Chapter

Recent Perspectives in Biochar Production, Characterization and Applications

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Abstract

This chapter presents the most promising features and applications of biochar along with their optimal pyrolysis conditions. Biochars have a range of physico-chemical properties depending on the feedstock and pyrolysis conditions, which greatly affect their wide applications. The biochar production and its characteristics, including the effect of feedstocks and different process-parameters on the properties and yield of biochar are thoroughly examined. The higher pyrolysis-temperature can give higher carbon-contents, pH, and surface-areas of biochars while volatiles and molar-ratios of O/C, H/C and N/C decrease with pyrolysis-temperature. Higher carbon-content and neutral-pH biochars have high affinity for organic pollutants due to high surface areas, making them attractive for adsorption and catalysis purposes. Biochars with higher-pH are preferred for soil application to correct soil-acidity. Thus, the pyrolysis temperature should be selected as per the final application of the biochar. Characterization of biochars of different feedstocks and pyrolysis conditions is reviewed and presented along with their proximate and ultimate analysis.

Keywords: biochar, pyrolysis, biomass, characterization, proximate analysis, ultimate analysis

1. Introduction

Biochar is a porous carbonaceous solid material produced by the thermal decomposition of biomass from plant or animal waste under oxygen-free or limited oxygen conditions [1–3]. The International Biochar Initiative [4] defines biochar as "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment". Biochars have a wide range of physicochemical properties [5], which greatly affect their potential applications in various agronomic and industrial sectors. The feedstock and the method of biochar production have a significant impact on the biochar characteristics, such as concentrations of elemental constituents, density, porosity, and pH, which collectively impact the suitability of the biochar for various applications [3]. Biochar is used to upgrade the soil quality [6, 7] in agricultural areas. It slows down the rate of decomposition and release of nutrients from the soil and hence, enhances the soil quality. In various industries, biochar is used in waste treatment [8–10] to remove organic contaminants and heavy metals. Biochar can be used as a fuel in power generation because it contains a high carbon percentage in it.

Biomass is a very potential source of renewable energy [11] materials and chemicals [12, 13]. Agricultural residues, algal biomass, forest residues, manures, activated sludge, energy crops, digestate, etc. are the main sources of biomass [14] to be used as a raw material. Biomass can be converted into high-value products using various physical, thermochemical and biochemical processes. Thermochemical conversion processes, such as pyrolysis, gasification, torrefaction, and hydrothermal carbonization of carbonaceous biomass are used for biochar is production, at high temperatures ranging from 300–900°C and under O_2-free conditions [15]. The physicochemical and mechanical properties of biochars depend on the pyrolysis operating conditions and feedstock used [16]. The selection of a suitable kind of feedstock is usually determined by the availability of that material in areas where the biochar is likely to be produced, as this reduces the cost of transport while decreasing the carbon footprint of the biochar technology. Biochar production from the biomass depends upon the thermochemical process used and process parameters considered. The literature on the biomass pyrolysis revealed that the production of the biochar depends upon several factors such as type of biomass, moisture content, and particle size, reaction conditions (reaction temperature, reaction time, heating rate) and surrounding environment (carrier gas type, flow-rate of carrier gas) and other factors (catalyst, reactor type) [3, 6, 8, 11, 16].

The main objective of this chapter is to show the potential use of waste biomass for the production of biochar which is an important material with numerous industrial and environmental applications. The biochar characterization is presented to understand the physical and chemical properties of biochar, including variations of the biochar properties as a function of production conditions and feedstocks, and to evaluate the applicability of biochar in desired fields. This chapter exhaustively describes the possible feedstocks for biochar production, biochar production processes particulary slow pyrolysis process, and pyrolysis process conditions, the properties of biochar such as biochar characterization, proximate and ultimate analysis of biochars. Some important industrial and environmental biochar applications are discussed and finally conclusion is presented.

2. Raw materials for biochar production

The main sources of raw material for biochar production include: municipal waste, agricultural and forest residues, energy crops, and animal waste, which are grouped as lignocellulosic and non-lignocellulosic biomasses. Lignocellulosic biomass [17–19] are abundant fibrous plant parts, non-food ‘second generation’ feedstock, including agro-industrial residues, forest-industrial residues, energy crops, municipal solid waste, etc. Chemically, biomass is a complex composition of carbon, hydrogen, oxygen, sulfur, nitrogen, and small quantities of few other elements which include alkali metals, alkaline earth metals, and heavy metals, depending upon the species or type of biomass. The proportion of these elements in the biomass is a function of species of biomass, growing condition, and geographical situation of the region [20]. Lignocellulosic biomass is mainly composed of cellulose (38–50%), hemicelluloses (23–32%), lignin (15–25%) and small amounts of extractives [3, 16, 21, 22]. Among these components, cellulose and hemicelluloses are linear and chain polysaccharides respectively, while lignin is a cross-linked phenolic polymer. Biomass with varying contents of hemicellulose, cellulose, and lignin may yield biochars with distinctive physicochemical properties. The abundant biomass reserves and its renewability have been the main driving forces for research and utilization of biomass. Thus, such agricultural and animal waste disposal can be reduced and converted into value-added products such as biochars using pyrolysis processes. A review by Li and Jiang presented on non-lignocellulosic biomass characteristics, thermochemical behaviors of main components (e.g., C, O, N, P, and metals), characterization methods, conversion process, and the main applications of non-lignocellulosic biochar [23]. Song and Guo studied the quality variations of poultry litter biochar generated at different pyrolysis temperatures [24]. Unlike lignocellulosic biomass, the non-lignocellulosic biomass has a greater threat to the ecological environment because of its higher contents of heavy metals and *heteroatom* like nitrogen, phosphorus, sulfur [25], which may dissolve in a water systems, leading to water pollution and accumulation in the food chains [26].

