Performance analysis of sustainable technologies for biochar production: A comprehensive review

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Review article

Performance analysis of sustainable technologies for biochar production: A comprehensive review

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A R T I C L E   I N F O

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A B S T R A C T

Biochar is a valuable product from thermochemical energy conversion technologies. Its yield, and properties vary vastly with the type of feedstock, technology and operating parameters applied, which also affect potential applications. Hence, in this paper various sustainable technologies for biochar production including slow pyrolysis, fast pyrolysis, intermediate pyrolysis, torrefaction, microwave, gasification, flash carbonization, and hydrothermal carbonization are reviewed, with a focus on performance analysis. Specifically, the relationships between biochar production technologies, biochar properties, and the applied feedstocks and operating conditions for each technology are discussed. The effect of critical operating parameters e.g., temperature and heating rate on the yield and quality of the biochar produced via these systems are also studied. This review provides researchers and energy decision makers, important information regarding to the most efficient pathways from feedstocks to biochar products by implementing of sustainable biochar production technologies.

Contents

1. Introduction

Burning different kinds of fossil-based resources releases huge amount of carbon pollution to the atmosphere which intensifies climate change. In order to lessen climate change and avoid devastating consequences of global warming and climate problems, using fossil fuels as fuel need to be pull in (Dinca et al., 2018; Safarian et al., 2020b). In addition to the urgent requirement to reduce conventional energy resources for environmental issues, the war in Ukraine has much more strengthened effort to substitute a large quantity of conventional fuels with instant effects, for instance by using of biochar produced from biomass (Chris, 2022).

Biochar is the solid carbon-rich product that is obtained by heating of biomass feedstocks in the absence or limitation of an oxidizing agent in a controlled process. On average, about 70 wt% of the biochar consists of carbon. The remaining fraction consists of hydrogen, sulphur, oxygen, nitrogen as well as minerals components in the ash. The properties of the biochar and the performance of the production process are influenced by many factors, including the operating conditions, the feedstock

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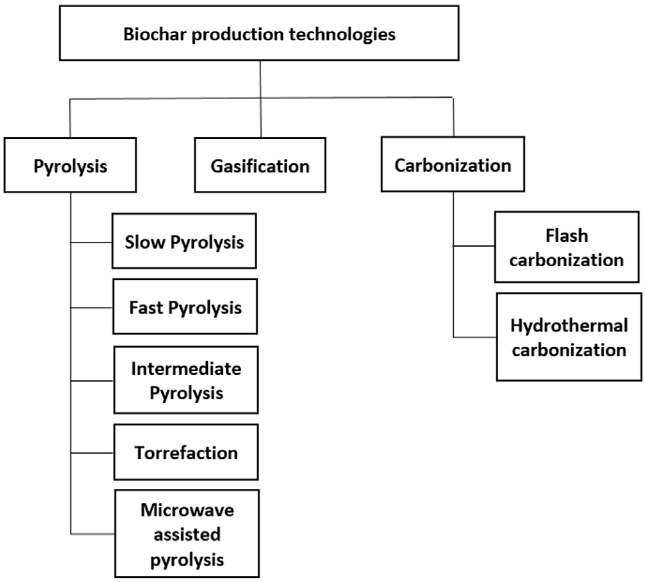

Fig. 1. Various technologies for biochar production.

characteristics and the employed technologies in the production process (Meyer et al., 2011; Wang et al., 2020). Various types of biomass like wood waste, agricultural crop residues, forestry residues, municipal solid waste (MSW) and animal manure can be used as feedstock to produce biochar. However, the adaptability of each type of biomass as feedstock with the production process is depending upon the heating value, proximate and elemental compositions of the feedstock, availability, environmental, and economic factors (Enaime et al., 2020). Various thermochemical conversion technologies for biochar production are shown in Fig. 1 (Gunarathne et al., 2018; Nartey and Zhao, 2014). These technologies change the physical state and chemical composition of the feed, as the various components of biomass go through the several steps of decomposition, cracking and combustion reactions which lead to the biomass conversion into biochar, along with a condensable organic liquid known as bio-oil/tar, and a non-condensable combustible gas composed of hydrogen, carbon monoxide, carbon dioxide, light hydrocarbons and steam (Safarianbana et al., 2019).

