temperatures (300–600 °C) in a closed reactor containing no to partial levels of air. Under these conditions, biomass undergoes thermochemical conversion into biochar [11–18]. Because of its numerous potential uses in agriculture, energy and the environment, much attention has been given to biochar in both the political and academic areas. Biochar can be used in a variety of applications such as energy production, agriculture, carbon sequestration, wastewater treatment and bio-refinery [19]; additionally, biochar provides an alternative strategy for managing organic waste. These advantages have renewed the interest of agricultural researchers in producing biochar from bio-residues and using the product as a soil amendment. Hakala et al. [20] conducted a study to assess the potential of crop residues for the 1997–2006 period and found that availability of crop residues varied from 4.8 to 5.1 billion tonnes.

Kumar et al. [21] reported that India has the potential for a large amount of biomass feedstock from different sources. Hiloidhari et al. [22] estimated that annually about 686 million tonnes of gross residues is available in India from agricultural crops, and about 234.5 million tonnes represents the surplus potential. This shows the availability of enough raw materials for an efficient and eco-friendly biochar production unit. The biomass used for biochar production can be classified [23] as illustrated in Fig. 1. Figure 2 summarizes the thermochemical conversion routes of biomass, including direct combustion to provide heat, liquid fuel and other elements for thermal and electrical generation. This review paper is written with the aim to highlight and discuss the different production processes, the use of biochar as a soil health enhancer, its effects on crop yield and its role in mitigation and carbon sequestration.

2 History of biochar technologies

Biochar has acquired new dimensions in the current organic farming era, but its origins are associated with soils of the Amazon region usually referred to as “terra preta” soils, which have been found up to 2 m depth. It is a highly fertile dark-coloured soil that has supported the agricultural needs of the Amazonians for centuries [24].

The presence of terra preta reveals that humans were deliberately responsible for its creation. Carbonization of biomass for producing biochar has been recorded as long as human evolution has existed [25, 26]. The wood distillation industry was flourishing in 1850, but petroleum industries developed between 1920 and 1950, diminishing the growth of wood distillation [25]. In 1970, the oil crisis accelerated the scope of alternative fuels and advanced pyrolysis reactors were designed to extract the bio-oil from biomass [27, 28]. Further development of pyrolysis occurred during the decades of 1970 to 1990 to understand the fundamentals of biomass pyrolysis reactions [29–32]. The commercial use of fast, flash, vacuum and ablative types of pyrolysis for the production of biochar and bio-oil appeared between the 1980s and 1990s [33–35]. A new technological achievement allowing a new bio-oil-based refinery to extract usable by-products from

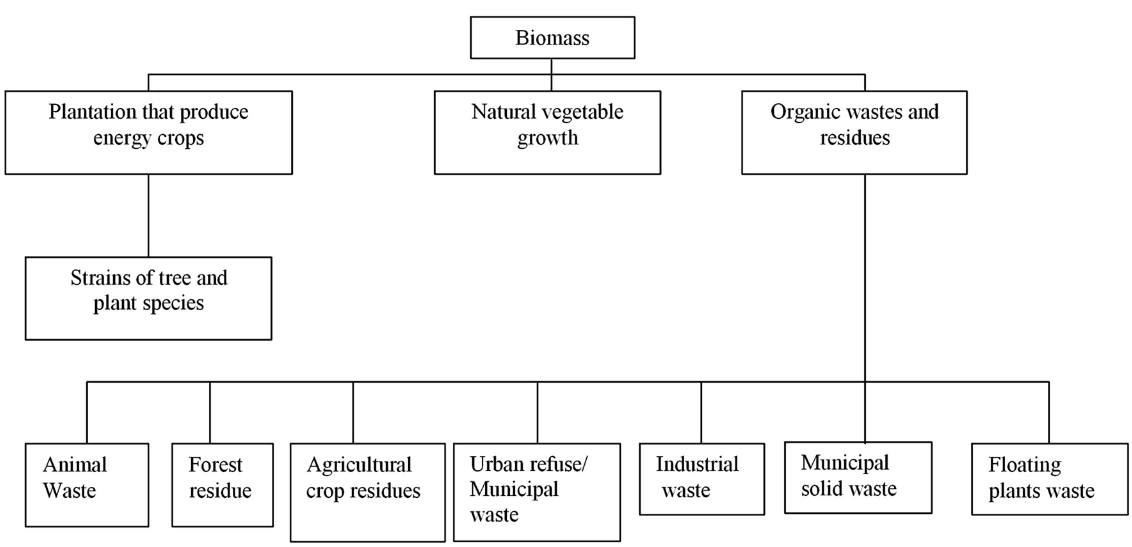
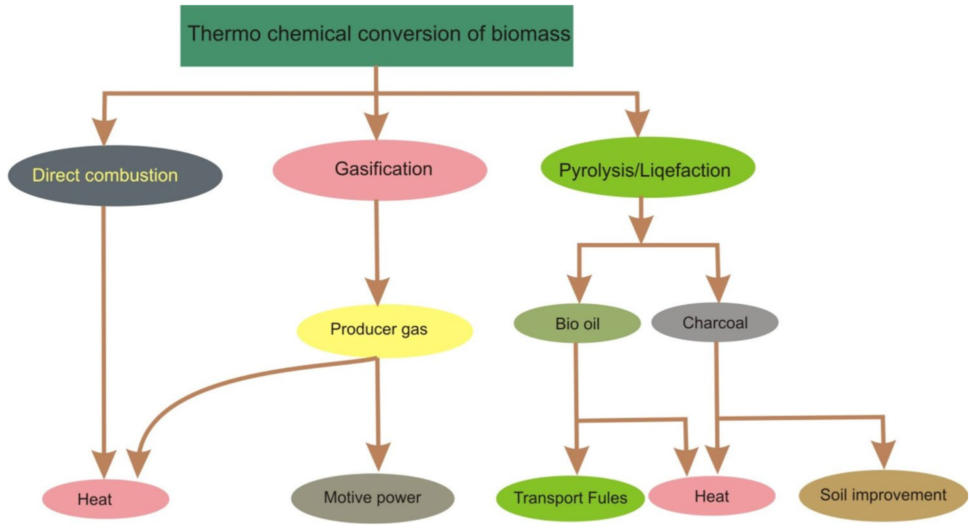


Fig. 1 Classification of biomass

Fig. 2 Biomass conversion routes



biomass has been proposed [36–41]. Biochar used for soil improvement is produced through a slow pyrolysis process because of its higher biochar yield compared with other production processes [42]. Basically, under a slow pyrolysis process, biomass is heated within the range of 300–600 °C for a longer period [43].

3 Biochar and sustainability

Biochar plays a major role in mitigating climate change, promoting environmental sustainability and increasing agricultural productivity [44–46], facilitating soil carbon storage and improving soil fertility to increase plant and overall crop yield [47, 48]. Lehmann and Joseph [49] have presented four motivational objectives of biochar application, i.e., soil improvement, waste management, climate change mitigation and energy. Either individually or in combination, these objectives can have social or financial benefits, or both, as illustrated in Fig. 3. Biochar always draws attention as a potential input for agriculture as it can improve soil fertility, aid sustainable production and reduce contamination of streams and groundwater [50–53].

De Gisi et al. [54] discussed the concept of terra preta sanitation (TPS), which has been extensively adopted in Amazon civilization. It was reported that TSP is a close loop process and beneficial for a sustainable lifestyle, integrating soil fertility, food security, waste management and renewable energy, as illustrated in Fig. 4. The terra preta sanitation process includes a diversion of urine through a charcoal mixture and is based on lactic acid fermentation with subsequent vermicomposting. It was found that lacto-fermentation is a biological anaerobic process where no gas or odour is produced.

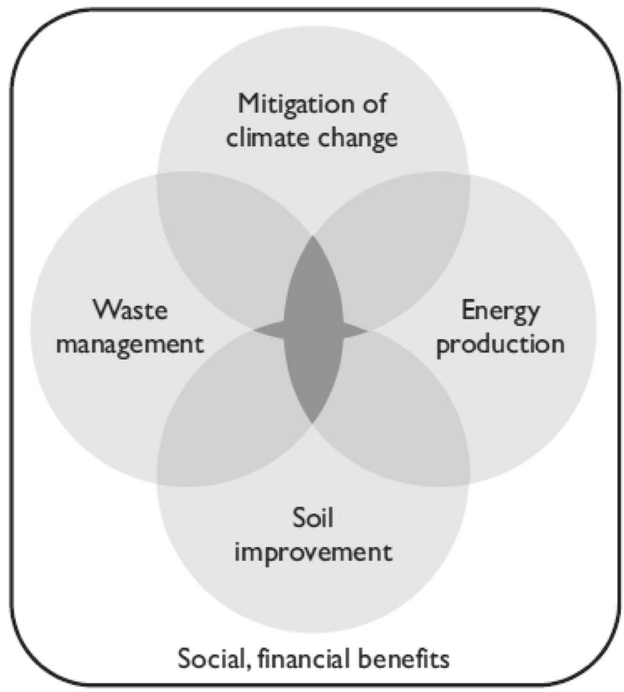


Fig. 3 Motivational objectives of biochar [49]

Woolf et al. [55] introduced a sustainable biochar concept, as illustrated in Fig. 5. Figure 5 clearly shows that atmospheric CO_2 is utilized by green plants during photosynthesis. Pyrolyzation of the biomass results in bio-oil and biochar. Furthermore, Woolf et al. [55] also reported a reduction in annual net emissions of CO_2, CH_4 and nitrous oxide by 1.8 pg. Biochar amendment to soil can prevent greenhouse gas emissions from the soil. The biochar can increase the water- and nutrient-holding capacities of soil, which typically then result in increased plant growth.

Fig. 4 Terra preta sanitation system [53]

4 Biochar production technologies

Biochar is derived from a wide variety of biomasses including crop residues that have been thermally degraded under different operating conditions. It exhibits a correspondingly immense range of composition. In this case, a compilation of different biochar conversion technologies along with their operating conditions and product yields was offered by Xie et al. [56], who found that with a longer residence period (up to 4 h) with moderate temperature (up to 500 °C), the biochar yield varied from 15 to 35% while the bio-oil yield varied between 30 and 50%. On the other hand, with less residence time (up to 2 s), more bio-oil (50–70%) was found.

Thermochemical processes such as pyrolysis and carbonization convert the biomass into bio-fuels and other bio-energy products. In the pyrolysis process, thermochemical conversion of biomass is carried out in the absence of air and at a temperature > 400 °C to form a solid product known as biochar. The biochar mainly consists of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S) and ash. Generally, there are three modes of pyrolysis: slow, intermediate and fast. A higher biochar yield was found with a slow pyrolysis process than with others [57]. Steiner et al. [58] produced biochar from rice husk using a top-lit updraft gasifier and found that this technology can be used relatively easily for farmers to produce biochar in the field, with an efficiency of 15–33%. Biochar produced from available on-farm crop residues is sufficient to contribute 6.3–11.8% of the production area annually [59].