Poultry litter (PL), a solid waste resulting from chicken rearing, is being explored as a feedstock for biochar production and examined the effect of pyrolysis temperature on the quality PL biochar and identify the optimal pyrolysis temperature for converting PL to agricultural-use biochar [24]. Physically, PL is a mixture of bedding materials (e.g., wood shavings, sawdust, and peanut hull), bird excreta, feather, feed spills, and chemical treatments like alum and sodium bisulphate. Through pyrolysis, PL can be readily transformed into biochar [24].

3. Biochar production processes

Biomass-derived biochar production is formed via a complex process, but the reaction mechanism of biomass pyrolysis can be described as occurring mainly through three general steps, as depicted in Eq. (1):

$$\begin{aligned} \text{Biomass} &\overset{heat}{\rightarrow} \text{Moisture} + \text{Dryresidues} \\ \text{Dryresidues} &\overset{heat}{\rightarrow} \text{Volatile\&Gases} + \text{Pre} - \text{biochar} \\ \text{Pre} - \text{biochar} &\overset{heat}{\rightarrow} \text{Volatile\&Gases} + \text{Biochar} \end{aligned} \tag{1}$$

The first step is the removal of available moisture from the biomass, which becomes dry feedstock by heating. Then pre-biochar and volatile compounds are formed. In the last step, chemical compounds in the pre-biochar rearrange and form a carbon-rich solid product known as biochar. Major thermochemical technologies for biochar production include pyrolysis, gasification, torrefaction, and hydrothermal carbonization. Pyrolysis is one of the thermochemical technologies for converting biomass into energy and chemical products consisting of liquid bio-oil, solid biochar, and pyrolytic gas [3, 11, 20, 27–29]. Depending on the heating rate, pyrolysis temperature, and residence time, biomass pyrolysis can be divided into slow, intermediate, fast and flash pyrolysis mainly aiming at maximizing either the bio-oil or biochar yields. Operating conditions of various pyrolysis processes and product distribution (biochar, bio-oil, and gas). Thus, biochar yield greatly depends on the type of pyrolysis used. Slow pyrolysis conducted at longer residence time and at a moderate temperature (350–550°C) in the absence of O_2 results in a higher yield of biochar (∼30%) than the fast pyrolysis (∼12%) or gasification (∼10%) [3, 11, 27, 28]. Pyrolysis requires relatively dry feedstock (usually moisture content < 30 wt %, but moisture contents of ≤ 10 wt % are preferred), and grinded to different particle sizes based on the type of pyrolysis. Feedstock with high moisture content consumes more energy accounting for increasing heat of vaporization during the heating of biomass towards the pyrolysis temperature. Additionally, the gases and vapors produced in pyrolysis using a high moisture feedstock are diluted with steam

