# Chapter 8
# Biomass Pyrolysis and its Multiple Applications

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**Abstract** In the twenty-first century, the growing demands of a modernized and growing population have led to the rapid expansion of agricultural and industrial sectors around the world. This expansion leads to produce a massive amount of biomass materials and various organic and inorganic pollutants. Biochar has promising potential in tackling such global concerns and can serve as a low-cost adsorbent for accomplishing sustainable development goals (SDGs). Biochar, a carbon-rich solid product, can be obtained by slow pyrolysis of biomass under an oxygen-limited atmosphere. Produced biochar can be used as an adsorbent to remove organic and in-organic pollutants from groundwater and industrial wastewater. However, biochar has a lower surface area and limited surface functional groups, which results in lower adsorption capacity. Hence, activation is required. Apart from adsorbent biochar is also used as a soil additive to sequestrate carbon to mitigate climate change and enhance its fertility and water retention capability hence lowering the frequency of irrigation in the field. In this chapter, the fundamentals of slow pyrolysis, its process parameters, product yield distribution, and various application of biochar will be discussed in detail.

**Keywords** Pyrolysis · Biochar · Activation · Adsorbent · Soil amendment

## Abbreviations

| | |
|---|---|
| ACB | *Araucaria columnaris* bark |
| BSA | Biochar soil amendment |
| CEC | Cation exchange capacity |
| DCFC | Direct carbon fuel cell |
| DFT | Density functional theory |

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| | |
|---|---|
| dw | dry weight basis |
| fw | Fresh weight basis |
| GRSB | Granular Rice Straw biochar |
| JPB | Jujube pit biochar |
| MB | Methylene blue |
| MBC | Magnetically modified rice husk biochar |
| OM | Organic matter |
| PAHs | Polycyclic aromatic hydrocarbons |
| PBB | Powdered bamboo biochar |
| PRSB | Powdered Rice Straw biochar |
| RE | Removal efficiency |
| RO | Reverse osmosis |
| SA | Sulfonamides |
| SPS | Spent *P. ostreatus* substrate |
| SSS | Spent shiitake substrate |
| TC | Tetracycline |
| TPH | Total petroleum hydrocarbons |
| WHC | Water holding capacity |

## 8.1 Introduction

The world's food, water, and energy demand are increasing rapidly as the global population increases. Large amounts of biomass waste (crop residues, forest residues, organic) are generated daily due to high living standards and economic development. Globally, the approximately 140 Gigaton biomass waste generated and managing such a huge amount of waste is a great challenge. Most of the biomass waste is discarded and open burning in the field, which negatively impacts the environment (Tripathi et al. 2019; Goswami et al. 2020a; Agrawal and Verma 2022). The conversion of biomass waste to biochar through pyrolysis is a feasible solution and creates value addition in society.

Biochar is a "carbon-rich solid product" formed by pyrolyzing biomass at high temperatures (300–600 °C) in an inert environment (Sakhiya et al. 2020; Goswami et al. 2020b, 2021). Biochar can be used for a variety of energy and environmental purposes, including clean solid fuel, fuel cells, catalysts, soil amendments, composting additives, groundwater and wastewater purification, air purification, carbon sequestration, hydrogen storage, etc. (Dillon and Heben 2001; Sakhiya et al. 2021a, b; Baghel et al. 2022). The pyrolysis product yield distribution is influenced by a variety of factors, including pyrolysis temperature, heating rate, residence time, and particle size. Presently, biochar is used as an economical adsorbent for removing organic (PAHs, pesticides, dye, surfactants, pharmaceutical) and inorganic (heavy metals such as As, Ni, Pb, Zn, and Cu) contaminants from groundwater and wastewater (Cha et al. 2016). Moreover, biochar has a good water holding capacity and nutrient retention capacity, improving agriculture sustainability and product yield. Biochar produced from agricultural waste and used in the soil can return the nutrients and develop a circular economy (Zhou et al. 2021).

However, there are certain limitations to using biochar as an adsorbent and other environmental application due to cation exchange capacity, limited surface functional groups, low porosity, and surface area. The activation is a process that improves the physicochemical properties of biochar using different activation agents and heating in the temperature range of 500–900 °C. According to the report "Global Activated Carbon Market Forecast & Opportunities 2017," demand for activated carbon is predicted to grow at a rate of higher than 10% per year for the next half-decade, reaching a market value of 3 billion dollars by 2025 (Park et al. 2013). The sustainable utilization of biomass to produce bioenergy and activated charcoal would not only assist in alleviating the environmental issues due to coal mining but also cuts down the price of producing efficient sorbents.

This chapter describes the biochar production through the pyrolysis, types of pyrolysis process, parameters influencing the pyrolysis. Activation of biochar via physical and chemical activation is also discussed in detail. Additionally, biochar has a wide array of uses such as solid fuel, catalyst, the adsorbent in water purification, additives in composting, and hydrogen storage were described in detail.

## 8.2 Pyrolysis

Pyrolysis is a thermochemical conversion technology in which biomass is thermally heated at elevated temperature and produced three different products: biochar, bio-oil, and gas. In addition to its efficacy, pyrolysis produces multi-products compared to other thermochemical conversion processes (Tripathi et al. 2016).

### *8.2.1 Physics of Pyrolysis*

In the pyrolysis process, organic material is thermally decomposed under an oxygen-limited environment. It's a particularly complicated process with a lot of various reactions in the reacting zone. Biomass contains three major constitutes, including hemicellulose, cellulose, and lignin (Kumar and Verma 2021a, b). The heating of biomass, biomolecules of hemicellulose, and cellulose break down in the form of volatile matter and produce bio-oil by condensation. The heating of biomass under an oxygen-limited environment allows a rise in temperature greater than its limit thermal stability and produces a more stable solid product called biochar.

The pyrolysis process mainly consists of two steps, i.e., primary and secondary pyrolysis. During primary pyrolysis, heat causes biomass molecules to cleave and devolatilize, forming numerous functional groups such as hydroxyl, carboxyl, and carbonyl. The process of devolatilization takes place by dehydration of biomass, followed by decarboxylation and dehydrogenation. Secondary pyrolysis begins after the completion of the primary pyrolysis process in which heavy hydrocarbon breakdown into condensable (bio-oil) and non-condensable gases (CO, $CO_2$, $H_2$, and $CH_4$). The cracking of heavy hydrocarbon compounds can be presented by the following reaction (Tripathi et al. 2016):

$$\begin{aligned}(C_6H_6O_6)_n \rightarrow\ & (H_2 + CO + CH_4 + \ldots + C_5H_{12}) \\ & + (H_2O + CH_3OH + CH_3COOH + \ldots) + C \end{aligned} \tag{8.1}$$

Where the initial part of the products in the reaction represents the non-condensable gases, the later part represents the mixture of condensable gases, and the last part is the char yield.

### *8.2.2 Types of the Pyrolysis Process*

The process parameters help in classifying the pyrolysis process into four categories: slow, fast, flash, and intermediate. Each type has its own set of benefits and drawbacks. The basic characteristics of each type of pyrolysis and the operating parameters are discussed in the following section. Table 8.1 represents the types of pyrolysis processes based on operating conditions.

