Chapter 7

Thermochemical Conversion of Lignocellulosic Waste to Activated Carbon: A Potential Resource for Industrial Wastewater Treatment

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Abstract In the last decade, the amount of contaminated water resources has increased dramatically with the rapid growth in industrial sectors. Additionally, the growth in world population and the effects of climate changes have also increased the water contamination levels in several areas. Thus, there is a crucial need for effective and eco-friendly water treatment materials. The current available water treatment methods and materials have multiples drawbacks that limit their usability. Materials such as metal oxide nanoparticles, carbon nanotubes, and polymer membranes are used widely in the water treatment field. However, the efficiency of these materials is limited by the complexity of the water contaminants. Therefore, highly efficient activated carbon is introduced as a proper approach to treat contaminated water. Typically, activated carbon is produced from different types of biomass. Hence, activated carbon can be produced almost everywhere. Currently, Lignocellulosic biomass is provided as a reliable renewable resource that can be used to produce activated carbon. Indeed, Lignocellulosic biomass can be utilized to produce several materials such as biogases, biofuels, and biochar. Activated carbon is produced from biomass using different thermal conversion technologies such as pyrolysis, anaerobic digestion, torrefaction hydrothermal processing, and gasification. Historically, pyrolysis technology is used for hundreds of years to produce biofuel and char from

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woody biomass. This chapter focuses on the different reaction phases during pyrolysis and the effect of the reaction conditions on biomass to produce activated carbon. Moreover, the impact of technological development on the energy density of the lignocellulosic residues is covered in the chapter.

Keywords Activated carbon · Pyrolysis · Biomass · Cellulose · Lignin · Water treatment

7.1 Introduction

The inevitability of seeking reliable wastewater treatment techniques is evident. Presently, the global supply of clean water relies on accessible natural resources such as rivers, lakes, and groundwater. Moreover, recent studies show a massive decrement in the amount of natural water resources. The vast demand for new water and wastewater treatment approaches is associated with the huge growth in the human population, climate changes, and industrial revolutions. The industrial revolutions have the most significant impact on the water treatment sector. In fact, the dramatic growth in the industrial fields is associated with the growth in the world population and climate change. Hence, the three factors are connected like a circle. Nonetheless, the impact of the industrial revolution on the environment is not comparable with population growth or climate change. In the last years, industrial fields have introduced new types of complex contaminants into the environment in the form of wastes known as industrial wastes. The danger of industrial wastes rises with industrial developments. Generally, industrial wastes are discharged in the natural water resources such as rivers and lakes. Consequently, the industrial waste leak from surface water to the surrounding area and groundwater. The industrial waste stored inform of wastewater causes other challenges in urban areas. Apart from the environmental effects, wastewater is associated with severe health issues in urban areas.

Researchers seek effective, inexpensive, and environmentally friendly techniques and materials for water treatment to eliminate the adverse health and environmental effects of wastewater. Lignocellulosic biomass is proposed as a promising precursor to produce highly efficient activated carbon from natural resources. The special characteristics of biomass products have drawn the attention of several researchers. Also, the inorganic component of biomass contains a few sulphur, ash, and nitrogen quantities that can be neglected or utilized for other applications. Thus, the combustion of biomass is preferable because it produces fewer toxic gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_X). Nevertheless, photosynthesis can be used to recycle and control carbon dioxide emissions (CO_2) [1]. At present, biomass products require more practical applications and demonstrations with an appropriate calculation of materials and energy. Indeed, there are multiple methods used to produce biomass products, such as biofuel, biogases, and char. Nonetheless, the thermotical base of the methods requires more sophisticated studies. Thermal conversion technologies such as pyrolysis, anaerobic digestion, hydrothermal processing, and gasification are used widely to produce biofuel and char from different biomass types. Typically, thermochemical production of liquids and chars is conducted via flash or fast pyrolysis on an industrial scale. However, these products have not been implemented for commercialization applications.

Several biological and thermochemical processes have been adopted to convert biomass into value-added products. In general, pyrolysis is considered the most convenient conversion process among the other processes. Indeed, the pyrolysis process is considered inexpensive, flexible, efficient, requires simple transportation methods, easy to operate, and requires simple storing of products. Despite the unique features of the pyrolysis process, some challenges face the process, such as processing solid waste and biomass. Furthermore, the pyrolysis process is considered at the initial stage; several practical challenges are facing the expansion of the process to compete with the conventional thermochemical technologies [2, 3]. The pyrolysis of different lignocellulosic residues to produce biomass products such as solid char, gas, or liquid biofuel has been intensively studied earlier. Examples of these biomass species include woody biomass [6, 7], straws [8], seedcakes [9], bagasse [5], municipal solid waste (MSW) [10, 11], and beechwood [4]. Figures 7.1, 7.2, and 7.3 illustrate the different types of biomass conversion processes with their outputs and the decomposition temperature.

Pyrolysis is a process where a thermal decomposition of lignocellulosic derivatives occurs under an inert atmosphere in the absence of oxygen. The word is derived from two Greek words: ‘pyro’, meaning fire, and ‘lysis’ which means separation into different parts. Historically, pyrolysis is used by people in Southern Europe and the Middle East to prepare charcoal as a source of energy [12]. Additionally, ancient Egyptians made tar for sealing boats using pyrolysis technology [13]. The recent widespread applications of pyrolysis technologies can be seen in the energy field in the form of char and biofuel production. The pyrolysis products are also used in multiple industries such as materials fabrication, electronics, and fertilizers. Typically, high temperature obtained from burning charcoal is used to melt copper with tin to produce bronze. Throughout the modern era, pyrolysis processes gained the attention of many researchers as an effective technology for transforming waste and biomass into bio-oil [14]. Most of the present studies revolve around eventual objectives to enhance pyrolysis processes and produce reliable high-value products that can compete and replace the non-renewable fossil fuels and conventional materials to treat wastewater. Biowaste to produce value-added products via pyrolysis shadows several global challenges such as waste management, energy, and water and wastewater treatment. However, gaining more knowledge about pyrolysis technology is the true challenge. Several ideas proposed the use of biofuel in the airplane, trains, ships, and vehicles to replace fuels such as petrol and diesel [15, 16]. Nonetheless, few studies focused on the use of biomass-based carbon materials to remediate wastewater. Pyrolysis technology is under continuous enhancements to increase the quality