Biochar has been recognized as a promising product for carbon storage, improving soil nutrient retention capacity, increase in soil water holding capacity, producing energy carriers with high energy density and improving environmental quality, thereby reducing greenhouse gas (GHG) emissions (Safarian et al., 2022). Recent reviews of biochar production demonstrate its potential in contribution to sustainable bioenergy production by using lignocellulosic biomass as a feedstock (Chi et al., 2021; Lee et al., 2020). Despite this potential, there is still limited experience with the implementation of potential production technologies, the practical operating conditions and the feasible biomass that can be used as the feedstocks for biochar production.

By now, there is a substantial body of literature on various types of technologies with different processes for biochar production. Thus, the objective of this paper is to thoroughly review various sustainable technologies for biochar production with focus on the performance analysis. At the first step, different technologies as shown in Fig. 1 are compared and investigated with regards to product types and distribution. Secondly, the proper biomass feedstocks that can be fed to these technologies and the practical operating conditions for each system are highlighted. Then, effects of critical operating parameters e.g., temperature and heating rate on the yield and quality of the biochar product are studied. The biochar yield is calculated based on Eq. (1) for all technologies and quality of biochar is defined based on carbon content percent in biochar.

$$\text{Biochar yield}, y_{char} = \frac{m_{char}}{m_{biomass}} \tag{1}$$

Finally, the most efficient technology(ies) that generally leads to the highest yield biochar production is(are) presented.

2. Biochar production technologies

Depending on the applied technology and the production process, the char product can be categorized into three classes: biochar, hydrochar and charcoal. The biochar can be produced from dry feedstock (moisture content less than 10%) through several pyrolysis technologies such as slow pyrolysis, fast pyrolysis, intermediate pyrolysis and microwave (Safarian et al., 2022). However, these technologies cannot be used directly for conversion of wet biomass (e.g. sewage sludge) to biochar because of the feeding wet biomass to a pyrolysis process would make the reactor so endothermic that it cannot maintain its temperature. Hence, it is required to use some kind of separate process steps before the pyrolysis reactor for moisture vaporization. Drying prior to the pyrolysis process make the overall system energy-intensive but as the pyrolysis process produces energy and heat, it can be recovered to dry the input biomass and make the system less expensive (Sharma et al., 2019). In order to overcome the problems associated with wet feedstocks, hydrothermal carbonization (HTC) has been developed for direct conversion of high moisture feedstocks to a carbon-rich solid product referred to as hydrochar. HTC is performed at elevated pressure till 10 MPa with presence of liquid water. In this process the feedstock is decomposed by a series of simultaneous reactions that occur in liquid phase, including hydrolysis, dehydration, decarboxylation, aromatization and recondensation, that lowers both the oxygen and hydrogen content of the feed (Benavente et al., 2015; Kumar et al., 2020). In addition, the term charcoal is used to describe a char with a highly porous, low density and brittleness that is produced by torrefaction or carbonization of biomass and subsequently can be applied as a fuel or as a reducing agent in metallurgical smelting applications. The elemental analysis of the outputs from the these alternatives demonstrates that the ratios of O:C and H:C in the gas product is similar to those of unprocessed biomass but these ratios in the charcoal product are less than the gas product (Ronsse et al., 2015).

Although, the biomass feedstocks utilized for biochar and hydrochar production have essentially the same chemical components of cellulose, hemicellulose, and lignin, the physical and chemical characteristics of the char solid products are remarkably different. For example, the ratios of H:C and O:C in hydrochar are higher than in biochar, and close to those in natural coal. In addition, the biochar contains more ash in comparison to the raw feedstocks, while hydrochar includes less ash than the raw feedstock (Shao et al., 2019). These variations in physicochemical properties of the chars are due to the differences in reaction mechanism, production approaches and operating conditions. Different properties of chars lead to variations in the potential applications in different fields like adsorbent materials. For instance, hydrochar has a high capability of contaminant adsorption due to an abundance of acidic functional groups on its surface, and increasing temperature and residence time can increase its porous structure that increases the potential usage of hydrochar as an adsorbent (Xiang et al., 2020).