#### 8.2.2.1 Slow Pyrolysis

It is a conventional method and widely used to produce charcoal in history and characterized by a modest heating rate and a prolonged residence time. It is generally carried out from 400–600 °C to get higher biochar yield with a small amount of

**Table 8.1** Operating conditions of types of pyrolysis processes

| Operation condition | Slow | Fast | Flash | Intermediate |
|---|---|---|---|---|
| Temperature (°C) | 550–950 | 850–1200 | 900–1300 | 400–650 |
| Heating rate (°C/min) | 0.1–1.0 | 10–200 | >1000 | 1.0–10 |
| Residence time (min) | 300–500 | 0.5–10 | <1 | 0.5–20 |
| Particle size (mm) | 5–50 | <1 | <0.5 | 1–5 |
| Reference | Bahng et al. (2009), Demirbaş and Arin (2002) | Bahng et al. (2009), Demirbaş and Arin (2002) | Bahng et al. (2009), Demirbaş and Arin (2002) | Zhang et al. (2010), Kebelmann et al. (2013) |

condensed bio-oil and non-condensable gases such as $CO_2$, CO, $CH_4$, and hydrocarbons ($C_1$–$C_2$) (Al Arni 2018). The slow pyrolysis is characterized by longer residence time (>60 min), lower heating rate (0.1–1.0 °C/min), a particle size of 5–50 mm, and performed at ambient pressure. The longer residence time provides an appropriate atmosphere and time to complete the secondary pyrolysis reaction. Additionally, a longer vapor residence time permits vapors formed during the secondary reaction to be evacuated, which results in higher biochar yield. Biomass with larger particle size, high lignin content, and lower ash content is best suited for the production of biochar (Demirbas 2004).

#### 8.2.2.2 Fast Pyrolysis

Fast pyrolysis is mainly used to produce the bio-oil (yield >50%). Biochar and gas yields are overshadowed by bio-oil production. It has a high heating rate as compared to slow pyrolysis. Fast pyrolysis is mainly performed within the temperature of 850–1200 °C, with a heating rate ranging from 10–200 °C/min, the particle size of <1 mm, and residence time less than 10 s (Greenhalf et al. 2013). Different reactor designs are utilized for fast pyrolysis, including rotating cones, bubbling fluidized beds, circulating beds, ablative reactors, etc. The main objective of fast pyrolysis is to raise the temperature of the feedstock to a point where thermal cracking takes place while decreasing the exposure time, which promotes biochar formation. The bio-oil produced through fast pyrolysis is corrosive because of its low pH value. Moreover, bio-oil contains a high amount of water fraction, which lowers its heating value. As a result, before using bio-oil, it must be upgraded (Xu and Etcheverry 2008).

#### 8.2.2.3 Flash Pyrolysis

Flash or rapid pyrolysis is a modified variant of fast pyrolysis and is characterized by a high heating rate, shorter residence time, and extreme reaction temperature. Rapid is carried out at a heating rate > 1000 °C/min and a short residence time of 1–10 s (Demirbaş and Arin 2002). Such an extreme condition is arranged in flash pyrolysis to obtain a high bio-oil yield with lower water fraction and biomass conversion efficiency of up to 70%. In flash pyrolysis, heat and mass transfer processes, chemical-reactions kinetics, and biomass transition phase behavior play a significant role in product yield distribution.

The most difficult aspect of implementing this pyrolysis on a large scale is designing a reactor in which the input biomass can be heated at an extreme heating rate for a short residence time. A major issue is the stability and quality of the bio-oil as it is heavily influenced by the presence of biochar in the product. The presence of biochar in bio-oil leads to catalysis of the polymerization reaction, resulting in a higher viscosity of bio-oil (Tripathi et al. 2016).

#### 8.2.2.4 Intermediate Pyrolysis

Intermediate pyrolysis is usually carried out to achieve the balance of product yield between fast pyrolysis and slow pyrolysis. It has a decent product yield distribution, and therefore, it can be used in the co-production of biochar, bio-oil, and gas. The process conditions of this pyrolysis lie between fast and slow pyrolysis. The pyrolysis is carried out in the temperature range of 400–650 °C with a heating rate of 1–10 °C/min and residence time of 15–20 min. The advantages of the conditions in intermediate pyrolysis are that they prevent the development of high molecular tar compounds with excellent quality bio-oil and generate dry biochar which is appropriate for soil amendment and bio-energy production (Kazawadi et al. 2021). The bio-oil produced through this pyrolysis can be used in engines and boilers directly because it does not have a high amount of reactive tar. This is a significant benefit of intermediate pyrolysis over fast pyrolysis (Mahmood et al. 2013).

## 8.3 Effects of Process Parameters

### *8.3.1 Process Temperature*

Temperature is the most crucial element to control the reaction process, and it directly influences the biochar physicochemical properties and yield. The increment in pyrolysis temperature negatively impacts biochar yield because it facilitates the thermal cracking of heavy hydrocarbon compounds leading to a rise in liquid and gas yield (Ahmad et al. 2014). Biochar developed in the primary pyrolysis reaction takes part in the secondary reactions and enhances the bio-oil and gas yield at the expense of biochar. Hence, a lower pyrolysis temperature is suitable for higher biochar yield. Moreover, biochar has a graphene-like structure when it is produced above the 300 °C temperature. Graphene holds a flat-polyaromatic and monolayer carbon structure, high electrical conductivity, and stability index. Additionally, biochar produced at higher temperatures enhances physicochemical properties such as pH, surface functional groups, and BET surface area (Wu et al. 2012). Biochar produced at higher temperatures can also have high aromaticity and recalcitrant carbon fractions in biochar which improves the stability.

### *8.3.2 Heating Rate*

In biomass pyrolysis, the heating rate affects the product yield and physicochemical properties to some extent. The pyrolysis process is mainly classified based on the heating rates. The process with a lower heating rate can minimize the secondary pyrolysis reaction and hence, it confirms that no thermal cracking arises, resulting in higher biochar yield. In contrast, higher heating rates promote the fragmentation of feedstock and increased the bio-oil and gas yield by restraining the possibility of char formation. The higher heating rate also enhances the depolymerization of lignocellulosic constitutes into primary volatile compounds, which reduces the biochar yield (Tripathi et al. 2016).

Dilek Angin performed the pyrolysis of safflower seed press cake for biochar production by altering the heating rates (10–50 °C/min) (Angin 2013). It was noticed that as the heating rate increased the biochar yield decreased. Similar results were observed in the literature (Ateş et al. 2004; Huang et al. 2017; Zhao et al. 2018).

### 8.3.3 *Residence Time*

Residence time has a crucial part in the minimalism of the product yield distribution, product properties, reaction mechanism, and product quality. The biochar production can be carried out at various scales of residence time ranging from a few minutes to several days. Low temperature combined with longer solid residence time is suitable for char production (Cha et al. 2016). The higher residence time supports the depolymerization of lignocellulose composition by offering them adequate reaction time. In contrast, lower residence time in the pyrolysis process minimizes the depolymerization reaction, which results in lower biochar yield (Park et al. 2008).