Ref.		Pyrolysis Temp. [C]	Pyrolysis Time	Characteristics			Proximate analysis (%)			Ultimate analysis (%)									Molar ratio			
			min	pH	BET $\frac{m^2}{g}$	Moisture (%)	Volatiles	Fixed carbon	Ash	C	H	O	S	N	Ca	Mg	K	Na	$\frac{H}{C}$	$\frac{O}{C}$	$\frac{(O+N)}{C}$	$\frac{(O+N+S)}{C}$
[1]	Date	RM		5.90	0.98	6.20	69.90	20.90	2.90	45.40	5.60	40.40	5.50	0.00					1.47	0.67	0.67	0.71
		400	11 hr	9.50	1.99	4.80	43.20	45.00	7.10	60.90	2.50	25.60	2.20	1.20					0.49	0.32	0.33	0.35
	Rhode	RM		6.10	1.97	7.80	66.50	11.00	14.70	2.50	5.50	28.70	5.30	1.90					1.54	0.51	0.55	0.59
	grass	400	11 hr	9.70	16.78	1.80	11.80	56.60	28.80	56.70	2.20	8.20	1.60	1.90					0.46	0.11	0.14	0.15
[31]	Date palm waste	RM				7.60	70.59	22.30	7.11	43.19	5.83	39.00	4.16	0.70	2.53	0.68	1.32	0.28	1.61	0.68	0.69	0.73
		300	240			3.29	40.08	45.49	14.42	57.99	4.08	20.82	2.14	0.54	4.85	1.53	2.18	0.40	0.84	0.27	0.28	0.29
		400				3.13	20.25	63.41	16.34	66.87	3.54	11.44	1.36	0.45	6.04	1.57	2.17	0.42	0.63	0.13	0.13	0.14
		500				2.96	9.31	71.00	19.68	72.30	2.11	4.50	1.02	0.42	5.81	1.93	2.23	0.48	0.35	0.05	0.05	0.06
		600				2.25	6.85	72.44	20.71	72.89	1.74	3.28	0.98	0.39	7.77	1.90	2.38	0.53	0.28	0.03	0.04	0.04
		700				2.12	5.47	73.49	21.05	73.42	1.14	3.19	0.85	0.35	7.65	1.92	2.69	0.50	0.19	0.03	0.04	0.04
		800				2.09	3.91	74.70	21.39	74.63	0.86	2.27	0.54	0.31	8.08	2.02	2.71	0.58	0.14	0.02	0.03	0.03
[32]	Bagasse	500		9.30	202.00	1.30	9.17	80.97	8.57	85.59	2.82	10.48		1.11	0.16	0.04	0.26	0.03				
	Cocopeat	500		10.20	13.70	2.55	14.30	67.25	15.90	84.44	2.88	11.67		1.02	0.27	0.06	2.30	1.37				
	Wood stem	500		9.50	316.00	1.46	12.79	83.47	2.28	89.31	2.57	7.34		0.78	0.17	0.02	0.20	0.01				
	Wood bark	500		9.60	13.60	0.36	18.14	68.66	12.84	84.84	3.13	10.20		1.83	1.97	0.11	0.65	0.00				
[33]	rice husk	RM		6.40		8.50	63.78	14.73	12.99	31.39	3.39	43.40		0.35								
		300	60	5.30		1.52	45.49	30.80	22.19	47.15	4.52	23.98		0.65								
		400	90	7.70		3.92	16.54	48.60	30.94	54.33	2.06	8.11		0.64								

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Ref.		Pyrolysis Temp. [C]	Pyrolysis Time	Characteristics			Proximate analysis (%)			Ultimate analysis (%)					Molar ratio
		500	120	8.30		2.16	7.44	60.10	30.30	57.35	1.48	8.08		0.63	
		300	120	4.20		4.18	46.67	31.87	17.29	46.16	4.51	27.19		0.68	
		400	60	5.70		3.24	22.18	45.89	28.70	52.13	2.67	12.64		0.63	
		500	90	7.40		2.35	12.38	53.81	31.46	58.41	1.75	5.27		0.77	
		300	90	4.10		3.59	43.10	30.64	22.67	46.14	3.83	23.33		0.44	
		400	120	7.20		2.52	16.97	49.49	31.02	54.56	2.25	9.16		0.50	
		500	60	8.80		1.61	8.58	57.43	32.38	56.28	1.36	7.74		0.63	
[27]	Geodae Uksae 1	300			0.49			53.34		66.19					
		400			3.11			73.89		74.69					
		450			21.93			78.48		78.29					
		500			180.96			82.59		79.42					
		600			293.04			88.07		83.67					
		700			368.98			91.66		85.93					
[34]	Rice straw	300		9.00	4.50		34.54	28.06	37.40	68.72	5.22	22.78		3.28	
		400		10.10	21.20		18.75	35.39	45.86	75.47	4.62	16.93		2.98	
		500		10.50	45.80		10.61	38.72	50.67	81.43	2.34	15.13		1.10	
		600		10.60	84.80		6.89	39.87	53.24	87.52	2.11	7.48		2.89	
		700		10.60	22.50		5.88	39.52	54.60	91.15	1.26	7.01		0.58	
[35]	Bamboo biomass	RM				9.37	70.31	17.75	2.57	39.00	6.10	54.00	0.02	0.60	
		500	60			6.50	8.10	81.50	3.90	82.10	2.72	14.60	0.00	0.54	

Ref.		Pyrolysis Temp. [C]	Pyrolysis Time	Characteristics			Proximate analysis (%)			Ultimate analysis (%)					Molar ratio	
[28]	beech wood feedstock	RM							0.19	48.45	6.12	45.08	0.02	0.15		
		470								79.58	3.60	16.57		0.25		
		520								85.04	3.81	10.79		0.37		
		570								91.45	3.05	16.82		0.11		
[17]	Pea pod									39.32	4.75	53.3		2.4		
	Cauliflower leaves									31.8	3.2	59.4		4.01		
	Orange peel									40.43	4.83	52.9		1.56		
[36]	LWB[1]	RM				7.41	83.82	12.48	8.25	49.31	5.61	39.88	0.62	0.56		
		800				0.40	13.00	73.36	13.64	75.80	2.43	7.15	0.30	0.68		
[37]	hinoki cypress	RM					84.75	15.09	0.16	51.88	6.21	41.76		0.16		
		350		7.95			41.17	58.52	0.32	75.74	5.29	18.75		0.22		
		400		8.24			33.45	66.10	0.45	77.85	4.90	17.06		0.20		
		500		8.48			21.26	78.06	0.69	85.79	3.89	10.10		0.23		
		600		9.66			12.45	86.73	0.83	91.56	2.96	5.11		0.38		
[38]	chichi manure	350		9.70			336.90	11.10	52.00	31.20	1.97	10.90	0.31		0.76	0.26
		450		10.20			30.60	14.10	53.30	27.20	1.92	11.40	0.44		0.85	0.31
		750		11.70			26.50	17.00	56.40	24.70	0.67	16.30	0.29		0.32	0.49
[39]	corrugated cardboard	RM			1.50			13.10	4.00	43.24	5.80			0.12		
		350			1.20			17.20	5.00	46.84	5.70			0.11		
		400			1.60			27.80	5.20	51.33	4.80			0.16		
		450			1.60			41.80	12.30	54.17	3.70			0.18		