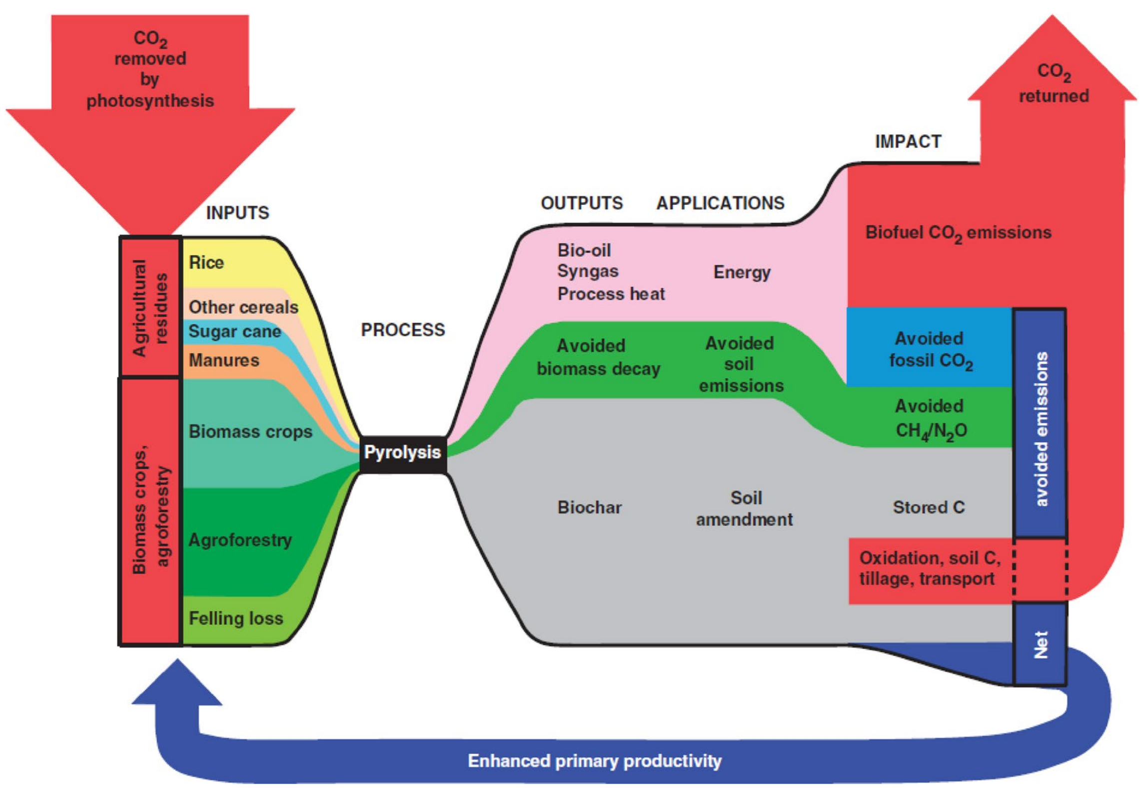


Fig. 5 Sustainable biochar routes [55]

Carbonization is a slow pyrolysis process that has been in use for thousands of years, and its main goal is the production of biochar. In slow pyrolysis, biomass is heated slowly in the absence of air to a relatively low temperature (≈ 400 °C) over an extended period of time [60]. Energy can drive the process in the following different ways: (1) directly as a heat of reaction, (2) directly by flue gases from the combustion of feedstock, (3) through indirect heating of the reactor wall using a hot gas and (4) through indirect heating of the reactor wall using sand or other non-gas materials. The biochar production process can be classified as illustrated in Fig. 6.

4.1 Batch processes

The batch process is an ancient practice and is still used in rural areas for biochar production. Though the charcoal yield in such a process varies over the low range of 12.5–30% [61], it is still preferred in the countryside because of its low operational and construction costs. The batch process for biochar production includes:

1. Earthen and mound kiln;
2. Brick, concrete and metal kiln;
3. Retorts.

4.1.1 Earthen and mound kiln

Duku et al. [62] conducted an experiment on the production of biochar by using an earthen mound kiln in Ghana. During the study, they used wood as a feedstock and found that the ground acts as an insulating material that resists the entry of oxygen during the carbonization process. Masek [63] performed an experiment on biochar production using an earthen mound kiln and found a yield > 10%. Bailis [64] used wood as a feedstock for charcoal production and found that moisture content affects the yield of charcoal in traditional processes. He reported that the yield of charcoal ranges from 10 to 30% when using wood as a feedstock. Lohri et al. [65] estimated an average emission component in the case of an earthen mound kiln. His analysis showed that the emission of carbon dioxide (CO_2) into the atmosphere was around 334 ppm. Significant emissions of the products of incomplete combustion adversely affect human health and the environment. FAO [66] found that a higher level of efficiency and product quality could be obtained at a maximum carbonizing temperature of approximately 500 °C.

4.1.2 Brick, concrete and metal kiln

Kristofferson and Bokalders [67] constructed a rectangular kiln using either masonry blocks or poured concrete combined with steel reinforcements. They reported charcoal production cycles in a cold climate to be 25–30 days long and in a warm climate to be 33 days with maximum charcoal yields of 25–33%. Deal et al. [68] conducted an experiment to produce biochar using a metallic kiln. During the experiments, five different feedstocks were used: eucalyptus, maize, rice husks, coffee husks and groundnut shells. The maximum temperatures reached inside the kiln were recorded as being between 400 and 600 °C at the top of the kiln and between 600 and 800 °C at the bottom. Furthermore, biochar yields were 140–290 g/kg of the initial biomass weight for eucalyptus, 240–250 g/kg for maize cobs, 450–490 g/kg for rice husks, 360–430 g/kg for coffee husks and 290–320 g/kg for groundnut shells.

Pennise et al. [69] tested a Brazilian round brick kiln with a capacity of 20,000 kg of woody biomass and noted a charcoal yield of approximately 68.9% with a carbon content of 85.7% and a calorific value of approximately 29.20 kJ/g. Mwampamba et al. [70] used wood as a feedstock for charcoal production, using a brick and metal kiln, and found that the efficiency of production fell between 25 and 35%. Kammen and Lew [61] compared the efficiencies of five metal kilns, including Siamese, Nilgiri, standard beehive, South African garage and commercial half orange, from different nations,

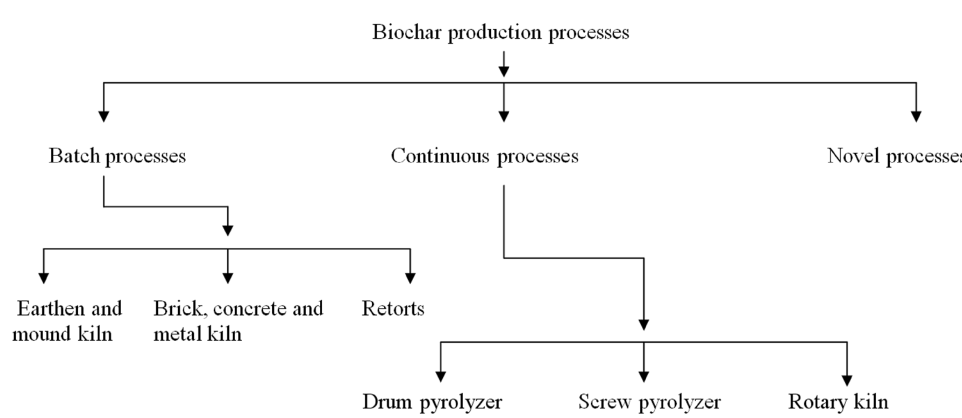


Fig. 6 Classification of biochar production process

including Malaya, India, Brazil, South Africa and Argentina, and found variations in charcoal yields that ranged from 12.5 to 30%, reported as the dry weight ratios of the charcoal output to the wood feedstock input.

4.1.3 Retorts

Peterson and Jackson [71] produced biochar by adopting two different processes, a retort-type oven with inert gas and a gasification technology using various crop residues (such as corn stover, wheat straw and wheat straw treated with glycerin). They reported that gasification is a simpler, easier and more cost-effective means to produce biochar compared with retort, because while the retort method effectively promoted pyrolysis in the absence of oxygen, it was costly during scale-up. This expense was due to the need to control the atmosphere with sealed systems in conjunction with the use of inert gas. For operation, as a batch reactor, atmospheric control is also required; otherwise, it cannot run with a continuous supply of feedstock. Adam [72] built an improved charcoal production system in India and East Africa from a low-cost retort kiln that produces charcoal from forest residue such as wood and that is more eco-friendly. Also, during the experiment Adam [72] realized that the charcoal production efficiency was approximately doubled (30–42%) compared with traditional charcoal production methods (10–22%). He also found that ICPS reduces emissions into the atmosphere up to 75% compared with traditional carbonization processes. Antal and Grønli [73] studied the required operating cycle for the production of charcoal from the Missouri kiln in the USA and reported that it produces charcoal in a 25% yield for every 7–12 days of its operating cycle. The average temperature required for the operation is between 450 and 510 °C; the working temperature varies significantly throughout the kiln, which affects the charcoal quality. Furthermore, Moreira et al. [74] produced biochar from cashew nut shells in a batch-type reactor. The temperature was varied from 200 to 400 °C and yielded 30% biochar, 40% liquid and 30% gas products.

4.2 Continuous process for production of biochar

At present, the continuous process for production of biochar is widely adopted in the commercial sectors because of maximum yield, energy efficiency and its quality. The biochar yield was between 25 and 35% [62]. The continuous production of biochar is ideal for medium- to large-scale production and it provides greater flexibility concerning the biomass feedstock, which are major benefits [75]. The continuous process for biochar production includes:

1. Drum type pyrolyzer;
2. Screw type pyrolyzer;
3. Rotary kiln.

4.2.1 Drum type pyrolyzer

Robert et al. [45] used a generalized model in which the feedstock is pyrolyzed in continuous operation, is horizontally mounted to a drum kiln and heated externally to around 450 °C. The continuous feeding and moving of biomass took place in the drum with the help of paddles, which increased the kiln efficiency about 50% so that 90% of the heat recovered from the kiln was used for drying the feedstock. Jelinek [76] developed a drum pyrolyzer which uses heating tubes placed in the centre of the durm. The tubes are subjected to low-temperature carbonization of trash and reuse material with a temperature of about 400–500 °C by slowly rotating the drum. The drum pyrolyzer feed material to be carbonized was located near one end of the face and discharge took place at the other end. Collin [77] discovered that aromatic pyrolysis oil can be produced by pyrolyzing special wastes containing hydrocarbons such as scrap tires, cable, waste plastics, etc., in an indirectly heated drum reactor at a temperature of around 700 °C. Collin [77] saw a yield of up to 50% in relation to the organic material. Becchetti et al. [78] studied the use of a conventional type rotary drum pyrolysis reactor for the production of pyrolysis gases and carbonaceous solid residue such as charcoal from municipal solid waste and observed that the pyrolysis process not only improved the energy yield but also minimized the waste disposal problem; solid waste was controlled to 10–15% of the total weight of the initial residue.