Residence time influences the char yield and the characteristic and physicochemical properties of biochar such as surface area, micro- and macropore development, and surface functional groups. It was reported that longer residence time in biomass pyrolysis enlarged the pore size (Tay et al. 2009). Pyrolysis temperature, particle size, heating rate, and other variables frequently govern the influence of holding time. This makes it difficult to give a clear picture of the role of residence time in the development of biochar.

### 8.3.4 *Particle Size*

Particle size is also one of the essential factors in the biomass pyrolysis process as it controls the reaction rate and heat transfer rate. The heat transfer rate of input feedstock decreased from the outer surface to the core of the material by increasing the particle size, which results in higher biochar yield (Encinar et al. 2000). Additionally, when particle size increases, the vapor released during the thermal breakdown of feedstock travels a greater distance inside the biochar layer, which triggers secondary pyrolysis and leads to an increase in biochar yield.

Hong et al. (2020) studied the effect of temperature and particle size on biochar yield using various agriculture waste. The biochar yield increased with increasing the particle size (Hong et al. 2020). Demirbas also studied the influence of particle size on char yield through pyrolysis of agriculture waste. It was observed that char yield improved from 19.3 to 35.7% for olive husk and 5.6–16.7% for corncob by rising particle size from 0.5 mm to 2.2 mm (Ayhan Demirbas 2004).

## 8.4 Biochar Activation

### 8.4.1 Physical Activation

In physical activation, biochar produced thermochemically from biomass is processed with activities such as steam, $CO_2$, and air/$O_2$ at a temperature range of 700–900 °C. Biochar porosity increases in an oxidizing environment at an elevated temperature during the activation process. Activation increases the surface area and pore size of biochar, which improves its adsorption capacities. The oxidizing agents penetrate the biochar layers and gasify the carbon atoms, causing inaccessible pores to expand and open (Tripathi et al. 2016). Unlike air activation, steam and carbon interaction is an endothermic reaction, making it simpler to curb (Demirbas 2009). Activation temperature, degree of activation, biomass feedstock, and activation agent strongly controls the physical activation. The generic trendline observed in the literature shows that with the increase in process temperature and time, porosity growth enhances. Moreover, this leads to an increase in pore size distribution. Using the air as an activation agent shifts the reaction in the direction of combustion because of the synergistic effect of air and biochar. An unregulated reaction can cause excessive ash formation and reduced activated carbon yield (Dawson et al. 2003). Tables 8.2 and 8.3 show the mechanism of the activation agent and the effect of the activation agent on biochar BET surface area, respectively.

**Table 8.2** The mechanism of activation agent on biochar BET surface area

| Oxidizing agent | Chemical reaction | Process | Reference |
|---|---|---|---|
| Steam/ $H_2O$ | $C + H_2O \rightarrow C(O) + H_2$<br>$2C + H_2 \rightarrow 2C(H)$ | Chemisorption | Ahmed et al. (2016), Belaroui et al. (2014), Mendoza-Carrasco et al. (2016) |
| $CO_2$ | $C + CO_2 \rightarrow C(O) + CO$<br>$C(O) \rightarrow CO$<br>$C + CO_2 \rightarrow 2CO$ | Carbon gasification by carbon dioxide | Aworn et al. (2008), Betancur et al. (2009) |
| Air/$O_2$ | $C + O_2 \rightarrow CO_2$ | Carbon gasification by oxygen | Jung et al. (2015), Singh et al. (2008), Xiao and Pignatello (2016) |

**Table 8.3** Effect of activation agent on the BET surface area of biochar

| Feedstock | Activation agent | Activation temperature (°C) | Activation time (h) | BET surface area ($m^2/g$) | Reference |
|---|---|---|---|---|---|
| White wood (Spruce) | Steam | 750 | 2.46 | 643 | Azargohar and Dalai (2008) |
| *Populus nigra* wood | Steam | 800 | 1 | 322 | Shim et al. (2015) |
| Mixed hardwood | $CO_2$ | 800 | – | 730 | Contescu et al. (2018) |
| Rice husk | Steam | 700 | 0.75 | 236.7 | Mayakaduwa et al. (2017) |
| Aspen wood | $CO_2$ | 800 | 3.6 | 910 | Veksha et al. (2015) |
| Poplar | Air | 250 | 0.5 | 570 | Suliman et al. (2016) |
| Waste rubber | Air | 500 | 0.08 | 240 | Heras et al. (2009) |

### 8.4.2 Chemical Activation

The biochar is doped with a different chemical agent to improve its physicochemical characteristics including surface area, pore volume, and fictional groups. The functional group, pore volume, and the surface area are changed according to the impregnation ratio of the chemical agent. The chemical activation of biochar generally takes place within the temperature range of 450–900 °C (Sakhiya et al. 2020). This activation of biochar is broadly classified into two categories: single-step and multi-step chemical activation. The chemical activation mechanism is ambiguous in comparison to physical activation. Mainly two types of reactions occurred on the surface of biochar during the chemical activation, i.e., dehydration and oxidation. The main advantages of chemical activation in comparison to physical activation are greater carbon yield, low temperature, high surface area, high porosity structure, and high efficiency. Chemical agents also suppress tar formation. Over a long period, the corrosion and depletion of equipment take place due to the corrosive nature of chemical agents, which is the major limitation of chemical activation. Even at high temperature, the corrosion increases and more rapidly harm the equipment. After chemical completion of activation, washing of biochar is mandatory which makes the process costlier as compared to physical activation.

There are different types of chemical activation methods available in the literature according to the desired application. If oxidation of surface functional group required acidic chemical agents were used (nitric, hydrochloric, phosphoric acids, hydrogen peroxide). Similarly, if basic modification is required NaOH and KOH agents are used for activation. Different modifications of biochar such as sulfonation, amination, and impregnation of various metals ($FeCl_3$, $ZnCl_2$, MgO, CaO, ZnO, etc.) were also used (Sajjadi et al. 2019). Among the above listed chemical agents, the

KOH is more suitable for activation due to lower process temperature, higher surface area (up to 3000 $m^2/g$), high product yield, and superior microporous structure (Li et al. 2020). The $CH_3COOK$ is a non-toxic chemical agent and can be used for biochar activation. Sakhiya et al. (2021b) studied the comparative study of steam and $CH_3COOK$-activated biochar for heavy metal adsorption. Results indicated that $CH_3COOK$-activated biochar had a higher surface area and adsorption capacity in comparison to the steam-activated biochar (Sakhiya et al. 2021b).

## 8.5 Biochar Applications

Biochar, a low-cost carbonaceous material has a stable carbon matrix capable of retaining materials such as water, air, organic compounds, and metals. Biochar has specific thermal and electrical properties that are still being investigated. With so many different characteristics, biochar is an efficient, eco-friendly, cost-effective alternative with a wide range of applications (Schmidt and Wilson 2014). Figure 8.1 shows the various applications where biochar can be used as a substantial alternative.