In order to obtain biochar product with higher yield and quality, several unit operations and reactors were developed for

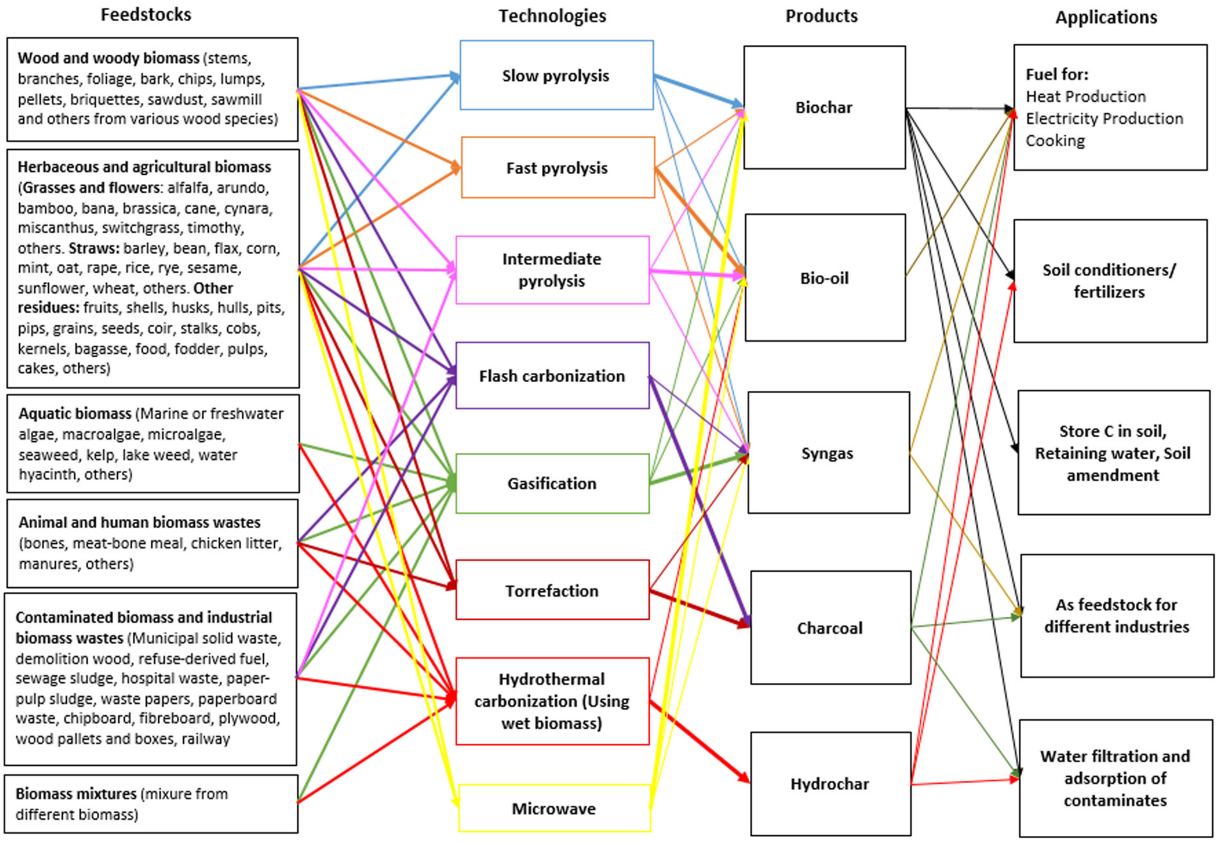

Fig. 2. Diagram of biomass conversion processes with regards to available feedstocks, common products, and their applications.

biomass conversion. The applied reactors are different in terms of, among others, the operating temperature, residence time, use of oxygen, heating rate, which leads to changes in the quality and distributions/yields of the final products (Boateng et al., 2015). Fig. 2 shows various types of thermochemical technologies for biochar production depending on the different process parameters such as oxygen supplied, type of reactor, temperature, vapor residence time, heating rate, yield and quality of the biochar product.