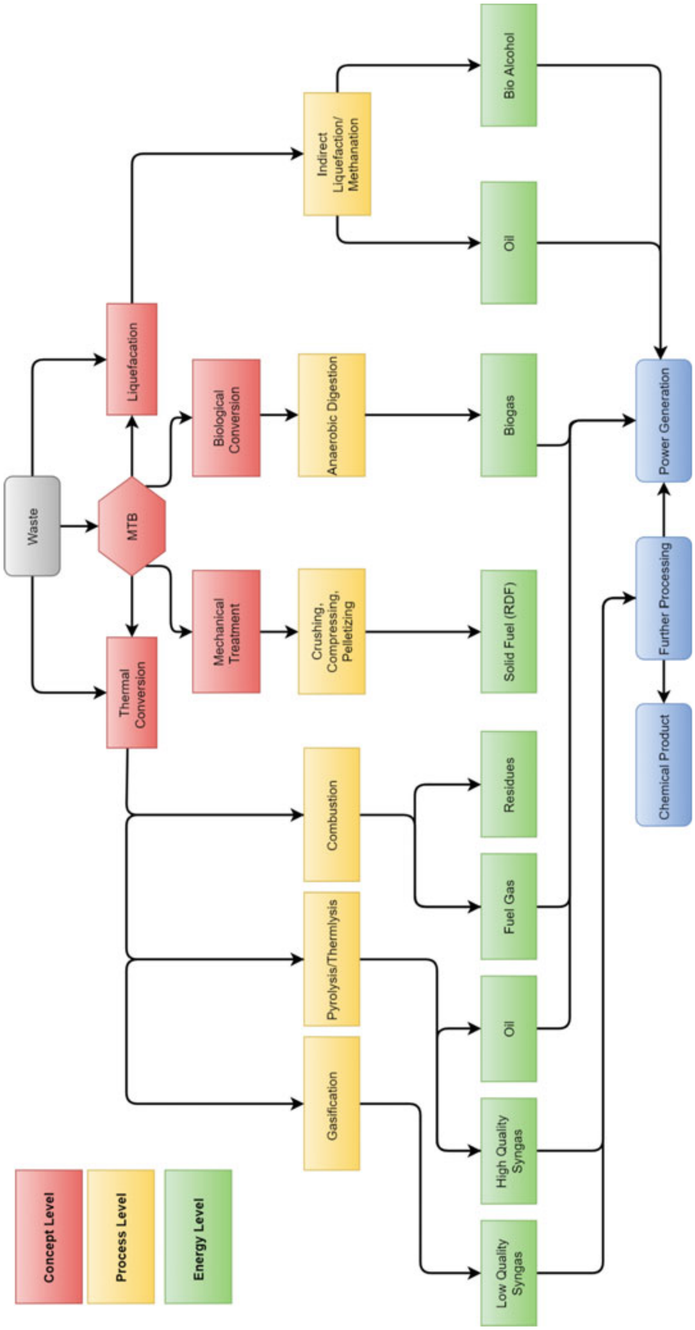

Fig. 7.1 Conversion processes of biomass feedstocks and their relative products

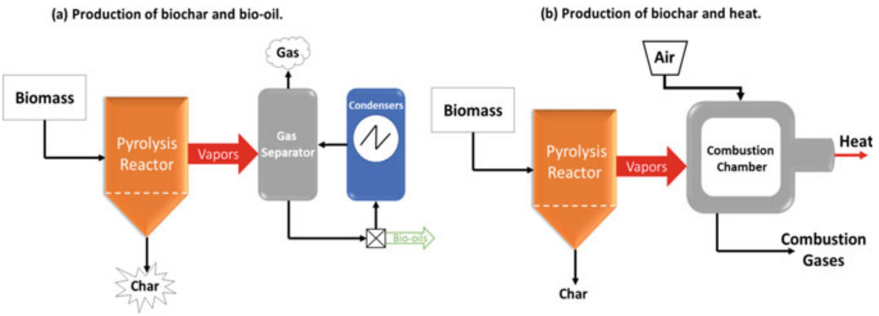

Fig. 7.2 Schematic diagram of simple pyrolysis reactors and the obtained products. **a** Production of biochar and bio-oil. **b** The production of biochar and heat

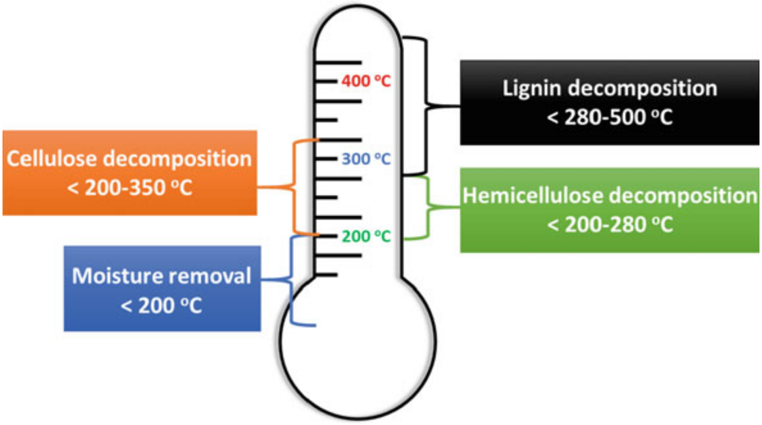

Fig. 7.3 The decomposition of lignocellulosic biomass components at different temperatures

of biomass products. Commonly, equipment such as pyrolysis reactor, lignocellulosic residues pre-treatment unit, and subsequent unit for downstream processing are parts of the pyrolysis system unit. The units are classified further into slow pyrolysis units to produce only heat and biochar or units that use fast pyrolysis to produce biochar and bio-oils.

Researchers have been working on the thermal conversion of biomass into biomass-based carbon products using advanced pyrolysis processes in the last year. The optimization of process parameters offers many advantages to pyrolysis technology over other thermochemical conversion technologies. Nevertheless, pyrolysis technology needs more improvements for commercial applications. Hence, this chapter investigates the current status of pyrolysis technology and the potential for practical application for biochar to produce highly efficient activated carbon. Additionally, the pyrolysis products, types of pyrolysis and principles, biomass compositions and characteristics, physiochemical properties of pyrolysis products, and the economic aspects of amorphous carbon for wastewater treatment are discussed in this chapter. Moreover, the production and properties of activated carbon are stated in this chapter to study the limitations in wastewater treatment. Eventually, the future of activated carbon production from biomass is discussed to enhance the wastewater treatment process.

7.2 Classification of Thermochemical Processes to Produce Activated Carbon

Thermochemical processes are the conversion of carbonaceous materials such as biomass into value-added products like gaseous and liquid fuels, solid fuel, and chemical feedstock. Indeed, thermal conversion techniques are used in ancient India and China before 4000 BCE to produce charcoal from biomass. At present, gaseous and liquid biomass products are treated and used in several fields. Besides that, charcoal is still used by several countries as a primary source of energy. Mainly, thermochemical conversion processes are classified into pyrolisation and gasification. The significant difference between the techniques relies on the final product. Pyrolisation is primarily used to produce char and liquid fuel, whereas gasification is used to convert biomass into a conventional gaseous product. The process of producing liquid fuel from biomass is known as liquefaction. Pyrolisation is further classified into multiple methods according to the preparation temperature and final production. In general, pyrolisation is classified into pyrolysis, carbonization, and torrefaction methods. Pyrolysis is the most adopted approach to convert biomass into carbon-rich materials. Pyrolysis, carbonization, and torrefaction processes are conducted in an oxygen-starved atmosphere. Therefore, carbonaceous materials are mainly formed from biomass via thermochemical conversion processes in the absence of oxygen. The presence of oxygen during the thermochemical convention will burn the biomass precursors and produce a large amount of ashes. The thermochemical process which involves oxidation is known as combustion. As discussed before, studying and improving the thermochemical processes will produce a high quality of carbon materials from biomass. Using high-quality activated carbon will improve the quality of wastewater treatment. In several publications, thermochemical conversion processes are stated to be independent due to the different temperature values. Nevertheless, the thermochemical convention processes used to produce solid carbon substances are interconnected. In fact, carbonization and torrefaction are part of the pyrolysis process. Figure 7.4 illustrates the connection between the thermochemical processes.

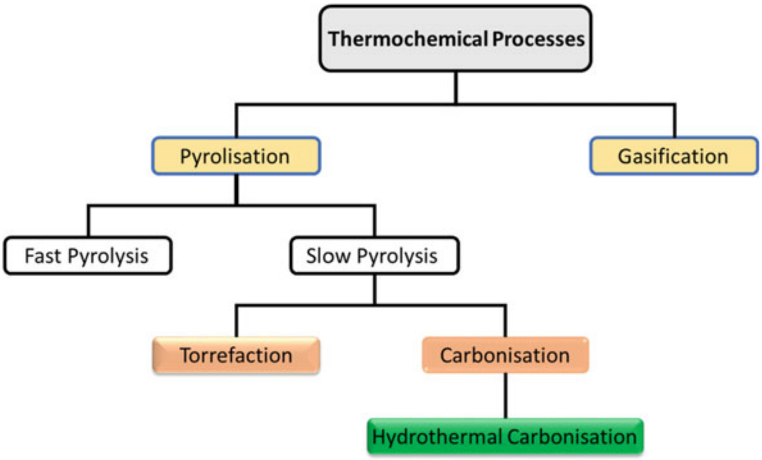

Fig. 7.4 Diagram of the relation between thermochemical processes for activated carbon, biogasses, and bio-fuels production

7.2.1 Pyrolysis

The thermal decomposition of pyrolysis using lignocellulosic biomass requires a special environment. Initially, the pyrolysis of lignocellulosic biomass occurs in an oxygen-deficient environment in an inert atmosphere. Followingly, nitrogen (N) or argon (Ar) gases are diffused into an inert atmosphere to complete the process. Generally, several steps are involved in the chemical reaction of the process, which makes it very complicated. The outputs of biomass pyrolysis are products such as biochar, gases, and bio-oil. The pyrolysis process emits materials that can be either discharged or used in further applications, such as hydrogen (H), carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4). The decomposition of organic materials based on biomass substrate starts around 350–550 °C. However, the decomposition can proceed until 700–800 °C in the absence of oxygen/air [17, 18].

The chemical structure of biomass consists of lignin, a long polymer chain of cellulose, pectin, hemicellulose, and others. The small molecules formed from the bulky molecules of organic materials. These small molecules are then released from the pyrolysis process as solid char, steam of gases, tar, and oil as condensable vapors. Multiple factors affect the proportion of the final products, such as heat rate, temperature, and types of precursors, pressure, reactor design, and system configuration. The effect of temperature on the decomposition process of prime lignocellulosic residues is shown in Fig. 7.3 and, the effects of pyrolysis on the lignocellulose components is illustrated in Fig. 7.5. Likewise, the moisture percentage of the biomass has a vital impact on the pyrolysis processes. The raw biomass moisture percentage must be around 10% during the fast pyrolysis process [18]. The high percentage of biomass moisture will turn the major final products into liquids.