### *8.5.1 Biochar as an Absorbent*

Biochar has emerged as a cost-effective alternative to other carbonaceous materials for removing various inorganic and organic pollutants from gaseous, aqueous, and solid phases, including heavy metals, aromatic dyes, polycyclic aromatic hydrocarbons (PAHs), phenols, and antibiotics (Oliveira et al. 2017).

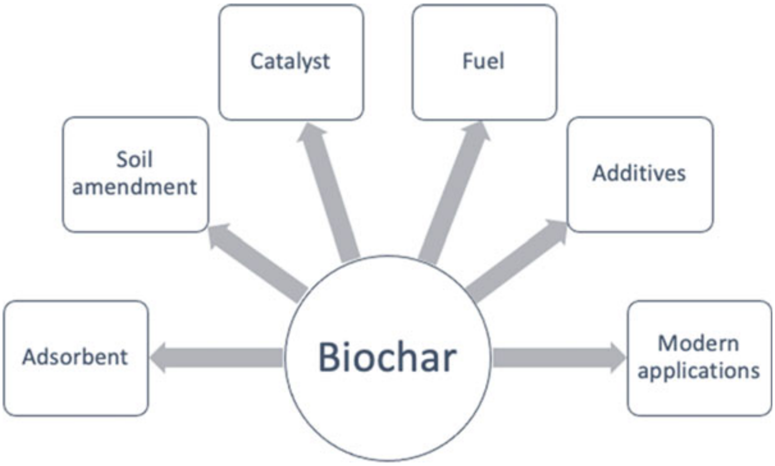

**Fig. 8.1** Various applications of biochar

#### 8.5.1.1 Biochar for Wastewater Treatment

Large volumes of wastewater effluent containing hazardous chemicals are generated by industries and are routinely deposited into adjoining environmental water sources, either directly or indirectly. Therefore, effluents must be treated before discharge to remove contaminants in order to safeguard the aquatic ecosystem and human health (Singh et al. 2020a, b). The global population is rising by 80 million citizens each year, causing a need for safe drinking water of around 64 billion cubic meters; the world must focus on creating methods for a safe water supply (Alam et al. 2014).

Some traditional wastewater treatment techniques necessitate the use of dangerous chemicals, which are both expensive and harmful to the environment (Khin et al. 2012). These processes often affect the environment by producing toxic and non-eco-friendly end products with considerable initial and ongoing capital costs (Singh et al. 2020a, b). The most used wastewater treatment processes are adsorption, reverse osmosis (RO), and membrane filtering. These processes have drawbacks such as membrane deformation, high operational costs, complex instrument handling, the development of undesirable sludge, and other disposal issues. As a result, an alternative, improved, substantial, and cost-efficient wastewater treatment technique is required.

Economically and environmentally sustainable wastewater remediation setups are based on biomass's highly efficient and ecologically sustainable materials. Biochar has specific characteristics such as high porosity, large surface area, and holding water for a longer time making it a suitable substitute for wastewater treatment (Yargicoglu et al. 2015). This section of the chapter emphasizes biochar's potential to remove undesired and hazardous species such as organic contaminants and heavy metals from wastewater. Figure 8.2 demonstrates the adsorption mechanism of heavy metals and organic compounds onto biochar's surface.

##### Biochar for Heavy Metal Removal

Heavy metals in wastewater have the ability to cause damage to the environment. Even at minor concentrations, long-term exposure to heavy metals can cause major health concerns. (Ahmed et al. 2016; Sakhiya et al. 2022). According to recent research, biochar generated from plant wastes and animal manure can effectively absorb heavy metals from waste and drinking water (Dai et al. 2017; Higashikawa et al. 2016; Tan et al. 2016; Zhou et al. 2017).

The functional groups such as OH and −COOH on the surface of biochar show a strong affinity towards heavy metals. The π conjugate aromatic structure of biochar allows it to change negative charge in π-orbital, resulting in losing electrons of a functional group more efficiently, and adsorption becomes more significant (Wang et al. 2018). Samsuri et al. (2014) showed that the polarity index, functional groups

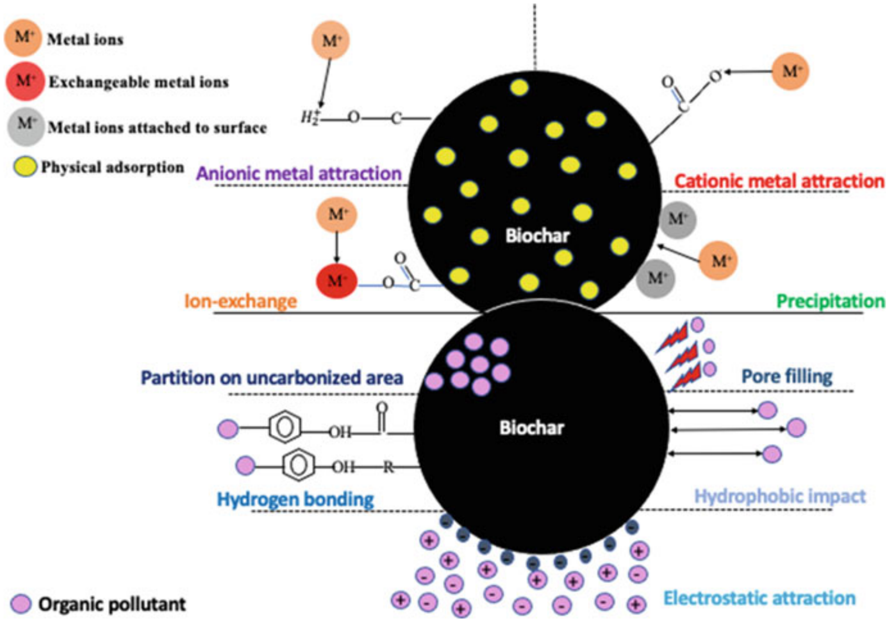

**Fig. 8.2** Adsorption mechanism of organic pollutants and heavy metals onto biochar

containing oxygen or O/C molar ratio has an important role in the heavy metal adsorption process (Samsuri et al. 2014).

Arsenic is found in both wastewater and drinking water and is highly toxic. Van Vinh et al. (2015) impregnated $Zn(NO_3)_2$ over biochar, and the results revealed an increase in adsorption capacity of $As^{3+}$ from 5.7 to 7.0 mg/g (Van Vinh et al. 2015). Furthermore, fresh and dehydrated banana peels biochar was used to remove $Pb^{2+}$ from wastewater, removal efficiencies obtained were of 359 mg/g and 193 mg/g, respectively (Zhou et al. 2017). Higashikawa et al. (2016) studied the effect of pyrolysis temperature on $Cd^{2+}$ adsorption using a mixture of biochar derived from rice husk, sugarcane straw, chicken manure, and sawdust. Rising the pyrolysis temperature from 350 to 650 °C increases the percentage of $Cd^{2+}$ removed (Higashikawa et al. 2016).

### Removal of Organic Pollutants

Organic contaminants are widespread in wastewater. Dyes, phenols, PAHs, and antibiotics have recently gained high attention due to their complex aromatic structure, high toxicity, and biodegradable resistances in the environment.