4.2.2 Screw type pyrolyzer

Agirre et al. [79] developed an auger reactor for the continuous carbonization process by using biomass waste. During the experiment it was realized that 900 °C temperature was required for suitable quality of charcoal production, which contains a high carbon content of approximately 85% and a low volatile amount of approximately 10%. For the auger pyrolysis reactor, many parameters, such as the moisture content, residence time, grain size and operating temperature, affect the yield of charcoal and its quality. Maschio et al. [80] studied a moving bed in the pilot plant, a continuous screw reactor for charcoal production, by using biomass with indirect heating. They found that a 350 °C to a 450 °C operating temperature was required for charcoal production. During the study they realized that a heating rate in the range of 20–40 k/min rate was required; the higher temperature could decrease the charcoal yield, and the particle size should range from 50 to 200 mm. Brown and Brown [81] developed a laboratory-scale reactor to pyrolyze red oak wood biomass for the production of char and bio-oil. During the experiment, they found that operating conditions, such as the flow rate of the sweep gas (3.5 standard l/min), heat carrier temperature (600 °C), high auger speeds (63 RPM) and high heat carrier mass flow rates (18 kg/h), were helpful for maximum bio-oil yield and minimum char yield. The result indicated that this reactor was well suited for bio-oil production, achieving > 73% liquid yield. Mozammel et al. [82] used a Herbold pyrolyzer in which a screw type shaft was fitted inside the reactor to produce activated charcoal from feedstock such as coconut shells using $ZnCl_2$ activation. While performing the experiment, results were obtained in which the initial calorific value of coconut shell was 18.38 MJ/kg, and the final calorific value of charcoal was 30.75 MJ/kg. The fixed carbon content was approximately 76.32% and had a maximum yield up to 32.96%. The activation time was 50 min for the production of activated charcoal at a temperature of 600 °C with an impregnation ratio of about 40%. Recently, Ferreria et al. [83] developed a screw reactor to produce biochar from elephant grass. The reactor temperature during the experimental study ranged between 400 and 600 °C. Their experimental results reveal that the maximum biochar yield was about 37.4% at 400 °C.

4.2.3 Rotary kiln

Ortiz et al. [84] carried out a study using a pilot rotary kiln to produce carbonized material from a variety of raw materials such as eucalyptus wood. The pilot rotary kiln was cylindrical and rotated around its longitudinal axis. To facilite the discharge of material, the pilot rotary kiln was slightly inclined (slope of about 2–6%). In their research project, Ogawa et al. [85] introduced an internal heating rotary kiln designed to produce charcoal using wood waste as a feedstock. During their experiment, they found that the rotary kiln produced around 358.0 Mg-C/year biochar from 936.0 Mg-C/year wood waste at a planned temperature in the range of 500–600 °C. Schimmelpfennig and Glaser [86] analyzed two different rotary kilns used in the carbonization of organic material that discharged pyrolysis gases suitable for heating purposes or for driving the processes. The experiment used rotary kilns that are heated externally and have a shape similar to a cylindrical pyrolyzer in which biomass is moved continuously by rotating the spiral inside the kiln. The rotary kilns produced a total of 16 samples of biochar. Ten samples were produced in a vertically constructed rotary kiln in China operating in a temperature range from 400 to 600 °C and using bamboo as a feedstock. Another six samples in Switzerland were produced from a horizontally constructed kiln heated to a temperature of 650 °C.

4.3 Novel processes

Flash carbonization is a novel process. In it, biomass is quickly and efficiently converted into biochar. The maximum biochar yield was around 40–50% with 70–80% fixed carbon content [87]. Antal and Grønli [73] examined the high yield of charcoal using different feedstocks, such as leucaena wood, oak wood, corncobs and macadamia nut shells, carbonized at high pressure (1 MPa) in controlled flash fires within a packed bed. In flash carbonization, the direction of the fire and the entry of the air were controlled with a counter current and at an elevated pressure. Charcoal with a fixed carbon yield was reached at < 30 min of reaction time. Furthermore, during the experiment, the charcoal yield was between 29.5 and 40%, fixed carbon ranged from 27.7 to 30.9%, and the energy conversion efficiency of biomass to charcoal ranged from 55.1 to 66.3%. Wade et al. [88] investigated laboratory-scale flash carbonization (a novel process) for the conversion of feedstock biomass (corncob and macadamia nut shell) into biocarbon. During the experiment, biomass feedstock was placed in a packed bed within a pressure vessel, and an initial pressure of 1–2 MPa was maintained through the use of compressed air. A flash fire was ignited at the bottom of the bed, and after a duration of 2 min, air was supplied to the top of the bed. It was found that biomass could be converted to biocarbon at a high yield. For corncob, a pressure > 1.31 MPa was achieved at a rate up to 1.21 MPa/s, for an initial system pressure of 2.17 MPa. In the case of macadamia nut shell, this phenomenon did not occur. Nunoura et al. [89] used biomass feedstock such as corncob and nut shell to produce charcoal by using a flash carbonization process. After the experiment was completed, they found that the fixed carbon yield from corncob feedstock reached 29.30% and the yield from nut shell was 32.0% at elevated pressures of 0.791–2.86 and 1.14–2.17 MPa, respectively. Gas chromatography was also used to analyze the composition of effluent gas coming from the carbonization canister. Both feedstocks contained up to 2% hydrogen, 14% oxygen, 60–80% nitrogen, 10% carbon monoxide, 3% methane and 2–20% carbon dioxide. Nartey and Zhao [90] studied the flash carbonization of biomass; their ignition of the flash fire took place at elevated pressure (1–3 MPa) in the middle of a packed bed, and 0.8–1.5 kg air per kg of biomass was required to complete the carbonization. Those researchers found a 50% biochar yield by using various feedstocks for reactor temperatures ranging from 330 to 650 °C, where the time required for flash carbonization was < 30 min. A two-step pyrolysis process was developed by Cheng et al. [91] to improve the biochar yield. With this process, the biochar yield was 39.3% at 600 °C. Furthermore, it was also noted that the fixed carbon yield obtained from two-step pyrolysis was higher than that from the one-step process.

4.4 Method of biomass heating to produce biochar

Biochar production from crop residues starts with the feeding of biomass into the biochar production unit and combustion in the absence of air. The formation of charcoal is completed in five different temperature stages: stage 1: At 20–110 °C, biomass absorbs heat as it dries, giving off moisture as water vapour. At this stage, the temperature remains at or slightly above 100 °C until the wood is dry. Stage 2: At 110–270 °C, biomass starts to decompose by giving off carbon monoxide, carbon dioxide, acetic acid and methanol, making an endothermic reaction. Stage 3: At 270–290 °C, this is the point when an exothermic reaction starts, generating a considerable amount of heat. Such a reaction leads to a continuous breakdown; the desired temperature is maintained to keep the wood from cooling down below the decomposition temperature. During the exothermic reaction, gases are released in vapour form with some tar. Stage 4: With increasing temperature, a vapour mixture of combustible gases (i.e., carbon monoxide, hydrogen and methane) and carbon dioxide is released into the atmosphere. As the temperature increases up to 400 °C, the condensable vapours such as water, acetic acid, methanol, acetone, etc., and tar are predominate. Stage 5: When the temperature reaches 400 °C, the transformation of biomass to charcoal will be practically complete, but appreciable amounts of tar are contained within the biochar, and some tar has condensed on the charcoal. To avoid this, the temperature should be further increased to 500 °C to complete the carbonization stage [92].

There are several ways to provide heat to maintain the desired temperature of pyrolysis kilns. One method involves combusting part of the biomass within the kiln. This is called autothermal pyrolysis, as illustrated in Fig. 7a. Due to the use of partial combustion, authothermal kilns typically have lower char yields. Another method is for the heat to be produced externally and to heat the biomass directly. This involves hot gas being brought into contact with the biomass, as shown in Fig. 7b, or heat being transferred through the reactor walls, as in shown Fig. 7c. Condensable pyrolysis vapour can be recovered during indirect heating, and this ultimately enhances the biochar yield [93].

A performance test of the Argentinean-type charcoal kiln (see Fig. 8) involving the carbonization of wood biomass was carried out by Mohod and Panwar [94]. The kiln was tested with Anjan (*Hardwickia binata*), Babul (*Acacia nilotica*), Behada (*Terminalia chebula*), Char (*Buchnania lazan*) and Dhawda (*Anogeissus latifolia*) wood, and the mass conversion efficiency was found to be 27.14%.

5 Factors affecting biochar production

The performance results of biochar production which occur via different production technologies broadly depend on the various types of feedstock used, the moisture content of said feedstock, and the operating temperatures and pressure points at which experiments were conducted. Biomass has three main groups, cellulose, hemicellulose and lignin, with trace amounts of extractives and minerals. These propositions are varied depending on the feedstock, a variation which highly affects the biochar yield [73, 95, 96]. Moisture content is another factor that affects the biochar properties and char yield. The moisture content affects the char reaction and is extensively used to produce activated carbon [97]. Bridgwater and Peacocke [98] reported that in the fast pyrolysis processes around 10% moisture content is fairly desirable during the charcoal-making process, with feedstock having 15–20% moisture that can be carbonized [73].

Production of biochar is a thermochemical process and temperature plays a major role in the properties of biochar and its suitability for soil health [99]. A laboratory-scale study on pyrolysis' ability to produce biochar from pin, mixed larch and spruce chips and from softwood pellets was conducted by Masek et al. [100]. In the study by Masek et al. [100] temperatures varied between 350 and 550 °C. Also, Masek et al. [100] reported that the stability of biochar increases as the temperature increases, and the yield of biochar is independent of temperature. Angin and Sensoz [101] also reported that the chemical and surface properties of biochar are affected by pyrolysis temperature. As the pyrolysis temperature is increased from 400 to 700 °C, the volatile matter, hydrogen and oxygen contents of the biochar were decreased, but the value of fixed carbon was increased. Biomass cannot be converted into biochar at low pyrolysis temperature (300 °C) because at this temperature the desired carbon frame structure has not developed [102].

The reactor operating temperature plays a vital role in deciding the fixed carbon and oxygen content of biochar. It has been found that higher operating temperatures have higher fixed carbon contents and lower oxygen contents, as presented in Table 1.

Operating pressure also affects the biochar yield. The effect of absolute pressure (0.1–1.5 MPa) and peak temperature (400–550 °C) on pyrolysis behaviour of two-phase olive mill wastes was examined by Manya et al.