Ref.		Pyrolysis Temp. [C]	Pyrolysis Time	Characteristics		Proximate analysis (%)			Ultimate analysis (%)		Molar ratio
[40]	wood	300	10	4.50		78.00	22.00	0.30	54.10	5.90	1.30
			60	5.70	6.0	42.60	57.40	0.50	71.30	4.70	0.79
		450	10	6.60	4.0	21.40	78.60	1.00	82.50	3.80	0.56
			60	6.70	23.0	16.80	83.20	1.20	86.30	3.50	0.49
		600	10	6.70	196.0	8.20	91.80	1.20	90.00	2.60	0.35
			60	9.10	127.0	6.40	93.60	1.30	92.30	2.30	0.30
		750	10	10.20	128.0	2.60	97.40	1.10	92.50	1.40	0.19
			60	10.40		2.60	97.40	1.10	92.50	1.10	0.15
	green waste	300	10	7.4		74.3	25.7	3.6	53.2	6.2	1.41
			60	8.1		48.6	51.4	6.8	69.3	5.4	0.94
		450	10	9.6		25.3	74.7	11.1	78.8	4.2	0.63
			60	10.0	17.0	18.5	81.5	12.0	82.9	3.5	0.51
		600	10	10.4		11.5	88.5	13.2	87.7	2.3	0.32
			60	11.3	46.0	8.8	91.2	13.4	88.4	2.0	0.27
		750	10	11.4		3.5	96.5	13.9	87.5	1.5	0.21
			60	11.6		1.9	98.1	13.4	93.2	1.3	0.16
	dry algae	300	10	4.9		70.0	30.0	46.3	62.7	7.2	1.38
			60	7.7		55.2	44.8	55.8	69.5	6.9	1.19
		450	10	9.1		27.5	72.5	68.6	74.5	4.5	0.72
			60	9.3	14.0	19.1	80.9	71.8	78.7	4.0	0.61
		600	10	11.1		18.9	81.1	72.2	80.1	2.7	0.41
			60	11.9	19.0	15.7	84.3	73.0	83.4	2.0	0.29

Ref.	Pyrolysis Temp. [C]	Pyrolysis Time	Characteristics	Proximate analysis (%)			Ultimate analysis (%)		Molar ratio
	750	10	12.4	10.1	89.9	74.8	86.4	1.5	0.21
		60	12.5	3.9	96.1	76.4	90.6	1.4	0.19

[1]*lignocellulosic waste biomass*
RM*: raw materal and* ***BET****: Brunauer–Emmett–Teller, surface area analysis.*

Table 1.
Characterization of raw biomass samples and biochar produced: Values for proximate and ultimate analysis.

and have a lower calorific value. Wet biomass, typically with 70 wt% or more water can be converted using hydrothermal carbonization processes. The common processes [11, 27, 28] include slow and fast pyrolysis, and the most successful approach for high-yield biochar production is via slow pyrolysis [3].

Slow pyrolysis is a conventional type of pyrolysis which is operated at moderate temperatures ranging from 300–550°C, slow heating rates of $0.1\frac{°C}{s}$ up to $0.8\frac{°C}{s}$, and longer residence time of 5 to 30 min or even 25 to 35 h [3, 30] conducted at atmospheric pressure. Slow pyrolysis is commonly used to produce biochar, with bio-oil and syngas as co-products. The typical yields of biochar, bio-oil, and syngas are 35%, 30%, and 35% of the dry biomass feedstock, respectively [3, 24] by slow pyrolysis. The main purpose conducting of slow pyrolysis is to maximize the biochar yield. The longer vapor residence times in slow pyrolsis favors the secondary reactions. Biochar produced in slow pyrolysis consists of both primary and secondary chars. The slow heating rate with moderate pyrolysis temperatures also promotes the production of biochar. Biochar yield usually depends on the raw material type & properties, and pyrolysis conditions such as processing temperature, heating rate, and pyrolysis environment [30]. The final biochar yields are decreased by increasing the process temperature because more volatiles are produced from tars at higher temperatures, leading to the production of more gases and bio-oils. Biomass containing more minerals yields less biochar [3]. The overall slow pyrolysis process can generally be exothermic due to the extensive occurrence of secondary reactions. Slow pyrolysis can accept a wide range of particle sizes (5–50 mm).