Globally, the textile sector is estimated to be worth $1 trillion, accounting for approximately 7% of total global exports and engaging roughly 35 million people (Desore and Narula 2018). The water pollution caused by the textile industry has a significant impact on the environment. According to the literature, biochar application can be an economical and environment-friendly solution to remove dyes from the aqueous solutions with more than 80% efficiency (Srivatsav et al. 2020). Various operational factors (such as temperature, solution's pH, biochar dosage, and concentration of dye) have a critical role in altering the adsorption of dye using biochar (Chu et al. 2020; Mahmoud et al. 2020; Park et al. 2019). Experiments were conducted to determine the threshold pH values, and the findings revealed that biochar could withstand pH levels as low as 2 and as high as 11. Despite this, removal efficiencies were higher than 80% (Srivatsav et al. 2020). Fan et al. (2017) used BC prepared from municipal sludge to extract methylene blue (MB), accurately represented by a pseudo-second-order model, and had a removal efficiency of up to 100% (Fan et al. 2017).

Furthermore, after three cycles, the clearance rate of MB has remained at 60%. The adsorption capacity increased with increasing pH throughout the adsorption phase is attributed to electrostatic interaction. Furthermore, Si–O–Si on BC can offer adsorption sites and interact with MB's functional group containing nitrogen. Moreover, MB can create a hydrogen bond with BC's hydrogen. Kelm et al. (2019) studied the performance of biochar derived from wood residues for adsorption of Indosol Black NF1200 dye and results indicated that at low pH values, biochar could be an efficient adsorbent for azo dyes removal from textile industries (Kelm et al. 2019).

Phenols are being widely used at an industrial scale, which leads to the release of phenolic pollutants in industrial wastewater (Mohammadi et al. 2015). PAHs are also released from various industries and are toxic, carcinogenic, mutagenic, and persistent. Phenols and PAHs have a complex aromatic structure, making them biodegradation resistant (Busca et al. 2008), thus emerging the need to remove these pollutants before moving into the aquatic system. Biochar is used to remove PAHs and phenols from aqueous solutions due to its high adsorptive ability. Various factors such as surface area, adsorbent and adsorbate concentrations, pore-volume, and size affect the adsorption of phenols and PAHs on biochar.

Recently, Chandola et al. (2021) conducted a study for removing phenols from aqueous solutions using biochar produced at different temperatures from *Araucaria columnaris* bark (ACB), 100% phenol removal was achieved with the biochar produced at a temperature of 500 °C (Chandola et al. 2021). A study showed that 57% of PAHs dissolved in sewage sludge can be removed using biochar (Oleszczuk et al. 2012). A review by Lamichhane et al. (2016) stated that more than 98% adsorption capacity could be achieved using biochar as adsorbent for PAHs removal (Lamichhane et al. 2016).

Antibiotic contamination and the emergence of antimicrobial-resistant microorganisms are significant environmental concerns across the world. Given the rising use of antibiotics, reducing their presence in the environment is critical (Krasucka et al. 2021).

Peng et al. (2016) studied the use of biochar for the adsorption of seven antibiotics in an environmental concentration of aqueous solutions. A significant amount of antibiotics were removed, and the adsorption energy increased significantly using the density functional theory (DFT) as the number of rings increased, showing the relevance of π–π interactions in the adsorption process (Peng et al. 2016). Peiris et al. (2017) studied the removal of Sulfonamides (SA) and Tetracycline (TC) using biochar and investigated the adsorption mechanism in detail. Electron donor–acceptor interactions of electron-withdrawing compounds with surface aromatic rings are the most common adsorption mechanism (Peiris et al. 2017). Fan et al. (2017) pyrolyzed rice straw at different temperatures to examine if BC could remove common antibiotics like TC. Due to its wide specific surface area and porosity, BC produced at a higher temperature showed a maximum adsorption capacity of 50.72 mg/g (Fan et al. 2017). Table 8.4 shows literature on biochar applications for removing heavy metals, PAHs, phenols, dyes, antibiotic pollutants.

#### 8.5.1.2 Biochar for Air Purification

When gaseous chemical pollutants are released into the atmosphere, they cause serious human health and environmental threats; hence, we need to prevent their emissions. Fabric filters, electrostatic precipitators, and activated carbon injections are the few techniques used to reduce the emission of toxic gaseous contaminants in the environment (Yang et al. 2018). The high maintenance and installation costs of these techniques limit their application on a large scale. According to recent research, biochar can also remediate gaseous pollutants (Bamdad et al. 2018). Biochar derived from palm kernel, eucalyptus wood, cotton stalk, and pine efficiently removed $CO_2$ with adsorption capacity ranging from 3.22 mmol/g to 7.32 mmol/g (Chatterjee et al. 2018; Heidari et al. 2014; Nasri et al. 2014; Zhang et al. 2014). Similarly, the $H_2S$ removal efficiency of more than 95% was achieved using biochar derived from various feedstocks (Bhandari et al. 2014; Das et al. 2019; Sun et al. 2017). Alkali medium is favorable for achieving high $H_2S$ adsorption. The interaction with biochar's surface functional groups COOH and OH is responsible for $H_2S$ adsorption (Shang et al. 2013). Table 8.5 shows the various recent studies which used biochar for removing toxic gaseous contaminants removal.

Biochar is also used as an adsorbent for the remediation of pollutants from soil. Since it is a very vast application, it has been reviewed in detail in the next section.

### *8.5.2 Biochar as a Soil Amendment*

Various studies have recommended biochar as an efficient soil additive in agricultural soils. Biochar application improves soil aggregate stability and enhances its capacity to hold water for a more extended period by improving its pore characteristics, surface area, particle, and bulk density. The kind of soil and its texture also plays an important role. Biochar amendment effects are more noticeable in soil having high sand-sized particles than in soil rich in clay (Blanco-Canqui 2017; Kavitha et al. 2018).

**Table 8.4** Biochar produced from various feedstocks is used to remove heavy metals and organic pollutants

| Biochar feedstock | Pyrolysis temperature (°C) | Pollutants | Residence time (h) | Adsorption temperature (K) | R.E$^{a}$/$Q_{max}$$^{b}$ | Reference |
|---|---|---|---|---|---|---|
| Long-root Eichhornia crassipes | 500 | Pb(II)<br>Zn(II)<br>Cu(II) Cd(II) | 4 | 298 | 39.09 mg/g<br>45.40 mg/g<br>48.20 mg/g<br>44.04 mg/g | Li et al. (2018) |
| Spent *P. ostreatus* substrate (SPS), spent **shiitake** substrate (SSS) | 700 | Pb(II) | 2 | 298 ± 0.5 | 326 mg/g | Wu et al. (2019) |
| Sesame straw | 700 | Cd, Cr, Cu, Pb, Zn | 4 | 298 | 8 6 mg/g<br>65 mg/g<br>55 mg/g<br>102 mg/g<br>34 mg/g | Park et al. (2016) |
| Mixed municipal discarded materials | 300 | Cu(II) | 12 | 303 | 4–5 mg/g | Hoslett et al. (2019) |
| Chicken manure | 700 | NAP | 2 | 298 | 84.3% | Liu et al. (2021a, b) |
| Jujube pit biochar (JPB) | 800 | Pb(II) | 2 | 298 | 137.1 mg/g | Gao et al. (2020) |
| Wheat straw | 600 | NAP | 1 | 298 | 69.6 mg/g | Jiang et al. (2014) |
| Soya bean straw | 700 | NAP | 3 | 298 | 25.66 mg/g | Hu et al. (2019) |
| Magnetically modified rice husk biochar (MBC) | 500 | PHE | 2 | 298 | 97.6 mg/g | Wei Guo et al. (2018) |
| Excess sludge | 700 | PHE<br>PYR | 1.5 | 298 | 87.32 mg/g<br>80.88 mg/g | Guo et al. (2017) |
| Rice straw | 550 | Naphthenic acid | 2 | 298 | 8.6617 mg/g | Singh et al. (2020a, b) |