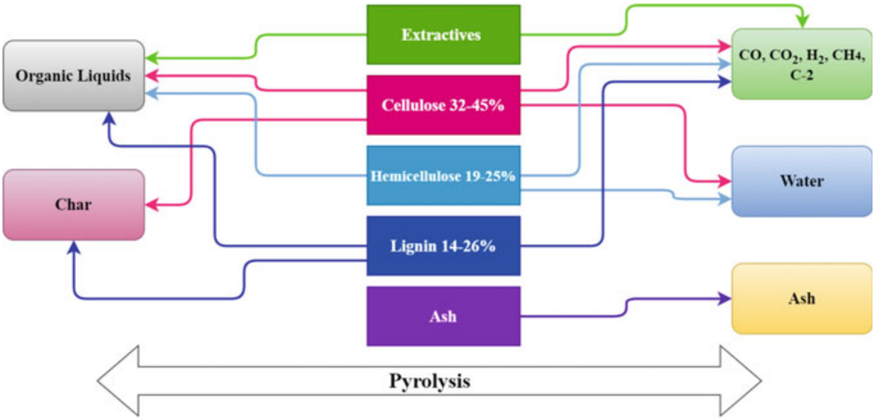

Fig. 7.5 The relationship between the composition of lignocellulosic biomass and obtained products during pyrolysis

On the other hand, the low water level will cause a high risk because the process will produce an enormous amount of dust instead of oil. Hence, it is necessary to dry the sludge produced from meat-processing wastes and waste streams before involving it in the pyrolysis process. To demonstrate, the required condition to produce biochar is a temperature less than 450 °C when the heating rate is slow. In contrast, when the heating rate is high and the temperature is higher than 800 °C, the obtained products are a large amount of gases and ash. In like manner, medium temperature when the heating rate is high, the main yield is bio-oil. When the temperature is between 250 and 300 °C at the beginning of the process, a large amount of volatile materials is disposed of almost ten times faster than the subsequent step [20].

As mentioned before, charcoal is mainly produced using woody biomass. The charcoal produced from wood has many advantages, like the production of a limited amount of smoke. Historically, charcoal is used to melt ore rocks to yield iron. Nevertheless, this process has many disadvantages, like it produces a huge amount of air pollutants, less production percentage, and less energy. Consequently, advanced technology has been adopted and developed to extract the extreme amount of energy from biomass via exothermic and endothermic processes such as combustion, gasification, and pyrolysis [21]. Combustion is used to produce heat by burning biomass in the presence of oxygen. The efficiency of combustion is not sufficient [22, 23]. Gasification may occur in an oxygen-starved environment to produce gaseous fuels. However, the pyrolysis process is more advantageous compared to combustion and gasification [24, 25]. Indeed, pyrolysis can be present as part of the combustion and gasification processes [26]. Figure 7.6 shows the products of biomass substrate during the pyrolysis process [27].

In general, the pyrolysis process is classified into slow and fast processes. The significant difference between the two types is the heating rate involved in the process. The required time of heating precursors to reach pyrolysis temperature in the slow

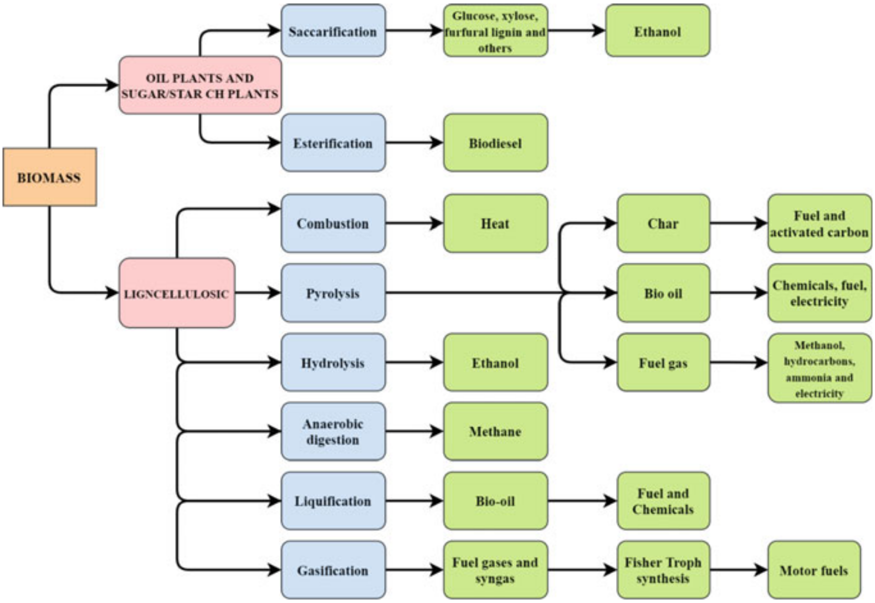

Fig. 7.6 The Conversion of biomass feedstock into value-added products through pyrolysis

pyrolysis process is longer than the time used to keep the substrate at the characteristic pyrolysis reaction temperature. On the other hand, the initial heating time of the biomass substrate in the fast pyrolysis process is less than the final retention time of the substrate at the maximum pyrolysis temperature. There are two other types of pyrolysis based on the ambiance of the process, hydro-pyrolysis and hydrous pyrolysis. As mentioned before, usually fast and slow pyrolysis process takes place in an inert atmosphere, while hydro-pyrolysis occurs in the presence of hydrogen and hydrous pyrolysis occurs in the presence of water. In the slow pyrolysis process, vapors present in the pyrolysis medium for a longer time. Hence, this process is utilized to produce more char and activated carbon. In fact, slow pyrolysis is usually classified into conventional and carbonization processes. Conversely, in fast pyrolysis vapors exist in the medium for seconds or milliseconds. Thus, fast pyrolysis is mainly utilized to produce gas and bio-oil. Fast pyrolysis is further classified into a flash and ultra-rapid pyrolysis process. Table 7.1 shows different types of pyrolysis processes with basic characteristics.

(i) Fast Pyrolysis

The fast pyrolysis process involves using a high heating rate to burn the precursors at high temperatures in the absence of oxygen. The quantity of the products produced via fast pyrolysis is related to the initial weight of the biomass. Using 15–25% of biochar precursors in the fast pyrolysis process can produce 60–75% of liquid biofuels [54]. Besides that, it is possible to obtain 10–20% of gaseous products, depending on the biomass type [54]. Fast pyrolysis

Table 7.1 Summary of pyrolysis processes for biomass

Pyrolysis process	Temperature (°C)	Heating rate	Products
Fast	500	Very high	Biofuel
Slow	400	Very low	Charcoal, biofuel, and biogas
Flash	<650	High	Chemicals, biofuel, and biogas
Ultra-fast	1,000	Very high	Chemicals and biogas
Hydro-pyrolysis	<500	High	Biofuel
Conventional	600	Low	Charcoal, biogas, and biofuel
Carbonisation	400	Very low	Charcoal
Vacuum	400	Medium	Biofuel

involves short vapors retention time. Nevertheless, the produced vapors and aerosol can be chilled quickly during the process to increase the percentage of obtained bio-oil [54]. Typically, the obtained liquid biofuels are used to operate engines, turbines, boilers, and industrial applications. Fast pyrolysis technology is receiving global attention as a liquid fuel producing process due to its practical advantages, such as the inexpensive development cost, simple storability and transportation of obtained products, and the utilization of second-generation bio-oil as industrial wastes, and municipal to produce. In addition, fast pyrolysis can derive secondary fuels and chemicals from motor fuels. Lastly, the process can assure a pre-disintegration of lignin portions and simple oligomers from lignocellulosic biomass with consecutive improvement [55–57].