Pyrolysis of biomass also produces syngas and bio-oil as co-products together with biochar. The fraction of each that is produced depends on the pyrolysis process, but slow heating rates are recommended when biochar is the main product desired. Furthermore, pyrolysis temperatures above 250°C are recommended for the conversion of lignocellulosic biomass because decomposition of hemicellulose and cellulose begins at 250°C and is maximal at around 400°C, whereas changes in lignin structure only start to occur after heating for long durations or higher temperature pyrolysis reactors. The pyrolysis conditions used for biochar productions are related to the type of biomass and biochar quality required. Variation of these reaction parameters finally results in a variety of physicochemical properties of the biochars and affects their final application types and performances. Thus several studies have been conducted to determine the suitable raw material and optimal pyrolysis condition. The challenge is to be able to predict the quality and performance of biochars produced from given biomass and a given pyrolysis process via analysis of its physicochemical properties. Thus, to produce the right type of biochar for specific applications from certain lignocellulosic biomass, elemental composition of different biomass resources and produced biochars need to be measured. A summary of proximate analysis and ultimate analysis along with elemental composition of different raw materials for biochar production are shown in **Table 1**. Conversion of raw biomass to biochars resulted in higher contents of fixed carbon and ash, and lower contents of moisture and volatiles. Fixed Carbon (FC) of biochar was calculated as the sum of moisture, ash, and volatile matter subtracted from 100, $(FC(\%) = 100 - moisture(\%) - ash(\%) - VM(\%))$ [41].

4. Biochar quality

The quality of biochar varies with feedstock used and production conditions. Some of the commonly measured quality parameters of biochar include pH, volatile compound content, ash content, bulk density, organic carbon content, nutrient content, elemental composition, surface area, porosity, surface functional groups, cation exchange capacity, iodine number, C stability, water holding capacity (WHC), moisture content, heavy metals, electrical conductivity, polycyclic aromatic hydrocarbons (PAH) and sorption properties. The European Biochar Certificate [42] defines biochar as a "heterogeneous substance rich in aromatic carbon and minerals. It is produced by pyrolysis of sustainably-obtained biomass under controlled conditions with clean technology and is used for any purpose that does not involve its rapid mineralisation to carbon dioxide and may eventually become a soil amendment." This definition differentiates biochar from other forms of carbonaceous materials such as char and charcoal considering the sources of biomass for the production of biochar need to be renewable and sustainable [3]. The International Biochar Initiative (IBI) [4] considers several parameters relevant for assessing and comparing different biochars. These include proximate analysis, elemental composition analysis, pH, porosity, and BET surface area. In this study, proximate analysis and ultimate analysis of biochars produced from different feedstock under different pyrolysis reaction conditions are presented along with other biochar characteristics and component molar ratios of its constituent elements.

The major constituent components of lignocellulosic biomass [43], cellulose, hemicellulose, and lignin play important roles for most of the physical and chemical property modifications during the pyrolysis process. The mechanisms of pyrolysis of these polymers are chemically different from biomass species to species due to the differences in their compositions. The thermal decompositions of cellulose and hemicellulose polymers occur over a narrower temperature range whereas lignin degrades over a wider temperature range compared to those of cellulose and hemicellulose. The lignocellulosic biomass may contain some minor components other than the aforementioned polymers including some inorganic compounds and organic extractives together with substantial quantities of free and bound water [3, 31, 37, 44]. The inorganic compounds of lignocellulosic biomass which constitute less than 10% by weight of biomass, form ash in the pyrolysis process. The organic extractives of biomass refer to the nonstructural components that can be extracted by polar or nonpolar solvents including fats, waxes, proteins, terpenes, simple sugars, gums, resins, starches, alkaloids, phenolics, pectins, glycosides, mucilages, saponins, and essential oils [23, 31, 37, 44].

The biochar properties that could affect its final application will depend on the type of feedstock material characteristics and pyrolysis reaction conditions used for its production [3]. Pyrolysis temperature is the main process parameter that determines the degree of devolatilisation of the biomass. Water content of the biomass, both free and bound, is the first constituent removed in heating of biomass to temperatures up to 160°C. Thermal decomposition of biomass begins with devolatilisation or decomposition of extractives at temperatures about $\leq$220°C. Hemicellulose is the least stable polymer and break down first at temperatures of 220–315°C. Cellulose has a high degree of polymerization and exhibits higher thermal stability and it decomposes in the temperature range 315–400°C. Lignin is the most difficult component to pyrolyse which decomposes in a wide temperature range from 160–900°C [45].

Biochar characterization methods are always independent of production feedstocks, methods, conditions, and properties of the final product [27]. Several chemical characterizations of biochar ranging from biochar surface analysis to elemental composition and physical properties such as the surface area, pore size, and pore volume are commonly analyzed. The quality of biochar varies with the feedstock type and pyrolysis process conditions. Pyrolysis parameters such as heating rate, residence time, and final temperature greatly influence biochar quality [11]. Pyrolysis temperature has a critical role in biochar properties such as elemental composition, particle size, specific surface area, pore size distribution, thermal capacity, and electrical conductivity.