(continued)

**Table 8.4** (continued)

| Biochar feedstock | Pyrolysis temperature (°C) | Pollutants | Residence time (h) | Adsorption temperature (K) | R.E[a]/$Q_{max}$[b] | Reference |
|---|---|---|---|---|---|---|
| Pine fruit shell | 550 | Phenols | 1 | 298 | 99% | Mohammed et al. (2018) |
| Pine chips | 300 | Acetaminophen and naproxen | 0.25 | 298 | 94.1% and 97.7% | Jung et al. (2015) |
| Alternanthera philoxeroides | 600 | Ibuprofen | 1 | 298 | 97% | Du et al. (2021) |
| Soybean dreg | 600 | Methylene blue | 1 | 318 | 1273.51 mg/g | Ying et al. (2021) |
| Palm Kernel shell | 350 | Crystal violet | 0.33 | 298 | 24.45 mg/g | Kyi et al. (2020) |
| Poplar wood | 750 | Trichloroethylene | 0.25 | 298 | 98% | Puppa et al. (2020) |

[a] *R.E* Removal efficiency

[b] $Q_{max}$ Maximum adsorption capacity

**Table 8.5** Literature of gaseous pollutants removed by biochar

| Feedstock | Preparation mechanism | Pollutant | Removal rate | Reference |
|---|---|---|---|---|
| Hickory chips | By simply ball milling of pristine biochar with ammonium hydroxide, N-doped biochar was prepared. | $CO_2$ | N-doped biochar resulted in 31.6–55.2% higher adsorption than the corresponding pristine biochar | Xiaoyun Xu et al. (2019) |
| Waste wood/ brominated flame retarded | Brominated biochar was prepared using one-step pyrolysis at 600 °C and biomass to plastic ratio 1:1 (mass basis) | Elementary mercury | 40% removal efficiency was achieved | Xu et al. (2018) |
| Black spruce and white birch residues | Activated biochar was prepared using KOH, $CO_2$, and superheated steam | $SO_2$ | The highest adsorption capacity of 76.9 mg/g was obtained using steam-activated white birch biochar. | Braghiroli et al. (2019) |
| Biomass | Biochar was produced by pyrolysis at 550 °C under an inert ($N_2$) environment at 12–15 min residence time. | Gaseous ozone | The removal efficiency obtained was 55 ppbv | Zhou et al. (2018) |
| Neem | Biochar was prepared through a moderate pyrolysis $N_2$ environment | Toluene | Adsorption capacity obtained was 65.5 mg/g | Kumar et al. (2020a) |
| Pinecone | Biochar was prepared at 500 °C with 5 °C/ min $N_2$ flow for 90 min Activation was done using hydrogen peroxide impregnation | Formaldehyde | The removal efficiency obtained was 89% | Yi et al. (2018) |

Biochar addition to soil affects its physicochemical parameters such as surface area, tensile strength, pH, cation exchange capacity (CEC), and water-holding capacity, which have a direct impact on plant growth (Chan et al. 2008; Lehmann and Rondon 2006; Zong et al. 2014). Various studies showed that biochar addition improves plant growth by facilitating the nitrogen (N), phosphorus (P), and potassium (K) biochemical cycle (Chan et al. 2008; Gul and Whalen 2016) and influencing soil microbial activities. The elements such as carbon (C), hydrogen (H), sodium (Na), calcium (Ca), magnesium (Mg), N, P, and K present in biochar (Zhang et al. 2015) supply nutrients to plants for sustainable growth. Biochar decomposes slowly in soil due to its long residence life of about 3000 years. Yuan and Xu showed that factors such as biochar's alkalinity, functional groups present on its surface, and strong pH buffering capacity help to regulate soil acidity (Yuan and Xu 2011).

**Table 8.6** Biochar application as a soil amendment

| Biochar feedstock | Contaminant | R.E. (%) | Reference |
|---|---|---|---|
| Rice straw | Cd | 87.1 | Tang et al. (2020) |
| Clover | TPH | 18.6 | Abbaspour et al. (2020) |
| Rice straw | PAHs | 40–58.84 | Zhang et al. (2020) |
| Poplar wood | Cu, Cd, Pb, and Zn | 72.8 | Chen et al. (2020) |
| Wheat straw | TPH<br>PAHs | 45.83<br>30.34 | Han et al. (2016) |
| Rice straw | TPH | 84.8 | Qin et al. (2013) |

*R.E.* Removal efficiency, *TPH* total petroleum hydrocarbons

Biochar amendment improves the nutrient cycle of a plant. A review by Tesfaye et al. (2021) showed a significant impact of biochar soil amendment (BSA) on plant P uptake and soil available P by 55% and 65%, respectively (Tesfaye et al. 2021). Scheifele et al. (2017) reported an increase in nodule dry matter and biological nitrogen fixation (BNF) by 1.8 and 1.2 folds, respectively, in soybean plants with the amendment of maize and wood biochar (Scheifele et al. 2017).

Biochar having a large surface area and pore volume has been an excellent means to remove heavy metals present in polluted soil (Ahmad et al. 2018). The soil amendment using biochar improves soil pore fraction, which provides more space for microorganisms to grow, and N, P, Ca, and K present in biochar provides nutrients for plant growth (Sakhiya et al. 2020). On the other hand, Warnock et al. (2007) examined the effect of BSA on microorganisms present in the soil. BSA results in a reduction in overall microbial biomass (Warnock et al. 2007). Few recent studies of remediations of various contaminants from soil using biochar have been mentioned in Table 8.6.

### 8.5.3 *Biochar as a Catalyst*

Biochar having high surface area and specific surface functional groups can be prepared by functionalization or activation. Biochar has plenty of potentials to be utilized as a flexible catalyst or catalytic assist in various chemical processes because of its unique chemical structure. Biochar can be utilized as a catalyst in biogas upgrading, biodiesel production, improved syngas production, biomass conversion to chemicals and biofuels, de-$NO_x$ processes, and microbial fuel cell electrodes (Cao et al. 2017; Lee et al. 2017). The biochar properties are enhanced by activation or functionalization procedure for being used as a catalyst. The biochar's physicochemical characteristics, mainly its specific surface area, pore-volume, and pore size distribution, can be enhanced to various degrees depending on the activation techniques used (Cao et al. 2017). According to a study by Do Minh et al. (2020), the electrical and chemical configuration of biochar, when correctly controlled, makes it a great photo-, electro-, and chemo-catalyst that might even be used in modern applications. Biochar can be used in combined catalysis with other phases due to its unique characteristics of semiconductivity (Do Minh et al. 2020).