As shown in Fig. 2, the different types of biomass are categorized in 6 groups: (i) wood and woody biomass (W&WB), (ii) herbaceous and agricultural biomass (H&AB), (iii) aquatic biomass (AB), (iv) animal and human wastes biomass (A&HWB), (v) contaminated biomass and industrial biomass waste (CB&IBW) and (vi) biomass mixtures. Each type of biomass has different elemental and proximate compositions and different properties (Vassilev et al., 2010).

The admissible range of feedstock properties is narrow for each technology design, because the chemistry and fluid dynamics of biochar production technologies are very sensitive to variations in feedstock composition, moisture, ash content and char (Safarian et al., 2020e; Safarianbana, 2021). W&WB and H&AB can be used as feedstocks for various types of biochar production technologies but AB having a high moisture content can only be used by gasification and hydrothermal carbonization technologies. Gasification can be used to process a wide range of biomass feedstocks because it has flexible operating conditions and it can be integrated with several preparation and post-processing technologies for pre-treatment of input feedstocks and removal of impurities and tar from the product gas, respectively (Safarian et al., 2020c,g). Pyrolysis technologies (slow pyrolysis, fast pyrolysis, intermediate pyrolysis and microwave assisted pyrolysis) can generally be fed with lignocellulosic materials (Nsamba et al., 2015; Yang et al., 2006). AB and A&HWB are mostly practical to be consumed through the torrefaction and flash carbonization technologies for production of mainly charcoal and small amounts of synthetic gas.

Biochar, bio-oil, syngas, charcoal and hydrochar are the products gained via applying various technologies shown in Fig. 2. Each product can be utilized for diverse applications in different sectors. The product in focus in this review, biochar, can be supplied to different carbon-intensive sectors such as energy production, agriculture, forestry and other land use intensive sectors. It can be consumed as fuel for heat production, power generation and cooking. Furthermore, biochar can be applied as a soil amendment because of its positive impact on cation exchange capacity and high surface area which leads to an increase in soil pH and water holding capacity, and affinity for micro- and macro-plant nutrients (Laird et al., 2009; Whitman and Lehmann, 2009). Biochar can also be applied as a feedstock for various industries like iron, steel and metal smelting (Safarian, 2023). Moreover, it has been discussed in the literature that biochar has the potential to remove various contaminants like pathogenic organisms, inorganics such as heavy metals, and organic contaminants such as dyes, from aqueous solutions (Kaetzl et al., 2020; Li et al., 2020b).

The general operating conditions and the product yields for each technology are gathered in Table 1. The most common technologies studied in the modeling and experimental works are slow and fast pyrolysis, and the most successful one for high-yield biochar production is slow pyrolysis (Manyà et al., 2018). Under slow pyrolysis conditions, the biochar yield can be in the range of 25%–50% (Chi et al., 2021). However, in some cases it has reached more than 70%, depending on the feedstock properties, reactor type as well as the applied operating conditions (Hernandez-Mena et al., 2014; Yuan et al., 2013). Typical operating conditions in slow pyrolysis are: (i) temperature is less than 700 °C, (ii) residence time of feedstock is long, (iii) reactor operates at atmospheric pressure and low heating rates which range from 0.01 to

Table 1
Operating conditions and product/byproduct yields of different technologies.