(ii) **Slow Pyrolysis**

The slow pyrolysis technology uses a low heating rate and low temperature to produce a high quality charcoal. In this process, the vapor residence time is longer than flash pyrolysis, around 5–30 min. To obtain char and liquid in slow pyrolysis, a reaction occurs between the volatile organic fragments [61]. Nonetheless, the quality of the obtained bio-oil in this process is very poor. Longer vapor residence time creates further cracking, which lowers bio-oil production. Slow pyrolysis has some drawbacks, such as the higher consumption of energy due to the low heat transfer rates with longer retention time [62, 63]. The charcoal produced via slow pyrolysis is the core of activated carbon production. Basically, high-quality charcoal means the high efficiency of activated carbon. The following equation is the stoichiometric Eq. (7.1) of charcoal production by [11].

$$C_6H_{10}O_5 \rightarrow 3.74C + 2.65H_2O + 1.17CO_2 + 1.08CH_4 \tag{7.1}$$

7.2.2 *Carbonization*

Thermochemical carbonization is a process where the pyrolysis of biomass precursors is conducted in a deficient oxygen atmosphere. Carbonization is conducted at a low temperature between 300 and 700 °C. Primarily, the carbonization process is used to produce carbon-rich char from organic substances. The carbonization of biomass is widely known in rural areas due to the simplicity of the process. Moreover, several industries are using carbonization to produce high-quality commercial char for energy sectors. Usually, carbonization is preferred to produce activated carbon as it is an inexpensive process and consumes low energy. In addition, the carbonization process produces a low amount of wastes compared to other thermochemical processes. Carbonization produces a char with a high volume of narrow pores on the surface. Frequently, a large amount of surface pores on the char are blocked by liquid tar and other substances. The tarry substances are attached to the pores of the char during the diffusion of volatile components out of carbon structure into the gas stream. Indeed, the diffusion process also forms cracks on the char structure. Thus, the structure of the char contains a high volume of pores and tunnels. The char produced by carbonization can be used for water and wastewater treatment as adsorbents. However, this char will have a poor adsorption capacity due to the existence of blocked pores. Carbonization involves four main phases at different temperatures (Table 7.2). Carbonisation of biomass is further subdivided into a process known as hydrothermal carbonization. Hydrothermal carbonization is utilized to reduce energy consumption and increase the porosity of produced char.

(i) Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is a widely used process to convert industrial and agricultural wastes into green products. It produces solids, liquids, and gaseous products [44]. The solids formed are known as hydrochar (HC), while liquids and gases are known as biofuels and biogases, respectively [44, 45]. Hydrochar is a carbon-rich product that is further treated to produce activated carbon. Meanwhile, the liquids are usually used in the agricultural field as fertilizer or converted into effective biofuels. Normally, HTC is used as a pretreatment process to optimize the surface chemistry of activated carbon [45].

Table 7.2 The phases of biomass carbonization

Phase	Temperature (°C)	Process
First	≤200	Beginning of drying process for biomass precursor
Second	170–<300	The pre-carbonization phase, few amounts of liquids and condensable gases are produced such as methanol and CO_2
Third	250–<300	The amount of produced tar increases, and some acids are formed from the biomass precursor to produce char
Fourth	>300	The percentage of carbon content in char increase while volatile compounds are leaving the char structure

After HTC, hydrochar yields are further treated with a pyrolysis process to produce high-quality activated carbon with low moisture percentage [44–46].

The major feature of HTC is the presence of oxidants in the form of deionized water. Indeed, deionized water is used as a green solvent. During the HTC, deionized water is added to the reactor along with the biomass feedstock. Subsequently, the biomass is carbonized at a low-temperature range between 180 and 250 °C. The deionized water evaporates and creates high inner pressure [44]. Followingly, the water molecules bounce at high speed inside the reactor and break down the bulky biomass into small particles. Simultaneously, water function as an oxidation agent that optimizes the surface chemistry of the hydrochar, hence enhancing the pores volume of the material [45].

HTC is used on an industrial scale as it consumes low energy, produces a low amount of toxic gases or tars, inexpensive, easy to operate, and eco-friendly [45, 47]. Besides, the process produces high-quality hydrochar, which is further treated through the pyrolysis process to obtain highly effective activated carbon. The activated carbon is subsequently treated with physical, chemical, or physiochemical activation to increase the surface area via open blocked pores and tunnels.

(ii) **Torrefaction**

Torrefaction is a new thermal conversion process used to produce carbon-rich solids from biomass. The torrefaction process is adopted in energy sectors as it is inexpensive and requires lower operational energy compared to carbonization. The principle of torrefaction is similar to carbonization but at a lower temperature. Typically, torrefaction occurs in the absence of oxygen. However, oxygen may introduce into the reaction but in a deficient percentage to prevent combustion.

Briefly, torrefaction converts biomass precursors into solids in slow heat under temperatures between 200 and 300 °C. During the heating process, the carbon content and energy density increase while the oxygen and moisture content decrease [46]. Thus, the obtained is a charcoal-like product with a high percentage of carbon content. Torrefaction is used to reduce storability and simplify the transportation process. Therefore, torrefaction is used to enhance the commercial value of wood by-products for energy production.

7.3 Preparation of Activated Carbon

The preparation of activated carbon using biomass precursors involves two stages, thermochemical conversion, and activation. The two stages may conduct simultaneously as one-step processes or sequentially as dual steps processes. At the first stage, a thermochemical conversion such as pyrolysis, carbonization, or torrefaction is used to produce char with high carbon content. As discussed before, the obtained char may have a very poor adsorption capacity due to the existence of a high volume of blocked pores on its structure. Thus, different activation types are used to eliminate the presence of blocked pores and increase the adsorption capacity. The activation process may include chemical activation, physical activation, or physiochemical activation. Basically, the primary objective of the activation stage is to convert biomass-based char into highly efficient activated carbon.

Briefly, the activation process is used to enhance the porosity and create a fine solid cavity on the surface of the char. Generally, the created pores are classified into three types, macropores (>50 nm), mesopores (2–50 nm), and micropores (<2 nm) [47]. Adjusting the percentage of pores type relies on the type of biomass precursor and activation process. Usually, activated carbon with a high percentage of micropores is used for gas filtration or as a base substance for other nanocarbon materials. On the other hand, macropores and mesopores are used in water and wastewater treatment to trap and hold different types of water contaminants such as heavy metals, pharmaceutical wastes, dyes, and pesticides. Chemical and physical activation processes are the most widely adopted activation methods to produce activated carbon. Physiochemical activation is a combination of physical and chemical activations which usually used to enhance the adsorption performance of activated carbon.

7.3.1 Physical Activation

Physical activation involves the oxidation of char using oxidizing agents such as air/oxygen, water steam (H_2O), diluted oxygen gas, carbon dioxide (CO_2), or their mixture [47]. Usually, physical activation conducts at an elevated temperature around 800–1,100 °C [48]. During the physical activation, the volatile chemicals on the char structure tend to skip in the form of gases. Simultaneously, existed narrow pores are widening, and new pores are formed, thence, the porosity and surface area of the char. At this stage, the modified char is known as activated carbon. Physical activation can be conducted in a single or dual stages process. There are no significant differences between the two processes on the efficiency of produced activated carbon. However, a single-stage process requires a shorter preparation time and lower operational energy.

The most remarkable oxidizing agents are water stream and carbon dioxide. Carbon dioxide has an endothermic nature and low reactivity at high temperatures [49]. Therefore, carbon dioxide is typically used to ensure high controllability of the activation process. In addition, carbon dioxide is simple to handle and provide a slow reaction rate at low temperature. Indeed, increasing the activation time and temperature will increase the CO_2 reaction. However, increasing the activation time and temperature to a certain limit may form ash residues and destroy the existed pores. Carbon dioxide as an activation agent tends to form more micropores, whereas water steam tends to expand the existed micropores. Hence, water steam generates activated carbons with low micropore volume and high meso and macropore volumes [49]. Nonetheless, both carbon dioxide and steam can be very effective activating agents because the most important factor is the conditions of the activation process. Therefore, steam and carbon dioxide can be suitable for certain types of biomass precursors.

The physical activation process is commercially favorable as it is inexpensive and requires no chemicals that will make it an environmentally friendly procedure. On the other hand, physical activation has drawbacks that limit its scalability, like it produces activated carbon with low adsorption capacity, consumes high energy, and usually, the process needs a long activation time [48, 49]. The precise selection of proper oxidizing agents for specific biomass precursors will help produce activated carbon with large pore size distribution and surface area. The detailed process for activated carbon production using physical activation is shown in Table 7.3.

7.3.2 *Chemical Activation*

The chemical activation method, also known as wet oxidation, uses chemical agents as dehydrating and oxidizing agents. The chemical activating agents can be acids, bases, or salt. Usually, the activation process is synchronized with the carbonization process at a temperature between 400 and 900 °C according to the used precursor and activating agents [48]. The chemical activation process is divided into three main steps. First, impregnation in which the carbonaceous materials are oxidized and dehydrated with chemicals. Subsequently, the mixture is dried and then heated for a given time at a specific temperature. Lastly, the mixture is washed repeatedly to remove the excess activating agent and obtain activated carbon [48]. Although several chemicals are studied as activating agents, only a few produce activated carbon with high efficiency. The activating agents with high potential are either alkaline or acidic groups. Examples of commonly used alkaline groups are sodium hydroxide (NaOH), potassium carbonate (K_2CO_3), potassium hydroxide (KOH), and calcium chloride ($CaCl_2$). On the other hand, the most used acidic groups are sulphuric acid (H_2SO_4) and phosphoric acid (H_3PO_4). In addition to acidic and alkaline groups, some metal salts exhibited high potential, such as zinc chloride ($ZnCl_2$) [48].