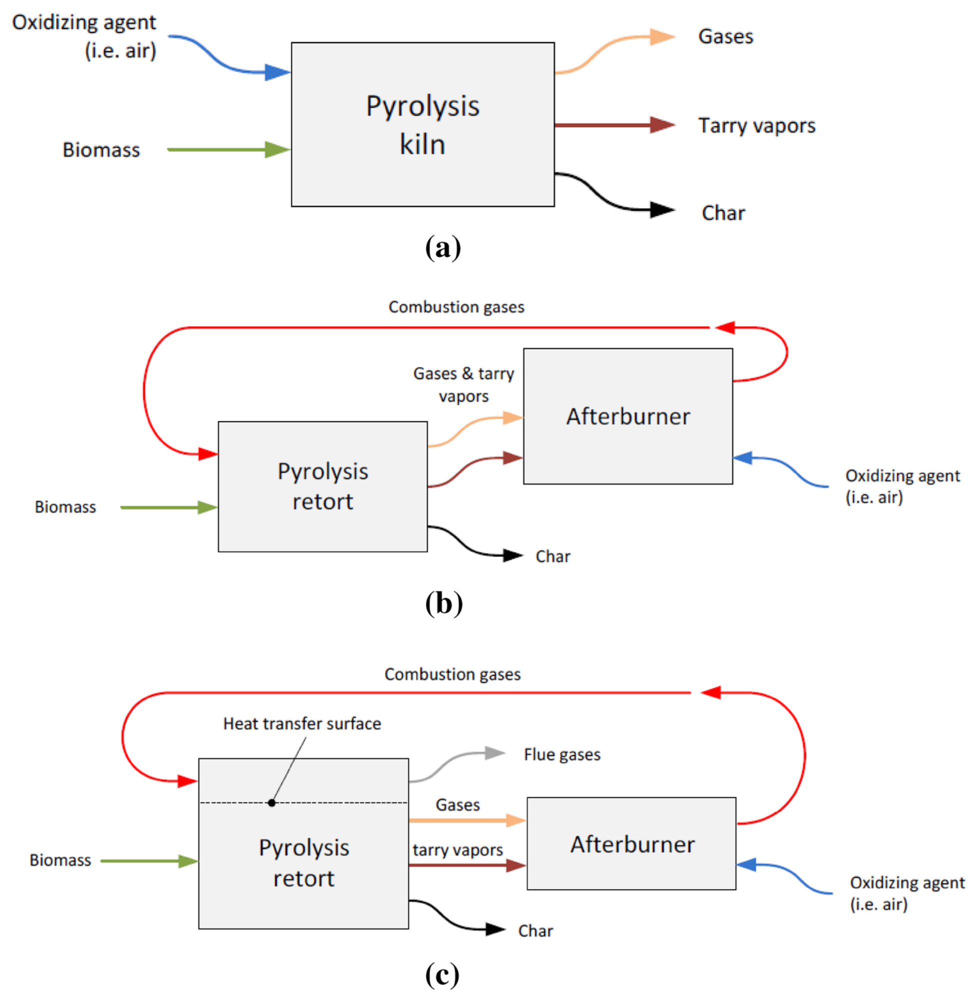


Fig. 7 **a** Kiln, autothermal carbonization [93]. **b** Retort with direct heating using pyrolysis gases [93]. **c** Retort with indirect heating using pyrolysis gases [93]

[107]. Increasing both absolute pressure and peak temperature results in a decrease in biochar yield; however, the fixed carbon yield increases [83, 107]. Furthermore, Manya et al. [108] investigated the effect of particle size along with pressure and peak temperature on the stability of vine shoot-derived biochar. It was found that operating a pyrolysis reactor under high pressure and high temperature maximizes pyrolysis gas production, but reduces the char yield. The pyrolysis process carried out at high temperature (750°C) electrical conductivity significantly increased, but there is scope vitalization of heavy metal (Zn) with the low melting point [109].

6 Energy required for the production of biochar

Energy consumption during biochar production obtained from a pyrolysis plant is the major issue involved in carbon-free emission in the carbon industry. The enthalpy for pyrolysis is the energy required to produce the biochar and syngases that mainly depend on biomass and its operating condition. The term enthalpy for pyrolysis or carbonization is the heat or energy used to produce pyrolysis. Daugaard and Brown [110] revealed that the enthalpy required for the thermal decomposition of oat shell and pine was approximately 1.04 ± 0.18 MJ/kg and 1.61 ± 0.26 MJ/kg, respectively. However, the corresponding energies required for thermal decomposition were approximately 0.8 ± 0.2 MJ/kg and 1.6 ± 0.3 MJ/kg, respectively, as presented in Table 2. Laird [111] reported that the net amount of energy required for the pyrolysis process is nearly 15% of the total energy obtained from dry biomass. Furthermore, Fing [112] estimated that the energy demand for obtaining biochar from biomass varied in the range of 1.1–16 MJ/kg, whereas 44–170 MJ/kg energy was required to produce activated carbon, which was approximately ten times higher than that of biochar production.

Ro et al. [113] used swine solid and blended swine solids (29% rye grass + 71% swine solids) to produce

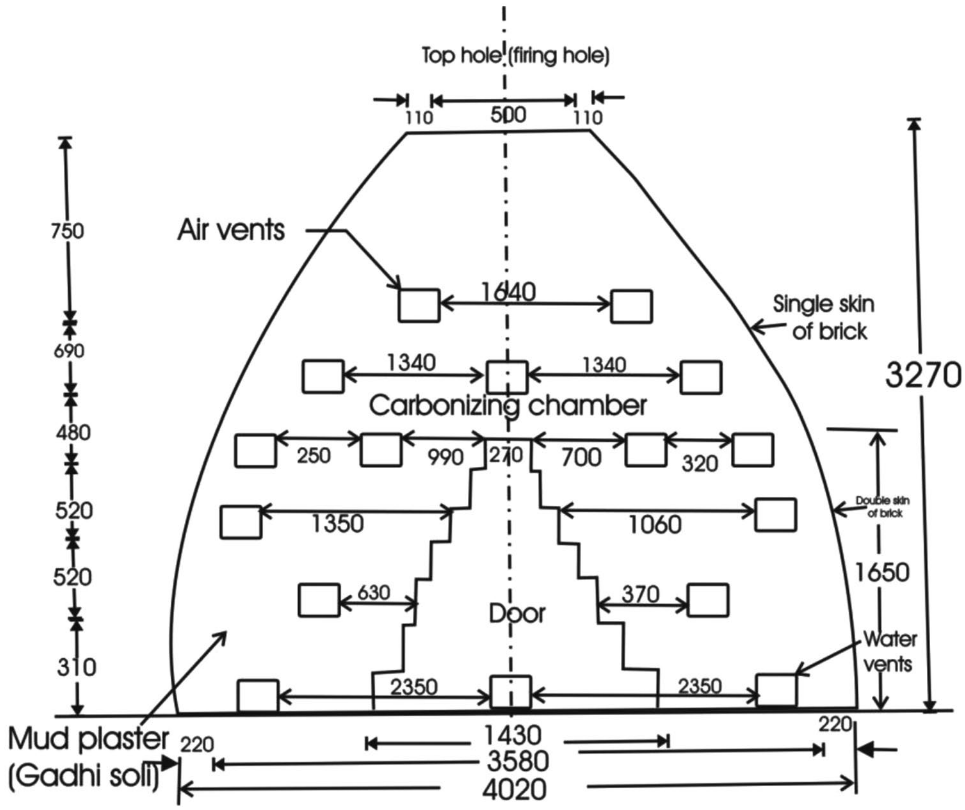


Fig. 8 Argentinean-type charcoal kiln (all dimensions in mm) [94]

high-temperature value-added biochar feedstocks. In the same study [91], the authors demonstrated the energy balance of their study for drying and pyrolysis, revealing that 12.5 MJ/kg energy was required for swine solids and 0.5 MJ/kg for blended material to obtain the desired value-added biochar, as mentioned in Table 2.

7 Classification of biochar

The International Biochar Initiative (IBI) broadly classifies biochar based on the carbon storage value, fertilizer value (P, K, S and Mg only), liming value and particle size distribution. Furthermore, Anon [114, 115] proposed three general classes of biochar on the basis of organic carbon content. In class 1 type biochar, the C_{org} mass fraction is about ≥ 60%, in class 2 in the range of 30 to < 60% and in class 3 < 10% [116].

8 Stability of biochar in soil

The stability of biochar depends on the conditions of its production and biomass feedstock. Spokas [117] conducted a study on the stability of biochar in soil and found that a lower oxygen-to-carbon (O:C) ratio resulted in a more stable biochar material. Conclusively, when the oxygen-to-carbon molar ratio (O:C) is > 0.6, biochar will probably possess a half-life on the order of < 100 years; if the range is 0.2–0.6, the accepted half-life range is between 100 and 1000 years. If the molar oxygen-to-carbon ratio is < 0.2, the half-life will be > 1000 years. In this way, the process temperature, i.e., pyrolysis temperature, is highly responsible for biochar stability [118].

9 Application of biochar

9.1 Biochar as soil improvement

Biochar improves soil physiology and increases productivity, and it also assists with crop residue management. After the application of biochar to soil, many studies report that the soil acidity was reduced considerably, and essential mineral uptake increased with residual effects for the following season [119]. In biochar significant quantities of K and small amounts of Mg, Ca, Cu, Zn and Fe are present, which have potential as fertilizer [70].

Stockmann et al. [120] reported that soil contains approximately 2344 Gt of organic carbon globally and is

Table 1 Effect of temperature on biochar composition

Feedstock	Pyrolysis temperature (°C)	Biochar elements (%)				References
		C	H	N	O	
Corn cob	400	75.23	3.37	0.82	14.11	[103]
	450	77.84	2.95	0.86	11.45	
	500	80.85	2.5	0.97	8.87	
	550	82.62	2.25	0.84	7.43	
Rapeseed	400	57.95	3.43	5.43	33.16	[104]
	450	59.77	2.36	5.12	32.75	
	500	61.98	1.92	4.12	31.78	
	550	67.29	1.75	4.35	26.21	
Safflower seed	400	68.76	4.07	3.77	23.49	[101]
	450	70.43	3.49	3.69	22.39	
	500	71.37	2.96	3.91	21.76	
	550	72.96	2.67	3.74	20.63	
	600	73.72	2.34	3.84	20.10	
Conocrpus waste	200	64.20	3.96	0.69	26.60	[105]
	400	76.80	2.83	0.87	14.20	
	600	82.90	1.28	0.71	6.60	
	800	85.00	0.62	0.90	4.90	
Wheat straw	400	57.80	3.20	1.50	21.60	[106]
	500	70.30	2.90	1.40	17.70	
	600	73.40	2.10	1.40	14.90	
	700	73.90	1.30	1.20	14.60	
Corn straw	400	56.10	4.30	2.40	22.00	[106]
	500	58.00	2.70	2.30	21.50	
	600	58.60	2.00	2.00	18.70	
	700	59.50	1.50	1.60	16.60	
Peanut shell	400	58.40	3.50	1.80	21.00	[106]
	500	64.50	2.80	1.70	18.50	
	600	71.90	2.00	1.60	15.00	
	700	74.40	1.40	1.40	14.20	

Table 2 Energy required to produce biochar from different feedstocks

Sample no.	Type of feedstock	Mode of process	Energy demand (MJ/kg)	Output products	References
1.	Oat shell	Pyrolysis	0.8 ± 0.2	Biochar, oil, gases	[110]
2.	Pine	Pyrolysis	1.6 ± 0.3	Biochar, oil, gases	[110]
3.	Swine solids	Carbonization (high temperature)	12.5	Oil, biochar, gases	[13]
4.	Blended swine solid (29% rye grass + 71% swine solid)	Carbonization (high temperature)	0.5	Oil, biochar, gases	[113]
5.	Biomass	Carbonization	1.1–16	Biochar	[112]

considered the largest terrestrial pool of organic carbon. Small changes in the soil's organic carbon stock could result in significant impacts on the atmospheric carbon concentration. The sustainability of agricultural production is highly dependent on the physical, chemical and biological integrity of the soil. Organic carbon plays a major role in maintaining these factors. The efficient conversion of surplus crop residues as a source of organic carbon is one way to improve the soil health and retain the water-holding capacity as well as essential nutrients [9]. Demand for food has drastically increased as the global population has grown. Growers are increasingly using chemical fertilizers in the soil to meet demand. Soil fertility has significantly decreased as a result of this. The addition of organic carbon is the only option for overcoming this issue. Biochar has tremendous potential to improve soil health, and it is currently attracting considerable interest globally because of the sustainable stability of carbon, which also helps in reducing the atmospheric carbon dioxide concentration. In the present context, biochar is globally considered a soil amendment tool because it has a suitable cation exchange capacity, which improves the soil pH, water-holding capacity and affinity for micro- and macro-plant nutrients [17].