Certain biochar quality parameters are more important than others depending on the expected final use or application of the biochar. For agricultural application in crop production, the important quality parameters of biochar include pH, volatile compound content, ash content, water holding capacity, bulk density, pore volume, and specific surface area [24]. Carbon stability of biochar is a critical quality parameter in carbon sequestration and soil fertility enhancement. The other important quality parameters in soil fertility enhancement include surface area and nutrient content. The molar ratio of hydrogen to carbon (H/C) is another important characterization parameter of biochar which is an indicator of the degree of carbonization and the stability of biochar. The higher values of molar H/C ratio greater than 0.7 indicate the lower biochar quality and pyrolysis deficiencies. Molar oxygen to carbon (O/C) ratio is also relevant for characterizing biochar and differentiating it from other carbonization products [42] with values greater than 0.4 indicating lower biochar stability. Literatures show that the molar H/C and O/C ratios of lignocellulosic biomass are approximately 1.5 and 0.7, respectively. During pyrolysis, the biomass undergoes devolatilization and the solid portion gets enriched in carbon. The H and O are preferably removed over C and the H/C and O/C ratios tend to decrease as biomass undergoes its transformation into biochar. The H/C and O/C ratios are used to assess the degree of aromaticity and maturation [46]. The characterization of biochar produced from different feedstock and their feedstock are discussed in the next section.

5. Biochar characterization

A summary of the characterization of raw biomass samples and their biochars produced at different temperatures and other pyrolysis reaction conditions along with their values for proximate and ultimate analysis is shown in **Table 1**. The carbon and ash contents of biochar increase on increasing pyrolysis temperature while the contents of volatiles decrease with temperature [1, 37]. Pyrolysis temperature influences the structure of biochar due to the release of volatiles, thus increasing the pyrolysis temperature leads to a decreased content of volatile matter. This was observed because the increasing temperature resulted in further cracking of the volatile fractions into low molecular weight liquids and gases instead of biochar [1, 31, 34, 37, 40]. The fixed carbon and elemental carbon content of biochar increase with increasing the pyrolysis temperature, as depicted in **Table 1**. Lee et al. [27] studied characteristics of biochar produced from slow pyrolysis of Geodae-Uksae and showed the increment of the carbon content of biochar at higher temperatures. The increase in elemental carbon content of biochar at higher pyrolysis temperature implies that the biochar became increasingly carbonaceous at high temperatures, releasing hydrogen and oxygen contents. A similar trend, an increase of carbon content with pyrolysis temperature, is obtained for different raw materials, date palm waste [31], rice husk [33], rice straw [34], beechwood feedstock [28], hinoki cypress [37], corrugated cardboard [39], chicken manure, Coffee husk, and sugarcane bagasse [38], pinewood, wheat straw, green waste and dry algae [40]. As one of the purposes of biochar production is to improve carbon contents in soil, thus, the high carbon content of biochar is beneficial in terms of maximizing the amount of carbon storage. Higher temperature pyrolysis is preferred for biochar production if the biochar application is to improve soil fertility. Several studies indicate that the yield of biochar is highly dependent on the pyrolysis conditions such as temperature, heating rate and heating time and is also greatly influenced by chemical, physical and biological properties of the biomass. **Table 1** shows that the temperature of pyrolysis plays an important role in the yields of the characteristic properties of biochar. The physicochemical properties of biochars depend not only on the nature of the starting biomass but also, to a very large extent, on the condition of preparation. Pyrolysis at lower temperatures would result in a large amount of biochar, indicating at high temperature large part of the biomass is lost as volatile matters.

The proximate analysis of biochar produced at different temperatures shows the fixed carbon and ash contents increase on increasing pyrolysis temperature, while the volatile contents decrease with temperature. The proximate analysis of date palm waste driven biochar [31] shows that the fixed carbon and ash contents increase from 45.49% to 74.7% and 14.42% to 21.39%, respectively while volatile contents decrease from 40.08% to 3.91% on increasing pyrolysis reaction temperatures from 300–800°C. Park et al. [34] reported the proximate analysis of biochar produced from rice straw at different temperatures ranging from 300C to 700. The volatile contents decrease from 34.54% to 5.88% upon increasing the aforementioned temperature range, while the fixed carbon and ash contents increase from 28.06% to 39.52% and 37.4% to 54.6%, respectively. A similar trend is also observed by different authors [27, 32, 33, 37, 40] using different raw material and different pyrolysis temperatures.