Generally, potassium hydroxide produces activated carbon with a high surface area. However, the surface area of the activated carbon is also related to the type of used precursors [47, 48]. Indeed, recent studies are focusing on enhancing the activation performance of potassium species to form different types of pores on the surface of activated carbons [50]. To obtain activated carbon with high pores size and volume, some variables need to be monitored, such as activation method, time, temperature and atmosphere, carbonization temperature and time, and impregnation ratio [45]. Although chemical activation produces activated carbons with more pores size distribution and high pores volume, the process has drawbacks that limit its applicability. For instance, the produced activated carbon by chemical activation requires repeated and long washing steps to remove the excess activating agent. Moreover, the process produces toxic wastewater, which contains some chemical agents that can be harmful to the environment upon discharging inappropriately [48]. Nonetheless, chemical activation has several advantages that make it desirable over physical activation. For instance, chemical activation produces activated carbon with a high adsorption capacity. Additionally, the process is economically viable

Table 7.3 Production of activated carbon via physical activation

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (mins)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Acrocomia karukerana	800	120	CO_2/Steam	850	–	1,029	[51]
Bamboo wastes	650	–	Steam	800–900	–	990–1,099	[52]
Baobad woods	–	–	CO_2	800	–	875	[53]
Bulgarian peach stones	599.85	–	Steam	849.85	120	1,258	[54]
Coconut shell	1,000	30	N_2/Steam	900	120	1,926	[55]
Coconut shell	1,000	120	N_2/Steam	900	30	901	[55]
Cypress saw dust and palm kernel shell ash	600	–	steam	–	–	1,668.1	[56]
Camellia oleifera	–	–	Steam	820	–	1,076	[57]
Date seeds	–	–	Steam	800	120	702	[58]
Date seeds	600	280	CO_2	900	–	490	[58]
Date palm leaves	–	–	Steam	577	30	1,094	[59]
Euterpe oleracea	800	120	Ar/CO_2	800	180	496	[60]
Guava seeds	800	120	CO_2/Steam	850	–	1,201	[51]

(continued)

Table 7.3 (continued)

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (mins)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Nuati woods	–	–	CO_2	800	–	801	[53]
Oil palm empty fruit bunch	–	–	Steam	–	–	720	[61]
Oil palm shell	–	–	CO_2	–	–	905	[61]
Pistachio nut shells	750–850	–	Steam	850	20	2,596	[62]
Pine sawdust pellets	–	–	CO_2	800	1	275	[63]
Phoenix dactylifera seeds	800	–	CO_2	900	1	723.7	[64]
Rice husk	–	–	Steam	850	105	1,180	[59]
Rice bran	–	–	CO_2	850	90	652	[59]
Tropical Almond shells	800	120	CO_2/Steam	850	–	1,074	[59]

because it requires a lower temperature and less activation time [48]. The detailed process for activated carbon production using chemical activation is shown in Table 7.4.

7.3.3 Physiochemical Activation

Physiochemical activation is a process where physical and chemical activations are performed simultaneously. The physiochemical activation is mainly used to enhance the pore volume and surface area of activated carbon. Typically, physiochemical activation is conducted via two approaches, a chemical treatment before the carbonization following by physical activation or a chemical treatment after the carbonization following by physical activation. Studies revealed that the sequence of chemical activation has negligible effects on the properties of produced activated carbon. Generally, activated carbon produced via physiochemical activation has a better pore structure and higher surface area compared to physical or chemical activations. Physiochemical activation can be used to increase the volume of mesopores on the surface of activated carbon. Thus, producing activated carbon is suitable for wastewater treatment. Apart from the advantages of physiochemical activation, the process is considered costly and time-consuming in comparison to physical activation and chemical activation. The detailed process for activated carbon production using physicochemical activation is shown in Table 7.5.

7.4 Types of Lignocellulosic Biomass Precursors for Activated Carbon

Lignocellulosic biomass is a natural material that is formed from living species such as animals and plants. Recently, lignocellulosic biomass is proposed as an alternative source of energy. In compassion to fossil fuel, biomass is inexpensive and environmentally friendly. Moreover, biomass is used to produce value-added products such as activated carbon and fertilizers. The new adoption of lignocellulosic biomass will solve the environmental challenges caused by waste management and fossil fuels.

Lignocellulosic biomass has a very complicated chemical structure as it is composed of several types of organic materials. In general, lignocellulosic biomass is composed of three biomacromolecules, Lignin, cellulose, and hemicellulose. In addition, the chemical structure contains minerals and extractives. Each type of biomass has a different percentage of chemicals in the structure [11, 29, 30]. Pyrolysis of cellulose and hemicellulose produce chemicals in the form of liquids and gases or condensable steam. However, the pyrolysis of lignin produces solid char, liquid, and gas. Additionally, the simplicity of extractives to evaporates and decompose

Table 7.4 Production of activated carbon via chemical activation

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (mins)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Acacia nilotica sawdust	–	–	H_3PO_4	900	60	1,701	[65]
Acacia nilotica	–	–	$ZnCl_2$	600	300	403	[66]
Argan nutshell	550	60	NaOH	700	60	798	[67]
Argan nutshell	550	60	H_3PO_4	700	60	1,372	[67]
Apricot stones	–	–	H_3PO_4	400	120	1,382	[60]
Apricot stones	–	–	$ZnCl_2$	600	60	1,111	[60]
Azadirachta indica leaves	–	–	$ZnCl_2$	800	120	705.4	[68]
Bamboo	–	–	H_3PO_4	600	60	1,335	[69]
Bamboo	–	–	HNO_3	–	–	295	[70]
Baobab woods	–	–	KOH	400	–	915	[53]
Ceratonia siliqua L. residues	–	–	$ZnCl_2$	600	60	1,693	[71]
Cocoa shell	110	24 (h)	$ZnCl_2$	500	36	–	[70]
Chestnut oak shells	–	–	H_3PO_4	450	–	989.4	[72]
Chestnut shell	–	–	$ZnCl_2$	700	60	173.21	[73]
Date seed	–	–	NaOH	600	60	1,282	[74]
Distillers grain	–	–	KOH	700–900	60–120	1,430	[75]
Dry okra waste	–	–	$ZnCl_2$	500	60	1,044	[59]
Euphorbia rigidia	25.0	24 (h)	H_2SO_4	850	30	–	[70]

(continued)

Table 7.4 (continued)

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (mins)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Euryale ferox shell	–	–	H_3PO_4	700	60	2,636	[76]
Eucalyptus bark	–	–	H_3PO_4	500	60	1,239	[69]
Fox nutshell	–	–	H_3PO_4	700	60	2,636	[59]
Mangosteen shell	–	–	K_2CO_3	900	120	1,123	[69]
Nuati woods	–	–	H_3PO_4	400	–	1,660	[53]
Plum stone	400	–	KOH	800	–	2,570	[63]
Pistachio wood wastes	–	–	NH_4NO_3	800	120	1,448	[77]
Pineapple plant leaves	–	–	H_3PO_4	500	60	1,031	[78]
Paper mill sludge	–	–	K_2CO_3	800	150	1,583	[79]
Posidonia oceanica leaves	–	–	$ZnCl_2$	600	120	1,483	[69]
Rice straw	–	–	$N_2H_9PO_4$	700	60	1,154	[69]
Ramulus mori	–	–	$N_2H_9PO_4$	800	120	1,061	[69]
Spent mushroom compost	600	60	KOH	500	45	–	[57]
Sewage sludge	–	–	NaOH	700	60	179	[59]
Sewage sludge	–	–	NaOH	700	60	179	[59]
Sunflower oil cake	–	–	H_2SO_4	–	–	241	[70]
Shorea robusta sawdust	–	–	Na_2CO_3	400	180	10.45	[80]
Sunflower seed husks	–	–	$ZnCl_2$	500	45	1,511	[81]

(continued)

Table 7.4 (continued)

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (mins)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Safflower biochar	–	–	$ZnCl_2$	900	60	801	[69]
Tomato paste waste	500	60	KOH	500	–	283	[82]
Tea seed shell	–	–	$ZnCl_2$	500	60	1,530	[69]
Walnut shell	600	–	$ZnCl_2$	700	–	5.95	[83]
Walnut shell	400	–	KOH	800	–	2,305	[63]
Walnut shell	600	–	KOH	700	–	1,239.92	[83]
Waste tea	–	–	$C_2H_3O_2K$	800	120	854	[69]
Waste sludge and bagasse	800	0.5	HNO_3	–	–	806.57	[84]
Walnut cake	–	–	H_3PO_4	400	30	–	[85]
Walnut cake	–	–	H_3PO_4	500	60	–	[85]