Laird [121], Glaser et al. [122], Novak et al. [123] and Muhammad et al. [124] found that the application of charcoal worked to increase the available water, build soil organic matter, enhance nutrient cycling, lower bulk density, act as a liming agent and reduce leaching of nutrients to groundwater. The application of biochar as a soil amendment significantly increased crop yield, even in the absence of nitrogen fertilizer [103]. Mogami et al. [125] reported that the soil water retention capacity with palm shell biochar application is significantly higher than that without biochar. Furthermore, Mogami et al. [125] also found that biochar application at 0–10 cm greatly controlled leaching of mobile nutrients such as potassium, thus improving water use efficiency, nutrient availability and plant growth. Jia et al. [126] conducted a pot experiment to estimate the effect of maize straw biochar application on nitrous oxide (N_2O) and methane (CH_4) emissions, N_2O emission factor and vegetable yield. They concluded that biochar application greatly reduced N_2O emissions and N_2O—N emission factors while maintaining vegetable production. They found that the methane emission was not affected by biochar amendment.

Chintala et al. [127] produced biochar from corn stover (*Zea mays L.*) and switchgrass (*Pencium vigratum L.*) using microwave pyrolysis at 650 °C and applied in acidic soil. Liu et al. [128] concluded that biochar can potentially reduce N_2O emission in soil by affecting ammonia and nitrite-oxidizing bacteria and these effects depend on the biochar application rate in soil. Ibrahim et al. [129] also revealed that the application of biochar significantly increases plant fresh weight, chlorophyll and chlorophyll b.

The environmental benefits can be maximized if recycling of organic wastes occurs through proper routes [130]. Maraseni [130] gives a very good example of value addition in the Australian pulp and paper industry, as illustrated in Fig. 9. Promoting fast-growing species on plantations can not only aid in achieving goals for greenhouse gas mitigation, but also help in carbon sequestration. Such a value addition approach increases employment in rural areas.

Iswaran et al. [131] applied biochar during the cultivation of pea and mungbean in Indian climatic conditions and found that adding 0.5 tonne/ha biochar in the field increased the yield of peas by 160%, while the yield of mungbean was increased by 122%. Kishimoto and Sugiria [132] conducted a study in Japan on soybeans grown on volcanic ash loam, revealing that the yield was increased by 151% with the addition of about 0.5 tonnes/ha biochar. By adding biochar at rates of 5 tonnes/ha and 15 tonnes/ha, the yield was increased by 63% and 29%, respectively. In addition, biochar produced using cow manure was mixed with sandy soil at rates of 0, 10, 15 and 20 tonnes/ha before the cultivation of a maize crop revealing biochar application at 15 and 20 tonnes/ha significantly increased

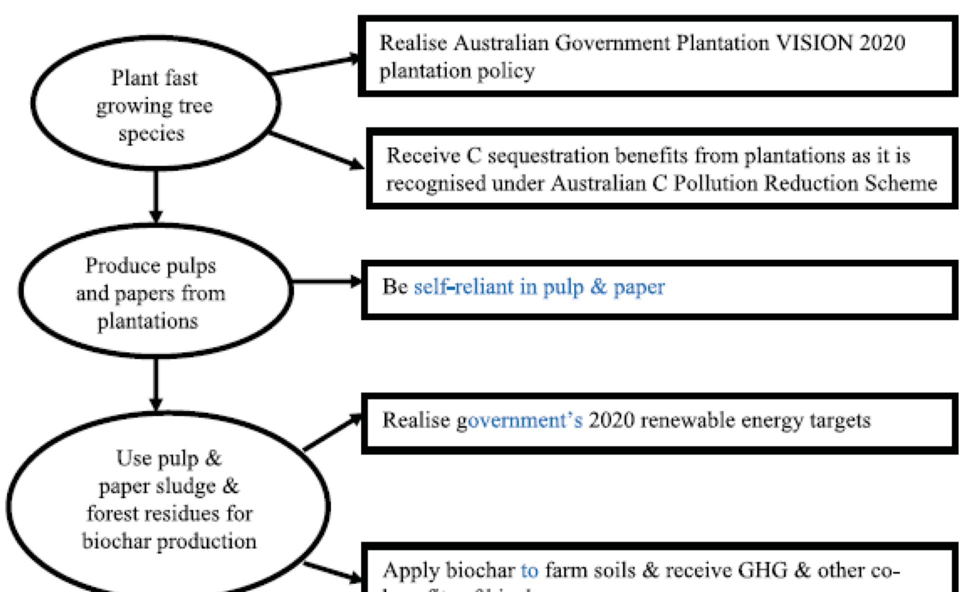


Fig. 9 Value addition for the pulp and paper industry [131]

maize yield by 150% and 98%, respectively. The study also found that application of cow manure-derived biochar to sandy soil not only improves the crop yield, but also significantly improves the physico-chemical properties of the coarse soil [133].

Nitrogen (N) is one of the most important elements that play a major role in plant growth and productivity as plants use inorganic N directly through the root system [134–138]. Nguyen et al. [139] reviewed the effects of biochar on soil inorganic nitrogen and found that biochar production temperature and biochar surface properties are the main factors affecting soil inorganic nitrogen. So far, there are limited long-term studies of > 1 year duration available in the literature; thus, the long-term effects of biochar on soil inorganic nitrogen still remain unclear.

Shanta et al. [140] demonstrated the effects of biochar along with plant growth-promoting rhizobacteria on plant growth variables (i.e., height, stand count, dry biomass). The 20 Mg/ha biochar treatment, in combination with 100 kg N fertilizer ha^{-1}, found almost the same biomass yield as the treatment with 50 kg N fertilizer ha^{-1} without biochar. Furthermore, it was reported that this effect was not consistent across study sites, highlighting the incomplete understanding of crop responses to biochar application at different study locations. Surprisingly, inoculation of switchgrass seeds with bio-fertilizers did not appear to improve crop yield in the presence or absence of biochar soil amendments.

9.2 Application of biochar in water treatment

Recently, biochar derived from biomass has been given significant attention, especially for the effective removal of heavy metals, toxic elements and contaminants from water and wastewater. Biochar is a promising low-cost and effective material with remarkable physiochemical properties such as high surface area, cation exchange capacity, aromatic character, carbon content and low H/C ratio, etc.

Shaheen et al. [141] derived wood-based biochar as an emerging bio-sorbent which has potential to remove toxic elements from water and wastewater. The biochar material's high surface area and its reactivity further its uses in water filters for the removal of pathogens such as lipids and phenol from water, as studied by Werner et al. [142]. Werner et al. [142] carried out a field experiment in Ghana using biochar-filtered water for irrigation and measured the increase in maximum crop yield (> 40%) in leafy green vegetable production. Gwenzi et al. [143] asserted that biomass-derived biochar-based water treatment systems are a potentially low-cost sustainable technology for the provision of clean water. Lee et al. [144] conducted experiments for removal of natural organic matters in water through biochar with different doses and reported that at 200 mg-C/l, biochar removes 90% of organic matter in 20 min of contact, with a capacity of 0.0064 mg-dissolved organic carbon/mg-C.

Biochar acts as a super sorbent with the ability to remove organic and inorganic contaminants from the soil as well as water because of its physiochemical properties. The activities of biochar and activated carbon (AC) are similar, but they differ from the type of raw material or feedstock, production techniques and final physiochemical properties, as studied by Qambrani et al. [145].

9.3 Biochar for climate change mitigation

To avoid the worst consequences of climate changes, humans need to significantly reduce global warming emissions and, if possible, remove the existing carbon dioxide from the atmosphere. Scientists have discovered a more environmentally friendly way to create charcoal by heating biomass, plants and animal manure in a low-oxygen environment. The result is called biochar; it consists mostly of carbon and is produced specifically to help reduce global warming [146]. Bruckman et al. [147] reported that incorporating charred organic matter in soil is a potential geo-engineering method for climate change mitigation. In addition, Bruckman et al. [147] reported that biochar amendment on forest floors in an acidic spruce ecosystem could lead to an increase of surface carbon stocks. It is a well-known fact that airborne black carbon, or soot, is a significant contributor to global warming. If biochar is simply spread on top of soil, there is the possibility of airborne black carbon. However, such issues can be avoided if biochar is tilled deep into the soil, which can also improve the soil's water retention and reduce leaching of agricultural nutrients [148]. Furthermore, Waters et al. [149] reported that issues of climate change mitigation impacts arise largely with the stabilization of soil organic matter using biochar and generation of renewable fuels, which can reduce fossil fuel consumption.

9.4 Carbon sequestration

Climate change is one of the biggest challenges presently. It affects the entire cropping patterns across the globe. Biomass is usually considered a carbon-neutral material, whereas biochar, which is produced through crop residues with stable carbon and returned to the soil, will act as a long-term sink for atmospheric carbon dioxide. It will enhance carbon fixation and reduce the emission of gases such as CH_4, N_2O and CO_2 [150]. Lehmann et al. [151] reported that the global carbon sequestration potential using agricultural and forestry wastes was estimated to be about 0.16 Gt on an annual basis. Furthermore, these authors also reported that by using renewable fuels the carbon sequestration potential may reach the range of 5.5–9.5 Gt/year by the year 2100. Smith et al. [152] estimated the carbon sequestration potential considering agricultural soils globally at about 1.4–2.9 Gt of CO_2 equivalents. Chatterjee and Lal [153] suggested a sequestration potential of agricultural soils of up to 6 Gt of CO_2 equivalents per year by 2030. An experimental investigation of carbon sequestration through silage maize was carried out under Denmark's climatic conditions by Kristiansen et al. [154]. They found that carbon from maize roots and stubble accumulated in the soil at a rate of 0.25–0.49 tonnes C/ha year. Furthermore, with the addition of 8 tonnes of dry matter per hectare, the carbon accumulation rate was between 0.71 and 0.98 tonnes C/ha year. Boddey et al. [155] conducted experiments in a subtropical region of Southern Brazil to assess the soil's organic carbon potential at 30 and 100 cm. The soil carbon accumulation rate at a depth of 30 cm was estimated to be between 0.04 and 0.88 mg/ha/year, whereas at 100 cm depth it was between 0.48 and 1.53 mg/ha/year.