The ultimate analysis indicates that pyrolysis temperature is the most influential parameter to determine the elemental composition of biochar samples as shown in **Table 1**. It is observed that carbon content of date palm waste driven biochar [31] increases from 57.99% to 74.63% on increasing pyrolysis temperature from 300–800°C. On the other hand Oxygen and Hydrogen contents decrease from 20.8% to 2.27% and 4.08% to 0.86%, respectively for the same pyrolysis temperature increase. Similarly, the ultimate analysis for metallic contents of Ca, Mg, K, and Na increase from 2.53% to 8.08%, from 0.68% to 2.02%, from 1.32% to 2.71% and from 0.28% to 0.58%, respectively for the same increment of pyrolysis temperature. Vieira et. el. [33] also reported the trend of increasing the carbon contents from 47.15–56%, from 46.14% to 58.4% and from 46.16% to 57.35% on increasing temperature from 300–500°C for pyrolysis reaction times of 60 min, 90 min and 120 min respectively, for biochar produced from rice husk. Moreover, a decrease of oxygen, hydrogen, and nitrogen contents of the biochar is observed on increasing the pyrolysis temperature. Lee et al. [27] showed the increment of the carbon content from 66.19% to 85.93% on increasing temperature from 300–700°C, for biochars produced from Geodae-Uksae 1. Several other researchers also reported the increment of carbon content and decrement of hydrogen, oxygen, and nitrogen contents with temperature for biochars produced from rice straw [34], beech wood [28], and hinoki cypress [37].

The molar ratios of Hydrogen, Oxygen, nitrogen, and sulfur to carbon are observed to decrease with temperature, as more volatile components are removed at higher temperatures making the biochar rich in carbon [31, 38].

pH of biochar is a guiding parameter to define the application of biochar as fuel or as soil fertility enhancing chemical and is correlated with the formation of carbonates and the contents of inorganic alkalis. Biochar is used in the soil as an acidity-correcting agent [47], so it is recommended that the pH conditions of the biochar should be basic because it can replace CaO due to such features. Soil acidity neutralization provides the most favorable conditions for microorganism proliferation and soil fertilization [9, 48]. Thus, the pH of biochar has been associated with having a liming effect on soil acidity, thus increasing the soil pH following the addition of biochar. Biochar can also be used as fuel, the use of acid biochar as fuel can lead to corrosion in the combustion equipment. Biochar having basic pH can cause fouling due to its mineral composition and, consequently, higher ash content than the raw biomass feed. Moreover, the pH of the biochar directly impacts the adsorption process when the carbon is used in filtration process. Therefore, a neutral pH is generally preferred [49]. Most of biochar products have alkaline pH. Some studies have indicated that ash content of feedstock in conjunction with pyrolysis severity could influence the final pH of biochar samples suggested that a large proportion of the ash in high-ash feedstock contains carbonates which could cause a liming effect [15]. The pH values of biochars produced from rice husk [33] is observed to increase with temperature, ranging from 5.3 to 8.8 for temperature range from 300–500°C with a reaction time of 60 min, and from 4.2 to 8.3 for the same temperature range with a reaction time of 120 min. Yu et al. [37] reported the pH of biochars produced from hinoki cypress at temperatures ranging from 350–600°C and their pH increases from 7.95 to 9.66. Similarly, Domingues et al. [38] reported the pH of biochars produced from chicken manure at temperatures ranging from 350–750°C and their pH increases from 9.70 to 11.7. The pH of biochar produced from different feedstock is observed to increase with temperature [40].

Thus, biochar with desirable properties can be deduced from both its proximate and ultimate analysis. The lower the O/C and H/C ratios, the higher is the loss of oxygen and hydrogen during the combustion process producing a product richer in higher elemental carbon. The International Biochar Initiative (IBI) recommends a maximum value of 0.7 for the molar H/C ratio [17] to distinguish biochar from biomass that has not been or only somewhat thermochemically altered. Thus suitable working conditions and technologies must be selected in order to produce biochar of high quality. The pH of biochar from different biomass is around 10 and the microscopic surface structure of biochars ranges from around $3\,\frac{m^2}{g}$ for rice husk biochar to around $500\,\frac{m^2}{g}$ for biochar from wood [20]. Biochar produced from different feedstock showed in increasing surface areas on increasing pyrolysis temperature [27, 34, 39].

6. Biochar applications

Biochar is considered as a multifunctional material related to carbon sequestration, contaminant immobilization by adsorption, greenhouse gas reduction, soil fertilization, and waste-water and industrial effluent treatments. Biochar is widely used in heat and power generation, in soil fertility enhancement to improve the physical properties of soil, especially in soils with bad soil structure or high bulk density [3, 47, 50], in adsorption and filtration processes in different industrial effluent treatments [3] and in catalysis or as a catalyst support [51].

Biochar is an economical adsorbent [10] removing various organic contaminants such as agrochemicals, antibiotics, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, volatile organic compounds, and various inorganic contaminants like heavy metals, ammonia, nitrate, phosphate, sulfide, etc. The high adsorption capacity, high specific surface area, microporosity, and ion exchange capacity of biochar are important characteristics for its applications. The feedstock types and pyrolysis conditions used during the biochar production greatly change its physicochemical properties such as surface area, polarity, atomic ratio, elemental composition and pH, giving the overall surface property of the biochar [8, 9]. These varieties in biochar qualities have significant implications on its suitability and efficacy in the remediation of targeted pollutants. Applications of biochar in soil improves the physicochemical and biological properties of the soils [5], which contribute to soil carbon sequestration and greenhouse gas emission reduction.