Table 7.5 Production of activated carbon via physiochemical activation

Biomass	Carbonisation temperature (°C)	Carbonisation time (mins)	Activation agent	Activation temperature (°C)	Activation time (min)	S_{BET} ($m^2 \cdot g^{-1}$)	Refs
Acacia nilotica	–	–	H_3PO_4/N_2	250	180	–	[86]
Date seeds	–	–	KOH/CO_2	850	120	763	[58]
Date seeds	600	–	H_3PO_4/Steam	–	180	1,100	[58]
Date seeds	600	–	HNO_3/Steam	–	180	950	[58]
Rambutan seed	–	–	KOH/CO_2	802	60	–	[57]
Oil palm fronds	–	–	KOH/CO_2	–	–	1,237.13	[87]
Oil palm shell	–	–	H_3PO_4/CO_2	–	–	642	[87]
Oil palm empty fruit bunch	–	–	KOH/CO_2	–	–	720	[87]
Rice husk	–	–	KOH/CO_2	800	120	1,836	[88]
Waste sludge	–	–	HCl/CO_2	800	–	269	[84]
Waste sludge	–	–	KOH/CO_2	–	–	984	[84]
Pandanus amaryllifolius stem	400	120	KOH/CO_2	794	~71	–	[57]

also helps in producing liquids and gases. The ashes in the char structure are mainly composed of minerals. To summarise, Table 7.6 shows the components of the biomass with its related products.

The obtained vapors from the primary stage of reaction go through a second stage to produce soot. This soot varies according to the type of pyrolysis, either fast or slow. Catalysts like alkali metals are added to enhance char production. The ignition properties of biochar are directly related to the percentage of minerals [11]. Typically, the cellulosic substrate produces bio-oils when the temperature is around 500 °C [31]. Lignin is mainly used to extract biochar. Hence, biomass substrate with a higher percentage of lignin derivatives is used to obtain char. Table 7.6 contains a list of biomasses with the proportion of hemicellulose, cellulose, and lignin substrate [1, 32–37].

Table 7.6 The distribution of biomass composites [1, 32–37]

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Almond shell	50.7	28.9	20.4
Bamboo	26–43	15–26	21–31
Banana waste	13.2	14.8	14
Barley straw	31–37	24–29	14–15
Corncob	50.5	31	15
Corn stover	28	35	16–21
Cotton seed fibers	80–95	5–20	0
Coastal Bermuda grass	25	35.7	6.4
Hazelnut shell	28.8	30.4	42.9
Jute fiber	45–53	18–21	21–26
Nut shell	25–30	25–30	30–40
Oat straw	31–37	24–29	16–19
Olive husk	24	23.6	48.4
Rice straw	32.1	24	18
Rye straw	33–35	27–30	16–19
Sunflower shell	48.4	34.6	17
Sugarcane bagasse	19–24	32–48	23–32
Silvergrass	24	44	17
Tea waste	30.20	19.9	40
Wood	35–50	20–30	25–30
Walnut shell	25.6	22.7	52.3
Wheat straw	33–40	20–25	15–20

7.4.1 Cellulose

Cellulose is the most abundant organic compound on earth. The basic structure of cellulose is a linear polymer contain six-carbon glucose units. The glucose units are connected together via β-(1–4)-glycosides bonds. Typically, cellulose is insoluble in some solvents due to the connection between glucose units and cellulose polymers. Indeed, the cellulose polymers are arranged and connected parallel to each other. The cellulose connection is influenced by the presence of intermolecular and intramolecular hydrogen bonds among the hydroxide groups (OH) of the cellulose polymer. The cellulose structure has two different terminals, which allow for different reactions at the same structure. One of the cellulose terminals is known as the reducing end group as it consists of the reducing hemiacetal group in position C1. The second terminal is known as a non-reducing group and consists of an extra secondary hydroxyl group in position C4. Biomass with high content of cellulose is typically used to produce biofuel through a thermochemical convention. Therefore, the new approach of studying cellulosic materials involves the modification of chemical structure to produce a high quality biofuel and replace fossil fuel.

7.4.2 Lignin

Lignin is a complex form of organic polymers found in lignocellulosic biomass. Lignin polymers are the core of biomass structure. Lignin consists of phenyl propane building blocks and has a form similar to resin. The structure of lignin consists of hydroxyl group and methoxyl group in para and meta positions, respectively. Moreover, the aromatic rings in the structure are connected via carbon-to-carbon or carbon-to-oxygen bonds. Lignin has a complex structure that contains multiple groups such as carbonyl, hydroxyl, and methoxyl groups. Therefore, lignin has a strong structure and insoluble. The lignin present in biomass at different percentages. On average, biomass may contain 10% to 30% of lignin. Nonetheless, materials such as coconut fibers and husk may consist of 45% of lignin. Additionally, hardwood contains 16–24% of lignin, and softwood composed of 25–31%. Lignin in hardwood is connected with xylans via a covalent bond, whereas softwood is connected to galactoglucommannans. Lignocellulosic biomass with a high percentage of lignin is used to produce carbonaceous solids such as char and activated carbon. Thus, the quality and structure of biomass have a significant impact on the properties of produced activated carbon used for wastewater treatment.

7.4.3 Hemicellulose

Hemicellulose (also known as polyose) is a heteropolymer that has a random amorphous structure. Typically, hemicellulose exists along with cellulose in the biomass structure. Hemicellulose structure consists of several monosaccharide units joined together. The primary units of hemicellulose are pentose sugar. In comparison to cellulose, the hemicellulose chain is shorter and unorganized. Thus, hemicellulose has better solubility compared to cellulose. The hemicellulose polymer has two forms, either a homopolymer or a heteropolymer. Homopolymer structure composes of units from a single type of sugar, whereas heteropolymer structure composes of different kinds of sugar units. Hemicellulose acts as an adhesive where it holds the fiber and cellulose in biomass structure.

7.4.4 The Physiochemical Properties of Lignocellulosic Biomass

The final obtained products of the biomass conversion process are significantly influenced by the percentage of moisture in biomass which is further affected by the type of biomass feedstock, the design of the reactor, and process parameters [11]. As discussed before, charcoal production involves two steps: the drying and pyrolysis processes. In the primer phase of the drying step, the water contained in the pores structure as free water tends to evaporate and diffuse at a temperature around 110 °C. The higher is the percentage of water, and the more energy is required to evaporate water. Additionally, when the temperature is between 150 and 200 °C, an obvious reduction occurs for the combined water inside the cellulose chain of wood. White smoke of water vaporizes from the charcoal oven chamber during the initial stage of carbonization. Generally, the rate of temperature rise does not rely on the evaporated water because the fast pyrolysis process is effective in drying the feedstock [38]. The existence of moisture in the wood is usually around 15–20% [11]. Moisture content can significantly affect the properties of the production of activated carbon [39]. The differences between the obtained char or liquid are directly connected to the particle size of the biomass matrix. When the particle sizes of the biomass are large, char is mostly formed. However, a secondary char forming reaction is usually required due to the low rate of disintegration caused by the size of the large particles [11]. Hence, to produce more carbon, it is better to use larger particle sizes, while smaller particle sizes are used to increase the percentage of gained liquid during the fast pyrolysis process. Better biochar substrate production is related to the temperature of the pyrolysis and lignin and carbon quantity. Thus, to obtain a better biochar substrate, a higher percentage of lignin and fixed carbon is used while the pyrolysis process occurs at a medium temperature of 500 °C. On the other hand, to obtain more bio-oils and syngas, the proportion of the volatile materials must be high [29]. Precursors such as olive stone, walnut shell, and hazel nutshell are highly selected to produce biochar because it contains a higher percentage of lignin. Furthermore, materials such as dead wood, cereal straw, and grasses are suitable to produce syngas and bio-oils [40]. Briefly, the physicochemical properties, transformation mechanisms, and composition of lignocellulosic biomass directly impact the type of final products as shown in Fig. 7.6.