9.5 Mitigation of greenhouse gas emissions

Carbon dioxide, methane and nitrous oxide are considered the major greenhouse gases that are primarily responsible for climate change. The concentration of greenhouse gases in the atmosphere has reached an alarming level. The atmospheric carbon dioxide concentration has increased from 280 ppm prior to industrialization to 379 ppm in 2005 [156] and 402.9 ppm in 2016. Carbon dioxide levels today are higher than at any other point in at least the past 800,000 years [157]. Global crop residues produce about 3758 million tonnes of carbon dioxide a year, which is equivalent to what is produced by approximately 7560 million barrels of oil. The energy equivalent of these yearly crop residues was estimated to be about 69.9 EJ [158].

On the Asian continent, straw burning is a common problem. Gupta et al. [159] reported the particulate matter produced by burning 1 tonne of straw as 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2. Furthermore, Gadde et al. [160] estimated that the burning of crop residues on the Asian continent annualy contributes about 0.10 Tg SO_2, 0.96 Tg NO_2, 379 Tg CO_2, 23 Tg CO and 0.68 Tg CH_4. Emission of such gases and aerosols adversely affects regional environments and is also responsible for global climate change. Renewable energy harvesting of surplus crop residues, forest residues and agro-industrial wastes has been encouraged to reduce greenhouse gases [161, 162].

In 2009, Roberts et al. [45] conducted a lifecycle assessment of the application of biochar derived from stover, switchgrass and yard waste. They reported that it has much lower greenhouse gas abatement costs of about 30, 45 and 1.5 euros per tonne CO_2e for biochar derived from stover, switchgrass and yard waste, respectively. Furthermore, Cowie et al. [163] examined the greenhouse gas mitigation potential of poultry litter biochar applied to maize crops and reported a reduction of 3.2 kg CO_2e per kg of biochar.

Zhang et al. [164] conducted an experiment to assess the effect of biochar with and without application of nitrogen on the net greenhouse gas balance and greenhouse gas intensity under the Jerusalem Artichoke Bioenergy Cropping System. During their experiment, it was found that soil CH_4 emissions were 72–80% lower in the biochar-amended plots than in the unamended plots. Furthermore, it was reported that biochar-amended soil improved the greenhouse gas sink capacity.

10 Safety measures during biochar production and its applications

There is limited literature available with details on the smooth operation and necessary safety measures for the production of biochar. Many reports have shown that the moisture content of crop residue or feedstock should be < 8% as feedstock with lower moisture content requires less energy to convert into biochar. It is well known that biochar is produced by heating of biomass and a considerable amount of smoke is generated during the process. Therefore, the workplace should be well ventilated. Sigmund et al. [165] investigated the cytotoxicity of biochar and reported that cytotoxic effects were likely related to its particulate nature and size distribution. They also suggested that, to minimize the risk of exposure, operators should wear respiratory protective equipment during biochar production and its application in the field. It was also suggested that biochar should be applied as a slurry and properly mixed with a soil matrix to avoid secondary dust formation.

11 Conclusions

In developing countries, crop residue has traditionally been used as animal feed. When not used as animal feed, it becomes a huge surplus biomass, and farmers burning it create a hazy and smoky environment. Conversion of such surplus biomass into biochar circumvents this problem and creates employment and economic opportunities. Quality biochar with high fixed carbon content can be produced by maintaining a reactor temperature between 400 and 600 °C. It is highly porous, has a larger surface area for absorbing soluble organic and inorganic nutrients and provides a favourable environment for the growth of useful microbes. It significantly increases microbial biomass carbon in soil compared with chemical fertilizers. Biochar is also considered a carbon sink and absorbs atmospheric carbon dioxide; hence, it is a good sink for carbon sequestration. Biochar remains in soil longer if its oxygen-to-carbon (O/C) molar ratio is < 0.2. The effect of biochar on crop yield has also been discussed, and most short-term studies have reported improvements in crop yield. The long-term effects of biochar on soil health are unknown and require further study.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Abioye AM, Ani FN (2015) Recent development in the production of activated carbon electrodes from agricultural waste biomass for super capacitors: a review. Renew Sustain Energy Rev 52:1282–1293
2. Siddiqui MTH, Nizamuddin S, Mubarak NM, Shirin K, Aijaz M, Hussain M, Baloch HA (2017) Characterization and process optimization of biochar produced using novel biomass, waste pomegranate peel: a response surface methodology approach. Waste Biomass Valorization. https://doi.org/10.1007/s12649-017-0091-y
3. Enweremadu CC, Mbarawa MM (2009) Technical aspects of production and analysis of biodiesel from used cooking oil—a review. Renew Sustain Energy Rev 13(9):2205–2224
4. Yaman S (2004) Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Convers Manag 45:651–671
5. Smets K, Roukaerts A, Czech J, Reggers G, Schreurs S, Carleer R, Yperman J (2013) Slow catalytic pyrolysis of rapeseed cake: product yield and characterization of the pyrolysis liquid. Biomass Bioenergy 57:180–190
6. Gurwick NP, Moore LA, Kelly C, Elias P (2013) A systematic review of biochar research, with a focus on its stability in situ and its promise as a climate mitigation strategy. PLoS ONE 8(9):e75932
7. Savci S (2012) An agricultural pollutant: chemical fertilizer. Int J Environ Sci Dev 3(1):77–80
8. Harmful effects of chemical fertilizer. http://www.bkpindia.net/Pdf/Effect_of_chemical_fertilizer.pdf. Accessed 16 Nov 2015
9. Srinivasarao C, Gopinath KA, Venkatesh G, Dubey AK, Wakudkar H, Purakayastha TJ, Pathak H, Jha P, Lakaria BL, Rajkhowa DJ, Mandal S, Jeyaraman S, Venkateswarlu B, Sikka AK (2013) Use of biochar for soil health enhancement and greenhouse gas mitigation in India: potential and constraints. NICRA Bull pp 1–51
10. Ji C, Cheng K, Nayak D, Pan G (2018) Environmental and economic assessment of crop residue competitive utilization for biochar, briquette fuel and combined heat and power generation. J Clean Prod 192:916–923
11. Shinogi Y, Yoshida H, Koizumi T, Yamaoka M, Saito T (2003) Basic characteristics of low- temperature carbon products from waste sludge. Adv Environ Res 7(3):661–665
12. Cheng C-H, Lehmann J, Engelhard MH (2008) Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. Geochim Cosmochim Acta 72(6):1598–1610
13. Liang B, Lehmann J, Solomon D, Sohi S, Thies JE, Skjemstad JO, Luizão FJ, Engelhard MH, Neves EG, Wirick S (2008) Stability of biomass-derived black carbon in soils. Geochim Cosmochim Acta 72(24):6069–6078
14. Cheng C-H, Lehmann J (2009) Ageing of black carbon along a temperature gradient. Chemosphere 75(8):1021–1027
15. Cao X, Harris W (2010) Properties of dairy-manure-derived biochar pertinent to its potential use in remediation. Bioresour Technol 101(14):5222–5228
16. Panwar NL, Kothari R, Tyagi VV (2012) Thermo chemical conversion of biomass—eco friendly energy routes. Renew Sustain Energy Rev 16(4):1801–1816
17. 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
18. Bernardino CA, Mahler CF, Veloso MC, Romeiro GA (2017) Preparation of biochar from sugarcane by-product filter mud by slow pyrolysis and its use like adsorbent. Waste Biomass Valorization 8(7):2511–2521
19. Kambo HS, Dutta A (2015) A comparative review of biochar and hydrochar in terms of production, physico-chemical properties and applications. Renew Sustain Energy Rev 31(45):359–378
20. Hakala K, Kontturi M, Pahkala K (2009) Field biomass as global energy source. Agric Food Sci 18:347–365
21. Kumar AN, Baredar P, Shukla A (2015) A review on biomass energy resources, potential, conversion and policy in India. Renew Sustain Energy Rev 45:530–539
22. Hiloidhari M, Das D, Baruah DC (2014) Bioenergy potential from crop residue biomass in India. Renew Sustain Energy Rev 32:504–512
23. Panwar NL (2010) Biomass for domestic and agro industrial applications. In: Wood: type, properties and use. Nova Science Publishers, Inc. pp 81–109
24. Neves EG, Bartone RN, Petersen JB, Heckenberger MJ (2004) The timing of terra preta formation in the central Amazon: new data from three sites in the central Amazon. Springer, Berlin
25. Klark M, Rule A (1925) The technology of wood distillation. Chapman & Hall Ltd, London
26. Boroson ML, Howard JB, Longwell JP, Peters WA (1989) Heterogeneous cracking of wood pyrolysis tar over wood char surface. Energy Fuels 3:735–740
27. Emrich W (1985) Handbook of biochar making. The traditional and industrial methods. D. Reidel Publishing Company, Dordrecht
28. Bridgwater AV, Meier D, Radlein D (1999) An overview of fast pyrolysis of biomass. Org Geochem 30:1479–1493
29. Evans R, Milne TA (1987) Molecular characterization of the pyrolysis of biomass. Energy Fuels 1(2):123–137
30. Piskorz J, Radlein DS, Scott DS, Czernik S (1989) Pretreatment of wood and cellulose for production of sugars by fast pyrolysis. J Anal Appl Pyrol 16(2):127–142