Biochar produced at low temperatures may be suitable for controlling fertilizer nutrients release, while high temperatures would yield material similar to activated carbon [52]. Because of the high aromaticity, the carbon in biochar is highly recalcitrant in soils with very long residence times. Thus, biochar incorporated in soil represents a potential terrestrial carbon sink and also a means of mitigating CO_2 emissions. In addition, biochar has a significant potential to mitigate greenhouse gas emissions from agriculture, both by storing carbon in soils and through mitigating N_2O emissions [48]. Furthermore, biochar can reduce the amount of fertilizer required and the emission of N_2O and CH_4 from the soil, thus the amount of carbon emissions prevented by biochar can be significant [27, 34]. Biochar application significantly reduced the leaching of applied N fertilizers. Biochar would not only enhance soil fertility but also sequester carbon from the atmosphere further research findings revealed that biochar has an affinity for organic compounds and may sorb toxic by-products from the wastewater treatment process. DAP (di-ammonia phosphate)-based fertilizer is used and studies have shown a large proportion (> 85%) of N applied as NH_4^+, N^- was lost through NH_3 volatilization within one week after application [53]. Therefore biochar application can increase nutrient retention capacity and N use efficiency [48, 54, 55]. Several researchers demonstrated the benefits of biochar for soil, for example, wood biochar applied into a Colombian savanna Oxisol increased available Ca and Mg concentrations and pH, and reduced toxicity of Al [56, 57], moreover, biochar improved soil structure [58], created a carbon sink in soil [59], and reduced CH_4 emissions [60].

In addition to being used as a soil conditioner and carbon sequestration regent, biochar has attracted much attention in wastewater treatment fields. Recent works of literature show biochar as a highly efficient, environmentally friendly, and low-cost adsorbent [61–63]. Biochar characteristic or quality plays a critical role in contaminant removal, which is usually governed by pyrolysis temperature and feedstock type. Fully carbonized biochar produced at a higher pyrolysis temperature (> 500 °C) has higher affinity for organic contaminants due to high surface area [20], microporosity, hydrophobicity carbon-to-nitrogen (C/N) ratio [17, 31, 38], and pH [9, 15, 33, 37, 38, 40]. Partially carbonized biochars that are produced at lower pyrolysis temperatures have higher content of O-bearing functional groups like hydroxyl and carboxyl compounds and lower porosity making them more appropriate for removal of inorganic pollutants [9].

Biochar is used as an electrode as well for various electrochemical devices, including lithium-ion and Li-S batteries [64], supercapacitors [65], and microbial fuel cells [66], etc. Such biochar, namely activated biochar, are found to ne more sustainable than their fuel-based counterparts owing to its high surface area and porosity, efficient electrical and thermal conductivity, high stability, low economical cost, and availability [66, 67].

The unique chemical structure of biochar with a large surface area and tailored surface functional groups can be easily prepared by activation or functionalization and shows great potential to be used as a versatile catalyst or catalyst support in many chemical processes [51, 68–70].

7. Conclusion

Biochar is considered as a multifunctional material related to carbon sequestration, contaminant immobilization by adsorption, greenhouse gas reduction, soil fertilization, and waste-water and industrial effluent treatments. The most promising feature of biochar is the fact that it represents a low cost and sustainable products with a spectrum of applications. Biochars have a tremendous range of physical and chemical properties, which greatly affect their wide applications. The feedstock and the method by which the biochar is produced has a significant impact on biochar characteristics, including concentrations of elemental constituents, density, porosity, and pH, which collectively impact the suitability of the biochar for various applications. This chapter examines in detail the production and characteristics of biochar resulting from slow pyrolysis process, including the effect of feedstock type and different pyrolysis process parameters on the properties and yield of biochar has been thoroughly studied. The selection of a specific type of feedstock is to a great extent determined by its in a place where the biochar is likely to be produced, as this reduces the cost of transport while decreasing the carbon footprint of the biochar technology. The pyrolysis temperature affects the biochar quality, higher carbon contents of biochars can be obtained at higher temperature while volatiles and molar ratios of O/C, H/C and N/C decrease with pyrolysis temperature. Biochars of higher carbon contents are preferable for most applications. Biochars produced at low pyrolysis temperature are suitable for controlling fertilizer nutrients release, while high temperatures would yield material similar to activated carbon. The pH of biochar is also another important parameter that determines its application. More basic, higher pH, biochar is preferred for soil application usually to correct soil acidity. Neutral pH biochar is also most preferable for adsorption processes for the removal of pollutants and contaminants from industrial effluents. Biochars produced at higher pyrolysis temperature have high affinity for organic pollutants due to high surface areas. In addition, neutral pH biochar is used as energy sources because acidic biochars cause corrosion and basic biochars cause fouling problems. Thus, the pyrolysis temperature should be selected as per the final application of the biochar.

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