7.4.5 The Influential Factors on Activated Carbon Production

(i) **Temperature**

Controlling the temperature profile is crucial for biomass product optimization because the heating rate, pressure, contact time, and peak temperature between solid and gaseous phases are partially affected by the temperature profile. During the fast pyrolysis, rapid heating and cooling rate are utilized to reduce the duration of secondary reactions. As a result, the product quality will be downgraded, whereas the liquid yield is reduced. Additionally, the obtained product will contain a mixture with high complexity and viscosity [38]. On the contrary, to increase the char yields, the pyrolysis process involves slow heating rates, though; this is not consistent [11]. Increasing the temperature can assure the release of more evaporative fractions, which increase the content of carbon in the biochar. At the same time, hosting the biomass for a long time under high temperatures will significantly reduce the biochar yield. In regard to liquid and gaseous products, the effect of temperature is very complicated. To obtain a higher portion of liquid, the pyrolysis temperature must reach up to 400–550 °C. Moreover, when the temperature is higher than 550 °C, the final products contain fewer liquid percentages due to the decomposition of condensable vapor via secondary reactions. A higher percentage of liquid can be obtained during the fast pyrolysis when the temperature is around 500 °C. Around 28–4% of liquid can be gained during the slow pyrolysis when the temperature is between 377 and 577 °C, and this depending on the type of biomass feedstock [13]. On the other hand, 4.93–45% of the liquid can be obtained at a temperature around 385–450 °C using different cellulose-rich feedstock [19].

(ii) **Gas Flow Rate**

The influence of the gas flow rate during the pyrolysis process appears on the degree of secondary char formation. Applying a low gas flow rate is preferable during the slow pyrolysis process to form char. Conversely, higher gas flows are applied during the fast pyrolysis to adequately and quickly remove formed vapors. High pressure will increase the formation of secondary char because it increases the activity of vapors at the surface of char particles and within the reactor. On the other hand, conducting pyrolysis under vacuum produces a higher proportion of liquid and less char. Moisture that exists in the form of vapors can increase carbon production systematically when pyrolysis takes place under pressure. This occurs due to water, which acts as a catalyst and lowers the activation time of pyrolysis reactions [46]. Conspicuously, the gas flow rate affects the thermodynamics of the pyrolysis process. Using a low gas flow rate, the reaction is more exothermic when the pressure is high. The exothermic pyrolysis process assures more char yield. Additionally, these conditions are favorable because the total energy balance of the processes will seek carbon and char as prime products. Generally, to form more char and gain less liquid, it is important to increase the contact between the main generated vapors and hot char surface during the pyrolysis process. This can happen using particles with large size, high pressure, slow heating rate, or low gas flow rate.

7.5 Applications of Activated Carbon for Water Treatment

Activated carbon is used in several industrial and agricultural applications. Primarily, activated carbon is used for air and water filtration. Indeed, the use of activated carbon in water treatment to remove contaminants and pollutants has increased dramatically [89]. It is stated that water purification and filtration consume around 80% of activated carbon worldwide [90]. Activated carbon is widely adopted in the water treatment field due to its unique physical and chemical characteristics. Activated carbon is used mainly as highly efficient adsorbents for several types of contaminants. The high adsorption capacity of activated carbon is directly related to its high surface area and porous structure [91]. Moreover, the surface of activated carbon contains several types of functional groups that interact efficiently with contamination particles in water.

The recent approaches of utilizing activated carbon in water treatments revolve around enhancing the adsorption performance via nanoparticles [92, 93]. Basically, activated carbons are loaded with nanoparticles to produce nanocomposites with high adsorption capacity and high chemical and mechanical stability. Popularly adapted nanoparticles include iron nanoparticles [94], tungsten oxide nanoparticles [95], silver nanoparticles [96], and zero-valent iron nanoparticles [97]. Typically, activated carbon modified with nanoparticles is used to remove metal ions and dyes from contaminated water. However, removing these types of contaminants relies on other factors such as the solution temperature and pH level. Indeed, pH level is considered as a key factor. pH level control both the anionic and cationic nature of the surfaces and the surface charge density. Therefore, a high pH level solution will attract cations, whereas a low pH level will attract anions. In general, the pH level is considered during the synthesis of modified activated carbon. Acidic carbons are preferred to catch cations, while basic carbons are used to remove anions from polluted water [90].

7.5.1 Elimination of Metallic Contaminants

Metallic contaminants exist in a high percentage of wastewater. Typically, metallic contaminants present as heavy metals and/or metalloids. Generally, metallic contaminants are extremely dangerous to human health. Moreover, metallic contaminants are subject to biomagnification in plants and animals. Above all, they are non-degradable materials that make the water purification and treatment process difficult and costly. Consuming food or water contaminated with metallic pollutants for the short term may cause several diseases such as diarrhea, fever, and damage to the liver and kidney. However, long-term exposure to metallic contamination via water or food can cause liver cancer, skin cancer and may lead to death. The impact of heavy metals on human health is associated with the long-term accumulation of these materials in the human body [98]. In general, metallic contaminants are introduced to the environment from different agricultural and industrial sources. These sources include activities such as mining, the metal industry, usage of pesticides and fertilizers, and semiconductors manufacturing [99].

In the last decade, removal processes of metallic contaminants from water have developed significantly. New technologies are explicitly designed to eliminate heavy metals and loids from water. However, most of the developed technologies are expensive and have low efficiency compared to activated carbon. Thus, several studies reported the use and development of activated carbon for metallic pollutant removal. Activated carbon is considered a low-cost and highly efficient solution for water contamination [98]. Activated carbon is used to remove metals such as lead (Pb(II)), cadmium (Cd(II)), copper (Cu(II)), chromium (Cr(II)), iron (Fe), and arsenic (As) [100]. Indeed, the elimination process of metallic contaminants from the water via activated carbon is considered a simple process due to the size of metallic contaminants and the properties of activated carbon. Usually, metallic contaminants present in the water as small charged particles. Hence, the interaction between the activated carbon and the metal ions occurs directly (electrostatic interaction) [101]. Similar to other types of contaminants, the adsorption process of metallic pollutants is affected by the pH level of the solution. Moreover, there are other factors that influence the adsorption behavior, such as the structure and size of metal ions, the surface area and porosity of activated carbon, and the functional groups present on the surface of activated carbon [84].

As mentioned before, the type of biomass used to produce activated carbon greatly influences the adsorption of metallic pollutants. Min et al. has conducted a study on the removal of Cd(II) from contaminated water using oil palm shell-activated carbon [57]. Their study revealed that oil palm shell-activated carbon has 99.5% removal efficiency for Cd(II). A similar study is conducted by Ahmed, where he used chemically activated date seeds activated carbon to remove Cd(II) ions from water [58]. His results exhibited a great tendency of date seed activated carbon to adsorb cadmium ions. The reported adsorption capacities were in the range of 118.1–127 $\mathrm{mg{\cdot}g^{-1}}$. Sajjadi et al. have published a study on the removal of mercury (Hg) from polluted water using chemically activated pistachio wood wastes activated carbon

[77]. The study used ammonium nitrate (NH_4NO_3) as an activation agent for the carbon. The produced activated carbon has a high surface area of about 1,448 $m^2 \cdot g^{-1}$. The maximum adsorption capacity was 201.095 $mg \cdot g^{-1}$.

Heavy metals are highly toxic metallic elements that have a higher density than other common metals. Indeed, heavy metals exist naturally in many areas and contaminate soil, air, and water. The danger of heavy metals is related to their toxicity, wide distribution, and extensive usage in industrial applications. There are several types of heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), nickel (Ni), mercury (Hg), chromium (Cr), selenium (Se), and cobalt (Co). These heavy metals contaminate the environmental resources at different levels. Generally, the dramatic increase in the concentration of heavy metals is associated with anthropogenic activities such as semiconductor manufacturing, mining, combustion of fossil fuel, and material fabrication.

Heavy metals can be found in natural water resources such as lakes, rivers, and groundwater. In fact, heavy metals such as arsenic can be found at high concentrations in groundwater as it leaks from surrounding soils and rocks. Such a high concentration of heavy metal above the standard level poses health risks. Moreover, in urban areas, the concentration of heavy metals increases in surface water resources, especially rivers. In general, urban areas discharge highly toxic wastes into rivers and coastal regions. The discharged wastes contain several contaminants such as heavy metals, polyaromatic hydrocarbons (PAHs), and polyfluoroalkyl substances (PFAS).

Primarily, heavy metals are removed from water using different types of adsorbents. Nonetheless, other methods such as membrane filtration and reverse osmosis are used to remove certain types of heavy metals. Generally, removing heavy metals from contaminated water using adsorbents is the most preferred treatment approach. Among the different types of adsorbents, activated carbon has exhibited an outstanding performance in removing highly toxic heavy metals such as arsenic, lead, and mercury. Activated carbon has special physical and chemical properties that make it suitable for wastewater treatment. Briefly, activated carbon is inexpensive, environmentally friendly, easy to regenerate, and has high adsorption capacity. Typically, activated carbon is used to eliminate arsenic and lead from water and wastewater. Arsenic and lead are used intensively in manufacturing and can spread quickly in the environment.