31. Scott DS, Piskorz J, Radlein D (1988) The effect of wood species on compstion of products obtained by the Waterloo fast pyrolysis process. In: Canadian chemical engineering conference, Toronto
32. Bridgwater AV, Peacocke GVC (1994) Engineering development in fast pyrolysis for bio-oils. In: Proceeding of biomass pyrolysis oil properties and combustion meeting. Estes Park. Co., pp 110–127
33. Yang J, Tanguy PA, Roy C (1995) Heat transfer, mass transfer and kinetic study of the vacuum pyrolysis of a large used tire particle. Chem Eng Sci 50:1909–1922
34. Roy C, Yang J, Blanchette D, Korving L, De Caumia B (1997) Development of a novel vacuum pyrolysis reactor with improved heat transfer potential. In: Developments in thermochemical biomass conversion. Springer, Netherlands, pp 351–367
35. Bridgwater AV, Czernik S, Piskorz J (2001) An overview of fast pyrolysis. In: Bridgwater AV (ed) Progress in thermochemical biomass conversion. IEA bioenergy. Blackwell Sciences, Hoboken, pp 977–997
36. Czernik S, French R, Feik C, Chornet E (2002) Hydrogen by catalytic steam reforming of liquid byproducts from biomass thermoconversion processes. Ind Eng Chem Res 41(17):4209–4215
37. Bridgwater AV (2005) Fast pyrolysis based bio-refineries. In: Presentation made to the American Chemistry Cociety. Wastington DC
38. Helle S, Bennett NM, Lau K, Matsui JH, Duff SJ (2007) A kinetic model for production of glucose by hydrolysis of levoglucosan and cellobiosan from pyrolysis oil. Carbohydr Res 342(16):2365–2370
39. Mahfud FH, Ghijsen F, Heeres HJ (2007) Hydrogenation of fast pyrolyis oil and model compounds in a two-phase aqueous organic system using homogeneous ruthenium catalysts. J Mol Catal A Chem 264(1):227–236
40. Ellott DC (2007) Historical development in hydro-processing bio-oils. Energy Fuels 21:1792–1815
41. Jones SB, Valkenburg C, Walton CW, Elliott DC, Holladay JE, Stevens DJ, Kinchin C, Czernik S (2009) Production of gasoline and diesel from biomass via fast pyrolysis, hydrotreating and hydrocracking: a design case. Pacific Northwest National Laboratory, Richland, pp 1–76
42. Prins MJ, Ptasinski KJ, Janssen FJJG (2006) Torrefaction of wood: part1. Weightloss kinetics. J Anal Appl Pyrolysis 77:28–34
43. Onay O, Kockar OM (2003) Slow, fast and flash pyrolysis of rapeseed. Renew Energy 28:2417–2433
44. Gaunt J, Cowie A (2009) Biochar, greenhouse gas accounting and emissions trading. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 317–340
45. Roberts KG, Gloy BA, Joseph S, Scott NR, Lehmann J (2009) Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ Sci Technol 44:827–833
46. Smith CR, Buzan EM, Lee JW (2012) Potential impact of biochar water-extractable substances on environmental sustainability. ACS Sustain Chem Eng 1(1):118–126
47. Steiner C, Teixeira WG, Lehmann J, Nehls T, de Macêdo JLV, Blum WE, 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(1–2):275–290
48. McHenry MP (2009) Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: certainty, uncertainty and risk. Agric Ecosyst Environ 129(1):1–7
49. Lehmann J, Stephen J (2009) Biochar for environmental management: an introduction. Biochar for environmental management-science and technology. Earthscan, London
50. Marris E (2006) Putting the carbon back: black is the new green. Nature 442(7103):624–626
51. Lal R (2008) Black and buried carbons impacts on soil quality and ecosystem services. Soil Tillage Res 99(1):1–3
52. Sohi SP, Krull E, Lopez-Capel E, Bol R (2010) A review of biochar and its use and function in soil. Adv Agron 105:47–82
53. Barrow CJ (2012) Biochar: potential for countering land degradation and for improving agriculture. Appl Geogr 34:21–28
54. De Gisi S, Petta L, Wendland C (2014) History and technology of terra preta sanitation. Sustainability 6(3):1328–1345
55. Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. Nat Commun 1:56
56. Xie T, Reddy KR, Wang C, Yargicoglu E, Spokas K (2015) Characteristics and applications of biochar for environmental remediation: a review. Crit Rev Environ Sci Technol 45(9):939–969
57. Kung CC, Kong F, Choi Y (2015) Pyrolysis and biochar potential using crop residues and agricultural wastes in China. Ecol Ind 51:139–145
58. Steiner C, Bellwood-Howard I, Häring V, Tonkudor K, Addai F, Atiah K, Abubakari AH, Kranjac-Berisavljevic G, Marschner B, Buerkert A (2018) Participatory trials of on-farm biochar production and use in Tamale, Ghana. Agron Sustain Dev 38(1):12
59. Phillips CL, Trippe K, Reardon C, Mellbye B, Griffith SM, Banowetz GM, Gady D (2018) Physical feasibility of biochar production and utilization at a farm-scale: a case-study in non-irrigated seed production. Biomass Bioenergy 108:244–251
60. Basu P (2013) Biomass gasification, pyrolysis and torrefaction: practical design and theory. Academic Press, Cambridge
61. Kammen DM, Lew DJ (2005) Review of technologies for the production and use of charcoal. Renewable and appropriate energy laboratory report. http://rael.berkeley.edu/old_drupal/sites/default/files/old-site-files/2005/Kammen-Lew-Charcoal-2005.pdf. Accessed 15 Dec 2017
62. Duku MH, Gu S, Ben HE (2011) Biochar production potential in Ghana: a review. Renew Sustain Energy Rev 15:3539–3551
63. Masek O (2017) Biochar production technologies, http://www.geos.ed.ac.uk/sccs/biochar/documents/BiocharLaunch-OMasek.pdf. Accessed 15 Dec 2017
64. Bailis R (2009) Modeling climate change mitigation from alternative methods of charcoal production in Kenya. Biomass Bioenergy 33(11):1491–1502
65. Lohri CR, Rajabu HM, Sweeney DJ, Zurbrügg C (2016) Char fuel production in developing countries—a review of urban biowaste carbonization. Renew Sustain Energy Rev 59:1514–1530
66. FAO (United Nations Food and Agriculture Organization): simple technologies for charcoal making (1983) 41.www.fao.org/docrep/S5328e/x5328e00.htm. Accessed 16 Dec 2017
67. Kristoferson LA, Bokalders V (2013) Renewable energy technologies: their applications in developing countries. Elsevier, Amsterdam
68. Deal C, Brewer CE, Brown RC, Okure MA, Amoding A (2012) Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics. Biomass Bioenergy 37:161–168
69. Pennise DM, Smith KR, Kithinji JP, Rezende ME, Raad TJ, Zhang J, Fan C (2001) Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. J Geophys Res Atmos 106(D20):24143–24155
70. Mwampamba TH, Owen M, Pigaht M (2013) Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa. Energy Sustain Dev 17(2):158–170

71. Peterson SC, Jackson MA (2014) Simplifying pyrolysis: using gasification to produce corn stover and wheat straw biochar for sorptive and horticultural media. Ind Crops Prod 53:228–235
72. Adam JC (2009) Improved and more environmentally friendly charcoal production system using a low-cost retort–kiln (Eco-charcoal). Renew Energy 34(8):1923–1925
73. Antal MJ, Grønli M (2003) The art, science, and technology of charcoal production. Ind Eng Chem Res 42(8):1619–1640
74. Moreira R, dos Reis Orsini R, Vaz JM, Penteado JC, Spinacé EV (2017) Production of biochar, bio-oil and synthesis gas from cashew nut shell by slow pyrolysis. Waste Biomass Valorization 8(1):217–224
75. Gwenzi W, Chaukura N, Mukome FN, Machado S, Nyamasoka B (2015) Biochar production and applications in sub-Saharan Africa: opportunities, constraints, risks and uncertainties. J Environ Manag 150:250–261
76. Jelinek H (1989) Pyrolysis system.U.S. Patent No. 4,840,129. 20 Jun. 1989. https://www.google.com/patents/US4840129. Accessed 20 Dec 2017
77. Collin GE (1980) Pyrolytic recovery of raw materials from special wastes. In: ACS Symp Ser (United States) 130 (CONF-790917-P5). Ruetgerswerke AG, Duisburg-Meiderich, Germany
78. Becchetti F, Von Christen FE (2011) Integrated process for waste treatment by pyrolysis and related plant. U.S. Patent No. 7,878,131. 1 Feb. 2011.https://patents.google.com/patent/US20090020052A1/en. Accessed 18 Dec 2017
79. Agirre I, Griessacher T, Rösler G, Antrekowitsch J (2013) Production of charcoal as an alternative reducing agent from agricultural residues using a semi-continuous semi-pilot scale pyrolysis screw reactor. Fuel Process Technol 106:114–121
80. Maschio G, Koufopanos C, Lucchesi A (1992) Pyrolysis, a promising route for biomass utilization. Bioresour Technol 42(3):219–231
81. Brown JN, Brown RC (2012) Process optimization of an auger pyrolyzer with heat carrier using response surface methodology. Bioresour Technol 103(1):405–414
82. Mozammel HM, Masahiro O, Bhattacharya SC (2002) Activated charcoal from coconut shell using $ZnCl_2$ activation. Biomass Bioenergy 22(5):397–400
83. Ferreira SD, Manera C, Silvestre WP, Pauletti GF, Altafini CR, Godinho M (2008) Use of biochar produced from elephant grass by pyrolysis in a screw reactor as a soil amendment. Waste Biomass Valorization. https://doi.org/10.1007/s12649-018-0347-1
84. Ortiz OA, Suárez GI, Nelson A (2005) Dynamic simulation of a pilot rotary kiln for charcoal activation. Comput Chem Eng 29(8):1837–1848
85. Ogawa M, Okimori Y, Takahashi F (2006) Carbon sequestration by carbonization of biomass and forestation: three case studies. Mitig Adapt Strateg Glob Change 11(2):421–436
86. Schimmelpfennig S, Glaser B (2012) One step forward toward characterization: some important material properties to distinguish biochars. J Environ Qual 41(4):1001–1013
87. Evans RJ (2008) The relation of pyrolysis processes to charcoal chemical and physical properties. National Renewable Energy Laboratory, diakses pada 18
88. Wade SR, Nunoura T, Antal MJ (2006) Studies of the flash carbonization process. 2. Violent ignition behavior of pressurized packed beds of biomass: a factorial study. Ind Eng Chem Res 45(10):3512–3519
89. Nunoura T, Wade SR, Bourke JP, Antal MJ (2006) Studies of the flash carbonization process. 1. Propagation of the flaming pyrolysis reaction and performance of a catalytic afterburner. Ind Eng Chem Res 45(2):585–599
90. Nartey OD, Zhao B (2014) Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: an overview. Adv Mater Sci Eng. https://doi.org/10.1155/2014/715398
91. Cheng X, Tang Y, Wang B, Jiang J (2018) Improvement of charcoal yield and quality by two-step pyrolysis on rice husks. Waste Biomass Valorization 9(1):123–130
92. Rathore NS, Panwar NL, Kurchania AK (2009) Renewable energy: theory and practice. Himanshu Publication, Udaipur
93. Ronsse F (2013) Report on biochar production techniques. A publication of the Interreg IVB project biochar: climate saving soil. Ghent University
94. Mohod AG, Panwar NL (2011) Evaluation of traditional half orange type charcoal kiln for carbonisation: a case study. World Rev Sci Technol Sustain Dev 8:196–202
95. Mohan D, Pittman CU, Steele PH (2006) Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 20(3):848–889
96. Brown R (2009) Biochar production technology. Chapter 8. In: Lehmann J, Joseph S (eds) Biochar for environmental management. Earthscan, London
97. Zanzi R, Bai X, Capdevila P, Bjornbom E (2001) Pyrolysis of biomass in the presence of steam for preparation of activated carbon, liquid and gaseous products. In: 6th World congress of chemical engineering
98. Bridgwater AV, Peacocke GVC (2000) Fast pyrolysis processes for biomass. Renew Sustain Energy Rev 4:1–73
99. Yuan W, Meng X, James A (2018) The role of biochar in sustainable agriculture and environment: promising but inconsistent. Adv Biotech Micro 9(4):AIBM.MS.ID.555770
100. Masek O, Brownsort P, Cross A, Sohi S (2013) Influence of production conditions on the yield and environmental stability of biochar. Fuel 103:151–155
101. Angın D, Şensoz S (2014) Effect of pyrolysis temperature on chemical and surface properties of biochar of rapeseed (Brassica napus L.). Int J Phytoremediation 16(7–8):684–693
102. Tan Z, Yuan S (2017) The Effect of preparing temperature and atmosphere on biochar's quality for soil improving. Waste Biomass Valorization. https://doi.org/10.1007/s12649-017-0145-1
103. Zheng W, Sharma BK, Rajagopalan N (2010) Using biochar as a soil amendment for sustainable agriculture. Submitted to the Sustainable Agriculture Grant Program Illinois Department of Agriculture
104. Angin D (2013) Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. Bioresour Technol 128:593–597
105. Al-Wabel MI, Al-Omran A, El-Naggar AH, Nadeem M, Usman A (2013) Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresour Technol 131:374–379
106. Gai X, Wang H, Liu J, Zhai L, Liu S, Ren T, Liu H (2014) Effects of feedstock and pyrolysis temperature on biochar adsorption of ammonium and nitrate. PLoS ONE 9(12):e113888. https://doi.org/10.1371/journal.pone.0113888
107. Manya JJ, Roca FX, Perales JF (2013) TGA study examining the effect of pressure and peak temperature on biochar yield during pyrolysis of two-phase olive mill waste. J Anal Appl Pyrol 103:86–95
108. Manya JJ, Ortigosa MA, Laguarta S, Manso JA (2014) Experimental study on the effect of pyrolysis pressure, peak temperature and particle size on the potential stability of vine shoots-derived biochar. Fuel 133:163–172
109. Wang K, Peng N, Lu G, Dang Z (2018) Effects of pyrolysis temperature and holding time on physicochemical properties of swine-manure-derived biochar. Waste Biomass Valorization. https://doi.org/10.1007/s12649-018-0435-2
110. Daugaard DE, Brown RC (2003) Enthalpy for pyrolysis for several types of biomass. Energy Fuels 17(4):934–939