Zhu et al. (2015) prepared chemically and physically activated biochar from rice husk. The evaluation of the biochar characteristics indicated that it could be employed as catalytic support. In methane catalysis, the activated biochar-assisted Ru (Ru/ABC) catalyst excelled or was equivalent to the standard AC-assisted Ru catalyst. Under the optimum reaction conditions, 98% of $CH_4$ selectivity was achieved and 100% CO conversion (Zhu et al. 2015).

### *8.5.4 Biochar as an Alternative to Fuel*

Biomass has enormous potential as a fuel source and a source of both thermal and electrical energy. Because of the limited reserves of conventional energy resources, lignocellulosic biomass is becoming the central focus of the modern period, which does not need any energy storage systems (Kumar et al. 2020b, c). Biochar is typically high in carbon and can be a pollution-free solid biofuel (Kane et al. 2016).

The high moisture content, bulkiness, low energy density, hygroscopic nature, and high transportation cost in various cases are certain drawbacks of raw biomass when utilized as a fuel (Abdullah and Wu 2009; Tsai et al. 2007), making it unsuitable for a variety of industrial applications. On the other hand, because of their biodegradability, environmental friendliness, and long-term viability, these organic materials have emerged as a leading contender for biofuels and bioenergy production. Pyrolyzing biomass at high temperatures to various value-added and energy-rich products is a preferable solution. Biochar, which has entirely different characteristics than the respective feedstock, has the potential to make significant and long-term improvements in guaranteeing a future supply of green energy and turning bioenergy into a carbon-negative sector (Kwapinski et al. 2010). Many studies have been carried out on producing biochar from various agro-residues for being used in fuel applications. Biochar's heating value (16–35 MJ/kg) is equivalent to, or nearly twice the raw biomass and many low-grade coals heating value for any given feedstock (Mullen et al. 2010; Sukiran et al. 2011). Around three billion people worldwide rely on conventional stoves, for example, three stone and open fires, to meet their cooking needs. These cookstoves emit hazardous fumes and are responsible for four million fatalities per year (Sakhiya et al. 2020). Biochar-fired cookstoves can minimize carbon and few other hazardous gas emissions in cookstoves when used for heat and cooking (Birzer et al. 2014). Compared to an open cooking fire, biochar stoves lowered particulate matter emissions by 92% and carbon monoxide emissions by 87% in laboratory tests (Schultz 2013).

## 8.5.5 *Biochar as an Additive*

### 8.5.5.1 Biochar Used as an Additive in the Construction Sector

In recent years, the spread of industry and urbanization has heightened the need for concrete for building purposes. The building industry, especially the cement industry, has been identified as one of the significant contributors to $CO_2$ emissions, accounting for around 7% of all GHG emitted into the atmosphere (Andrew 2018; Benhelal et al. 2013; Gupta et al. 2018). As a result, rising importance for developing greener solutions to decrease the company's carbon footprint and raw material usage (Miller et al. 2018). Several researchers have utilized biochar as an eco-friendly filler in cement manufacture and cement-based construction products to reduce carbon emissions. Biochar has poor heat conductivity, excellent chemical stability, low flammability, and conductivity, making it a suitable candidate for construction material and a filler in cement mortar products (Gupta and Kua 2017). Suarez-Riera et al. (2020) utilized biochar microparticles as a filler and a replacement for cement powder in cement paste and mortar composites. The results indicated that 2 wt% biochar fragments are adequate to improve the strength and resilience of cement and mortar mixtures. When used instead of cement, mechanical properties equivalent to the reference samples were achieved (Suarez-Riera et al. 2020). Another research uses biochar made from wood, food waste, and rice as a carbon-sequestering additive in mortar, attaining comparable mechanical strength results by adding 1–2 wt% biochar to the control mix.

Gupta and Kua (2019) also discovered that adding finer biochar particles at the start guarantees an increment in early strength and water tightness when utilized in cement mortar fusions. It was reported that timber waste biochar can be utilized as a filler material in concrete structures to improve strength and moisture resistance (Gupta and Kua 2019).

Poor thermal conductivity, directly impacted by the availability of broad arrays of pores on biochar, depends mainly on the process temperature and biochar's feedstock (Brewer et al. 2014). Extraction of oxygen functional group from the biochar's surface reduces the energy sites, forming the biochar to cause less hazardous reactions when blended with concrete mixes (Cross and Sohi 2013).

### 8.5.5.2 Biochar as an Additive in Composting

The swift development of humans and lifestyle changes have caused high waste creation. Furthermore, the animal farm business is expanding, posing its own set of problems. Biochar production involves transforming biodegradable carbon (biomass) into aromatic carbon (biochar), which is less degradable. Therefore, along with waste management, biochar production has an additional quirk of being an atmospheric carbon sequestration technique. Composting also promotes a more orderly breakdown of organic waste materials biologically and physicochemically.

An integrated technique employing biochar in composting reduces ecological concern throughout the waste treatment process by decreasing harmful chemical leaching and emission (e.g., heavy metals, $H_2S$, $NH_3$) as well as pathogen levels (Antonangelo et al. 2021).

Biochar has several advantages as a compost addition, including boosting composting and humification performance, promoting microbiological activities, lowering GHG and $NH_4$ emissions, and immobilizing heavy metals and organic contaminants (Guo et al. 2020). Various studies showed that biochar helps reduce nitrogen losses (Awasthi et al. 2018), as compounds like $NH_3$ and $NH_4$ are adsorbed by biochar (Janczak et al. 2017). The temperature goes up quicker in the course of the composting process in the presence of biochar, and the thermophilic phase lasts longer. When biochar is added at the beginning of the composting process, it enhances the water holding capacity (WHC), assuring that most composts have the required moisture content of 50–60% w/w. The carbon to nitrogen (C/N) ratios of various feedstock-derived biochar and composts vary, which has a direct impact on the rate of organic matter (OM) breakdown (Godlewska et al. 2017). Biochar has a high specific surface area (SSA) and a highly porous structure, providing nutrients for soil microorganisms to grow. Various functional groups on the biochar surface result in high cation exchange capacity (CEC), which acts as an electron carrier, making it easier to transfer and transport electrons (Antonangelo et al. 2019). Biochar application rates to compost have ranged from 5 to 10% (mass basis) to 50% or more (Jindo et al. 2012). A dose of more than 20–30% biochar (mass basis) is not encouraged since an excessive quantity of biochar compared to the composting material might obstruct biodegradation. Biochar has been proven to speed up the composting process when used in sufficient amounts, primarily by enhancing the consistency and structure of the mix and boosting microbial activity in the composting mixture. This enhanced activity results in higher temperatures and shorter compost development time (Camps and Tomlinson 2015). Table 8.7 shows the impact of biochar addition to compost in various other studies.