7.5.2 Elimination of Non-Metallic Contaminants

The threat of non-metallic contaminants on human health has been observed in the last few years. Similar to metal ions, anions as non-metallic contaminants are considered essential elements to human bodies. Nonetheless, excessive consumption of non-metallic pollutants can cause diseases and lead to death. Molybdate, phosphate, and fluoride are the most popular types of anions consumed by humans. These anions are detrimental not only to humans but also to other living species. Globally, millions of people have consumed excessive fluorosis and suffered from fluorosis

[102]. Typically, people consume fluoride through contaminated water, especially in developing countries. Indeed, fluoride is used in some water treatment plants as part of the process in controllable percentages. However, in some developing countries, fluorides are used in excessive amount due to the lack of monitoring and regulations. Viswanathan et al. have published a study on the impact of fluoride ions on human health [103]. In the study, they measured the level of fluoride ions in drinking water. The level of fluoride ion was 3.24 ppm, and children are the most affected with fluorosis. Like fluorides, molybdate ions can accumulate in humans and animals and cause severe diseases [104]. Anions can be removed easily via activated carbon. The removal of anions is influenced by the type of activated carbons and the pH value of the solution.

7.5.3 Elimination of Various Dyes from Water

In the last decades, the rapid development in the industrial sectors caused severe damage to the environment via introducing new types of complex contaminants. Dyes are one of the most extensively used materials in several industries such as textiles, papers, cosmetics, and paint production. Indeed, the textile industry is considered the major source of water contamination in several areas [105]. It is estimated that there are around 3,600 types of dyes in the industries, where 2–20% are typically discharged directly into the environment [106, 107]. Dyes discharged into the natural water resources are highly toxic and deadly. Regarding the environmental effects, the presence of dyes can reduce the photosynthesis process of the aquatic flora and fauna [89].

Several studies have proposed activated carbon as a great solution to remove different types of dyes from water. The adsorption of dyes is directly influenced by the types and properties of activated carbon, such as the porosity and high surface area, the functional groups. Besides that, the solubility and molecular size of dyes and the pH level of the aquatic medium affect the adsorption behavior [108]. Katheresan et al. stated that pretreating and activating carbon via steam could produce activated carbon with a high tendency to adsorb dye [109]. Further studies have revealed the great performance of activated carbon prepared from Acacia Mangium and Acacia Nilotica in removing different types of dyes such as Methyl orange (90.5%) and Methylene blue (250 $mg \cdot g^{-1}$) [66, 110].

Methylene Blue (MB) is considered the most popular among the different types of dyes. In fact, MB present in wastewater at high percentages. Wang et al. have published a study on the removal of MB using activated carbon [111]. The study used potassium hydroxide (KOH) as an activation agent. The analytical data showed that activated carbon has a surface area of 1,430 $m^2 \cdot g^{-1}$. Moreover, the obtained adsorption capacity was 934.579 $mg \cdot g^{-1}$ at pH 5.8. Further study has been published by Ahmed on the removal of MB via rice straw and Ramulus mori-based activated carbon [112]. The study involved the use of diammonium phosphate ($N_2H_9PO_4$) as an activation agent. The adsorption capacities of both rice straw-based and Ramulus mori-based activated carbon was 129.5 and 1,061 $mg \cdot g^{-1}$, respectively.

7.5.4 Elimination of Phenolic Compounds

Phenolic compounds are highly toxic chemicals that can affect the ecosystem for decades. Usually, phenolic compounds are discharged into the environmental system through chemicals and petrochemical industries [113]. The impact of phenolic compounds is monitored by the environmental protection agencies. Phenolic compounds are carcinogenic and can destroy the aquatic ecosystem [114]. Different standards are made to limit the amount of phenolic compounds in water bodies [115]. For instance, the Environmental Protection Agency (EPA) has limited the amount of phenolic pollutants to 0.1 $mg \cdot L^{-1}$ at maximum. However, the World health organization (WHO) has made the acceptable standard lower to 0.001 $mg \cdot L^{-1}$ for drinkable water [115]. Activated carbon has shown an outstanding performance in removing phenolic compounds from contaminated water. The removal of phenol via activated carbon relies mainly on surface functionality. Therefore, the presence of functional groups such as carboxyl and hydroxyl on the activated carbon surface will increase the adsorption of the phenolic compounds. The interaction between the activated carbon and phenol is directed by pi-pi bond [116]. Besides the surface functionality, the pH level of the solution has a significant impact on the removal of phenolic compounds from water. Indeed, the adsorption performance decrease for both high and low pH values [117].

7.5.5 Elimination of Pesticides

Recently, pesticides are used intensively in agricultural fields to eliminate pests and several plant diseases. However, the intensive use of pesticides has formed global environmental threats. Pesticides can leak from the agricultural fields to the surrounding water resources. As a result, the contamination level of the natural water resources increases and destroys the ecosystem. The most commonly used pesticides include. 2,4-dichlorophenoxyacetic acid, carbofuran, and bentazon. Generally, the environmental protection agencies have set a permissible concentration of these pesticides to 0.1, 0.05, and 0.09 $mg \cdot L^{-1}$ for 2,4-dichlorophenoxyacetic acid, bentazon, and carbofuran, respectively [118]. Typically, pesticides are removed from water via highly efficient activated carbon. The removal process relies on the presence of organic matter and the flow rate in the adsorption [108].

7.5.6 Elimination of Pharmaceutical Contaminants

Recently, pharmaceutical contaminants have been introduced in the ecosystem due to the increase in the usage of medical products. Pharmaceutical contaminates involve the waste and the byproducts of pharmaceutical products discharged into the environment. The pharmaceutical compounds are difficult to remove due to their high stability and hydrophilicity. Thus, they can present in water bodies for a long time. Although the concentration of pharmaceutical contaminants is considered low, the longtime exposure to contaminated water via drinking can cause severe diseases [119–121]. Activated carbon is used as an adsorbent for different types of pharmaceutical compounds [119]. Indeed, the adsorption of pharmaceutical compounds via activated carbon relies on operational conditions, type of precursor, activation method, and the properties of a pharmaceutical compound. The operational conditions involve the pH level of the solution, temperature, organic structure, adsorbent (activated carbon) dose, and ionic capability [122].

7.6 Conclusions

In summary, the production of value-added products using proper biomass feedstock requires more studies and experiments to enhance the overall technology. There is a crucial need for more experiments on the consistency of pyrolysis reactions to be used in large-scale applications and become more sustainable. Moreover, the relation between the general operation of the pyrolysis plant and the applied feedstock or precursors must be more evident. Nevertheless, the fundamentals of pyrolysis technology have been covered elaborately in this chapter to specify the influential factors on the process performance. This includes different factors to design the process and obtain a preferred product, such as an activated carbon with high adsorption performance for wastewater. The major influential factors involve the selection of conditional parameters for the pyrolysis process, types of reactors, and the type of lignocellulosic biomass.

The suggestions for future studies on the thermochemical convention of biomass include the improvement of the biochar separation process to enhance the quality of biofuels and activated carbon production. Moreover, the type of selected biomass is considered a vital factor in the process. Lignocellulosic biomass with a high portion of cellulose is preferred to obtain a maximum bio-oil yield. On the other hand, lignin-based biomass can be used to obtain biochar. Apart from activated carbon production, there are few studies on the enhancement of gas production from biomass precursors. Hence, there is a crucial need for sophisticated studies on the development of gaseous products via metal catalysts. Several methods can be utilized for the kinetics of the pyrolysis of biomass. Initially, to obtain char and gas, lower activation energy is used by applying a low temperature. On the other hand, applying higher temperature results in higher activation energy and produces condensable fumes, liquid aerosols, and oils. However, heating biomass quickly at a proper high temperature will lead to obtaining a high percentage of liquid fuels. For fast biomass heating, it is preferable to use smaller particle sizes of precursors to initiate constant particle heating. The pyrolysis processes require more development from the environmental and economic aspects. As a result, the cost of biomass products will become competitive with conventional products. In addition, maximizing the activated carbon production is also related to the quality of pyrolysis reactors. Attention must be drawn towards the pyrolysis efficiency, physicochemical properties of the biochar, carbon and slag deposition, and emission of microparticles during the pyrolysis process. Presently, activated carbon exhibited a great performance in treating wastewater at an industrial scale as an alternative to metal oxides and membrane polymers. However, the need for development in activated carbon production is continuous as novel contaminants become more challenging to remove from wastewater.

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