111. Laird DA (2008) The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agron J 100(1):178–181
112. Fing (2016) Biochar versus activated carbon. http://fingerlakesbiochar.com/biochar-vs-activated-carbon/. Accessed 2 Oct 2018
113. Ro KS, Cantrell KB, Hunt PG (2010) High-temperature pyrolysis of blended animal manures for producing renewable energy and value-added biochar. Ind Eng Chem Res 49(20):10125–10131
114. Anon (2003) Standardized product definition and product testing guidelines for biochar that is used in soil, IBI-STD-01.1, International Biochar Initiative, Westerville, OH
115. Anon (2014) Standardized product definition and product testing guidelines for biochar that is used in soil, IBI-STD-2.0, International Biochar Initiative, Westerville, OH
116. Klasson KT (2017) Biochar characterization and a method for estimating biochar quality from proximate analysis results. Biomass Bioenergy 96:50–58
117. Spokas KA (2010) Review of the stability of biochar in soil: predictability of O:C molar ratios. Carbon management 1(2):289–303
118. Baldock JA, Smernik RJ (2002) Chemical composition and bioavailblity of thermally, altered *Pinus resinosa* (Red Pine) wood. Org Geochem 33(9):1093–1109
119. Blackwell P, Riethmuller G, Collins M (2009) Biochar application to soil. In: Lehmann J, Joseph S (eds) Biochar for environmental management: science and technology. Earthscan, London, pp 207–226
120. Stockmann U, Adams MA, Crawford JW (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric Ecosyst Environ 164:80–99
121. Laird DA (2008) The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. Agron J 100:178–181
122. Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—a review. Biol Fertil Soils 35:219–230
123. Novak JM, Busscher WJ, Laird DL, Ahmedna M, Watts DW, Niandou MAS (2009) Impact of biochar amendment on fertility of a southeastern coastal plain soil. Soil Sci 174(2):105–112
124. Muhammad N, Brookes PC, Wu J (2016) Addition impact of biochar from different feedstocks on microbial community and available concentrations of elements in a Psammaquent and a Plinthudult. J Soil Sci Plant Nutr 16(1):137–153
125. Mogamia A, Tanoa Y, Matsumotoa H, Nishiharaa E (2011) Improvement of sandy- soil water and nutrient use efficiency using palm shell biochar under controlled moisture conditions. In: Asia Pacific biochar conference, APBC Kyoto
126. Jia J, Li B, Chen Z, Xie Z, Xiong Z (2012) Effects of biochar application on vegetable production and emissions of N_2O and CH_4. Soil Sci Plant Nutr 58(4):503–509
127. Chintala R, Schumacher TE, McDonald LM, Clay DE, Malo DD, Papiernik SK, Clay SA, Julson JL (2014) Phosphorus sorption and availability from biochars and soil/biochar mixtures. Clean-Soil Air Water 42(5):626–634
128. Liu L, Shen G, Sun M, Cao X, Shang G, Chen P (2014) Effect of biochar on nitrous oxide emission and its potential mechanisms. J Air Waste Manag Assoc 64(8):894–902
129. Ibrahim OM, Bakry AB, El kramany MF, Elewa TA (2015) Evaluating the role of bio-char application under two levels of water requirements on wheat production under sandy soil conditions. Glob J Adv Res 2:411–418
130. Maraseni TK (2010) Biochar: maximising the benefits. Int J Environ Stud 67(3):319–327
131. Iswaran V, Jauhri KS, Sen A (1980) Effect of charcoal, coal and peat on the yield of moong, soybean and pea. Soil Biol Biochem 12:191–192
132. Kishimoto S, Sugiura G (1985) Charcoal as a soil conditioner. Int Achieve Future 5:12–23
133. Uzoma KC, Inoue M, Andry H, Fujimaki H, Zahoor A, Nishihara E (2011) Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manag 27(2):205–212
134. Lynch J (1995) Root architecture and plant productivity. Plant Physiol 109(1):7–13
135. Atkinson CJ, Fitzgerald JD, Hipps NA (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337:1–18
136. Bai SH, Blumfield TJ, Xu Z, Chen C, Wild C (2012) Soil organic matter dynamics and nitrogen availability in response to site preparation and management during revegetation in tropical Central Queensland, Australia. J Soils Sediments 12:386–395
137. Reverchon F, Flicker RC, Yang H, Yan G, Xu Z, Chen C, Bai SH, Zhang D (2014) Changes in $\delta^{15}N$ in a soil–plant system under different biochar feedstocks and application rates. Biol Fertil Soils 50:275–283
138. Bai SH, Dempsey R, Reverchon F, Blumfield TJ, Ryan S, Cernusak LA (2017) Effects of forest thinning on soil-plant carbon and nitrogen dynamics. Plant Soil 411:437–449
139. Nguyen TTN, Xu CY, Tahmasbian I, Che R, Xu Z, Zhou X, Wallace HM, Bai SH (2017) Effects of biochar on soil available inorganic nitrogen: a review and meta-analysis. Geoderma 288:79–96
140. Shanta N, Schwinghamer T, Backer R, Allaire SE, Teshler I, Vanasse A, Whalen J, Baril B, Lange S, MacKay J, Zhou X, Smith DL (2016) Biochar and plant growth promoting rhizobacteria effects on switchgrass (Panicum virgatum cv. Cave-in-Rock) for biomass production in southern Quebec depend on soil type and location. Biomass Bioenergy 95:167–173
141. Shaheen SM, Niazi NK, Hassan NE, Bibi I, Wang H, Tsang DC, Ok YS, Bolan N, Rinklebe J (2018) Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. Int Mater Rev. https://doi.org/10.1080/09506608.2018.1473096
142. Werner S, Kätzl K, Wichern M, Marschner B (2018) Biochar in waste water treatment to produce safe irrigation water, recover nutrients and reduce environmental impacts of waste water irrigation. In: EGU general assembly conference Abstracts 20, 15820
143. Gwenzi W, Chaukura N, Noubactep C, Mukome FN (2017) Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. J Environ Manag 197:732–749
144. Lee DJ, Cheng YL, Wong RJ, Wang XD (2018) Adsorption removal of natural organic matters in waters using biochar. Biores Technol 260:413–416
145. Qambrani NA, Rahman MM, Won S, Shim S, Ra C (2017) Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: a review. Renew Sustain Energy Rev 79:255–273
146. Gurwick NP, Kelly C, Elias P (2012) The Scientific basis for biochar as a climate change mitigation strategy: Does it Measure Up? Union of concerned scientist. Citizens and Scientists for Environment Solutions
147. Bruckman VJ, Terada T, Uzun BB, Apaydın-Varol E, Liu J (2015) Biochar for climate change mitigation: tracing the in situ priming effect on a forest site. Energy Procedia 76:381–387
148. Ernsting A, Smolker R (2009) Biochar for climate change mitigation: fact or fiction. Agrofuels and the Myth of the Marginal Lands 1–10

149. 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. Springer, Berlin, p 29
150. Tan Z, Lin CS, Ji X, Rainey TJ (2017) Returning biochar to fields: a review. Appl Soil Ecol 116:1–11
151. Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems—a review. Mitig Adapt Strateg Glob Change 11(2):395–419
152. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, McCarl B, Ogle S, O'Mara F, Rice C, Scholes B, Sirotenko O. Chapter 8: agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (2007) Climate change 2007: mitigation. In: Contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, New York
153. Chatterjee A, Lal R (2009) On farm assessment of tillage impact on soil carbon and associated soil quality parameters. Soil Tillage Res 104:270–277
154. Kristiansen SMHEM, Jensen LS, Christensen BT (2005) Natural ^{13}C abundance and carbon storage in Danish soils under continuous silage maize. Eur J Agron 22:107–117
155. Boddey RM, Jantalia CP, Conceicao PC, Zanatta JA, Bayer C, Mielniczuk J, Dieckow J, Dos Santos HP, Denardin JE, Aita C, Giacomini SJ, Alves BJR, Urquiaga S (2010) Carbon accumulation at depth in Ferrasols under zero-till subtropical agriculture. Global Change Biol 16(2):784–795
156. Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (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, UK
157. Lindsey R (2017) Climate change: atmospheric carbon dioxide. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide. Retrieve 14 Dec 2017
158. Lal RA (2005) World crop residues production and implications of its use as a biofuel. Environ Int 31(4):575–584
159. Gupta PK, Sahai S, Singh N, Dixit CK, Singh DP, Sharma C (2004) Residue burning in rice–wheat cropping system: causes and implications. Curr Sci 87(12):1713–1715
160. Gadde B, Bonnet S, Menke C, Garivait S (2009) Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ Pollut 157:1554–1558
161. Pacala S, Socolow R (2004) Stabilization wedges: solving climate problem for the next 50 years with current technologies. Science 305:968–972
162. Goldemberg J (2007) Ethanol for a sustainable energy future. Science 315:808–810
163. Cowie AL, Cowie AJ, Solutions RC (2013) Life cycle assessment of greenhouse gas mitigation benefits of biochar. Report IEA Bioenergy Task 38:136–145
164. Zhang Y, Lin F, Wang X, Zou J, Liu S (2016) Annual accounting of net greenhouse gas balance response to biochar addition in a coastal saline bioenergy cropping system in China. Soil Tillage Res 158:39–48
165. Sigmund G, Huber D, Bucheli TD, Baumann M, Borth N, Guebitz GM, Hofmann T (2017) Cytotoxicity of biochar: A workplace safety concern? Environ Sci Technol Lett 4(9):362–366