### 8.5.6 *Other Modern Applications*

Besides the above-discussed applications, biochar can be used in energy storage gadgets such as supercapacitors, lithium, and sodium-ion batteries etc. Biochar is used as electrode material in supercapacitors. Biochar activation was done to increase its specific surface area, resulting in an increased capacitive performance of biochar (Tan et al. 2017). For supercapacitor fabrication, Jin et al. (2014) prepared biochar from corn stover using microwave-assisted slow pyrolysis coupled with KOH activation. At a current density of 0.1 $Ag^{-1}$, the biochar had a specific capacitance of 246 F $g^{-1}$ (Jin et al. 2014). Biochar is a carbon-rich material, highly porous and conductive, which makes it a suitable material to be used for sulfur-carbon (S/C) cathode composite for lithium-sulfur (Li-S) batteries (Vivekanandhan 2018). The activation process enhances biochar characteristics such as surface area,

**Table 8.7** Impact of biochar on composting

| Biochar feedstock | Scale | Biochar dosage | Compost material | Impact on the composting process | Reference |
|---|---|---|---|---|---|
| Corn biochar | | 1% w/w | Corn waste compost, corn biochar (1:1) | Shoot concentration, N, P, and K availability increased by 16, 38, and 15%, respectively, after biochar + compost addition over control soil | Liu et al. (2021a, b) |
| Powder and granular rice straw and bamboo biochar | Lab | 10% (fw[a]) | Pig manure, wheat straw (10:1) | • When compared to GRSB,[b] PRSB,[c] and PBB,[d] GBB had the lowest $CH_4$ and $N_2O$ emissions<br>• GBB had the highest cumulative $NH_3$ emissions (957 mg/kg) | He et al. (2019) |
| PRSB (500 °C) | Field | 10% (dw[e]) | Pig, dry chicken manure, rice straw (10:10:1 fw) | • The GWP achieved from biochar treatment was 19.8% lower than that obtained from the control treatment<br>• Biochar reduces energy consumption in turning piles and has the potential to enhance the oxygen supply | He et al. (2017) |
| Rice hull biochar | Lab | 20% fw | Chicken manure, hardwood sawdust, and rice hull biochar (7:1:2) | • BM drastically reduces $N_2O$ and $CO_2$ emissions by 27% and 35%, respectively<br>• Biochar amendment in chicken manure compost reduces soil $N_2O$ emissions significantly by controlling soil organic stabilizing and functional group activities | Yuan et al. (2017) |
| Bamboo biochar | Pilot | 3% w/w | Pig manure, wood chips, and sawdust (3:2) | • The addition of biochar lowers the $NO_2$-N concentration and also reduces the $NO_2$ emissions from pig manure composting | Wang et al. (2013) |

(continued)

**Table 8.7** (continued)

| Biochar feedstock | Scale | Biochar dosage | Compost material | Impact on the composting process | Reference |
|---|---|---|---|---|---|
| | | | | • Manure has lower moisture content and higher pH<br>• The addition of biochar significantly changed the number of denitrifying bacteria | |
| Broad-leaved tree konara oak biochar | 2% v/v | Field | Poultry manure, apple pomace, rice husk, oak bark (2:5:2:1) | • Biochar increased the amount of carbon collected by humic substance extraction by 10% and decreased the amount of water-soluble carbon by 30%<br>• Phosphate, urease, and polyphenol oxidase activities improved by 30–40% due to biochar blending despite lower biomass | Jindo et al. (2012) |
| Eucalyptus grandis biochar | 50% | Pilot | Biochar, coffee husk, and sawdust (1:1 fw) | Biochar amendment in poultry manure reduces the loss of nitrogen. This enrichment allows process optimization through odor emission and nitrogen loss reduction via nutrient balancing | Dias et al. (2010) |

[a] *fw* fresh weight basis
[b] *GRSB* Granular Rice Straw biochar
[c] *PRSB* Powdered Rice Straw biochar
[d] *PBB* Powdered bamboo biochar
[e] *dw* dry weight basis

carbon content, surface functional groups, porosity, and pore volume, which improves metal encapsulation. Sajib et al. (2017) used KOH-activated biochar derived from canola meal as cathode composite. At the 0.05 °C rate (83.75 mA/g), the biochar cathode composite showed a high initial discharge capacity of 1507 mAh/g (Sajib 2017). Further, biochar is gaining a huge interest for fuel cell applications. Biochar can be used as a fuel in the electrolyte, as the chemical energy accumulated in biochar is a source for electricity generation, in direct carbon fuel cell

**Table 8.8** Biochar applications in energy storage devices

| Feedstock | Energy storage device | Biochar role | Reference |
|---|---|---|---|
| Fish scale | Supercapacitor | Electrolytes | Senthil and Lee (2021) |
| Walnut shell | Supercapacitor | Electrodes | Xiaoyang Xu et al. (2017) |
| Coconut shell | Supercapacitor | Electrodes | Jain and Tripathi (2014) |
| Cornstalks | Li-ion battery | Anode | Shengbin Wang et al. (2015) |
| Ginkgo leaves | Li-ion battery | Anode | Ou et al. (2016) |
| Pinecone | Sodium-ion battery | Anode | Zhang et al. (2017) |
| Sepals of palmyra palm fruit | Sodium-ion battery | Anode | Damodar et al. (2019) |
| Cherry petals | Sodium-ion battery | Anode | Zhu et al. (2018) |
| Banana peel | Li-S battery | cathode | Yang et al. (2016) |
| Almond shell | Li-S battery | cathode | Benítez et al. (2018) |

(DCFC) (Huggins et al. 2016). Table 8.8 shows the application of biochar in various energy storage devices.

Altogether, enhancing biochar's physical and chemical properties through activation has many applications, such as energy storage devices. Utilizing biochar is a sustainable approach; therefore, we can expect exponential growth in its usage in the coming years.

## 8.6 Conclusion

The world's population is increasing at an alarming rate (approx. 80 million people annually), leading to the increased demand for food, energy, safe water supply, etc. Agricultural production has been increased around 50% in the last two decades, resulting in the generation of a massive amount of biomass waste daily. The majority of biomass waste is thrown or burned openly in the field, which has a severe influence on the ecology and public health. Biochar is a cost-effective and sustainable option to address the above-mentioned problems. This chapter reviewed different types of pyrolysis processes for biochar production and the factors affecting the biomass pyrolysis process.

The chapter also discussed the different biochar applications such as adsorbent in water purification, air purification, soil amendment, additives in composting and construction sector, an alternative to fuel, catalyst in various processes such as syngas production, biogas upgradation, and biodiesel production. Moreover, there are certain modern applications including, electrodes and electrolytes in supercapacitors, anode, cathode composites in lithium and sodium-ion batteries, and hydrogen storage. The application of biochar is highly dependent on its physicochemical characteristics such as porosity, specific surface area, and surface functional groups. These properties of biochar are enhanced using various types of activation processes: physical and chemical. Worldwide biochar gets attention due to its desired physicochemical properties which can be useful in different types of applications to generate the circular economy.

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