Technology	Typical conditions			Product/byproduct yields %			Ref
	Temperature	Residence time	Heating rate	Biochar	Bio-oil	Syngas	
Slow pyrolysis	300–700 °C	Long (from minutes to days)	Slow, less than 30 °C/min (generally 5–10 °C/min)	21%–80% (generally 35%)	30%	35%	Ahmad et al. (2012), Claoston et al. (2014), Devi and Saroha (2015), Enders et al. (2012), Li et al. (2020b), Nsamba et al. (2015), Suliman et al. (2016), Yuan et al. (2013)
Fast pyrolysis	300–1000 °C	Very short (less than 2 s)	Very fast, about 1000 °C/s	5%–38% (generally 12%)	50%–75%	13%	Enaime et al. (2020), Kim et al. (2012), Laghari et al. (2016), Li et al. (2020b), Liu et al. (2012)
Intermediate pyrolysis	300–500 °C	Moderate (1–15 min)	Moderate, 1–10 °C/s	30–40%	35%–50%	20%–30%	Brownsort (2009), Duku et al. (2011a), Jung and Kim (2014), Nsamba et al. (2015)
Flash carbonization	300–600 °C	Moderate (less than 30 min)	Very fast	50% (charcoal)	0	50%	Duku et al. (2011a), Kumar et al. (2020), Nunoura et al. (2006)
Gasification	600–1500 °C	Short (10–20 s)	Moderate-very fast	10%	5%	85%	Enaime et al. (2020), Safarian et al. (2021a,b), Wang et al. (2020), Yang et al. (2021)
Torrefaction	200–300 °C	Relatively long (10–120 min)	Slow, less than 20 °C/min	60%–80% (charcoal)	0	40%–20%	Chi et al. (2021), Enaime et al. (2020), Meyer et al. (2011), Wang et al. (2020)
Hydrothermal carbonization	100–300 °C	Long (1–16 h)	Slow	45%–95% (hydrochar)	5%–20%	0%–5%	Chi et al. (2021), Enaime et al. (2020), KAVINDI and LEI (2019), Libra et al. (2011), Zhang et al. (2018a)
Microwave	350–650 °C (400–2700 W)	Moderate (1–60 min)	Fast (25–50 °C/min)	15–80%	8–70	12–60	Hossain et al. (2017), Kumar et al. (2020), Mutsengerere et al. (2019), Shukla et al. (2019), Wallace et al. (2019)

2.0 °C s^{-1} (Duku et al., 2011a; Sohi et al., 2009). These conditions allow all the volatile materials (VM) present to leave the solid char and it (Wang et al., 2020; Weinstetn and Broido, 1970).

As seen in Table 1, intermediate pyrolysis is the pyrolysis which is between fast pyrolysis and slow pyrolysis and results in higher biochar yields similar to slow pyrolysis, although the process is somewhat faster. This process has a good distribution of product and hence can be used in the coproduction of biochar, bio-oil, and gas (Brownsort, 2009). Intermediate pyrolysis differs from fast pyrolysis in terms of the heat transfer to the feed. The heating rates are much lower, in the range of 1 to 10 °C/s. This leads to less tar formation as more controlled chemical reactions take place instead of the thermal cracking of the biopolymer (Hornung, 2013). The residence times through this process are dependent on the reactor type, but mainly are less than 15 min (Brownsort, 2009).

Fast pyrolysis gives higher liquid yields because it aims at bio-oil production and the biochar yield is small, approximately 12% of the total feedstock. In order to, produce a high yield bio-oil, fast pyrolysis of biomass needs to meet three conditions: medium temperature (450–600 °C), high heating rate (around 1000 °C s^{-1}) and very short vapor residence time (<2 s) (Al Arni, 2018; Bridgwater, 2012). This indicates that although several types of biomass feedstocks can be utilized to produce biochar, the yield mainly depends on the operating conditions including temperature, pressure, particle size, moisture content, feedstock properties, the reactor type, and mode of heating rate (Nsamba et al., 2015).

Flash carbonization involves the partial combustion of a packed bed of biomass in a pressurized reactor along with a controlled air injection. The temperature and residence time are moderate but the heating rate is very fast due to the combustion process. A high yield of char and gas without liquid product is achieved under these reaction conditions (Brownsort, 2009).

Gasification is another thermochemical conversion alternative for treatment of various kinds of organic materials such as municipal solid wastes and hydrocarbons like coal. It also includes partial combustion of biomass in a gas flow containing a specific amount of agent (e.g. oxygen, air and steam) at relatively high temperatures (600–1500 °C) yielding a main product of combustible syngas with some char and little bio-oil/tar (Safarian et al., 2019a). In fact, the amount of tar that exits either with the product gas, or condenses out in downstream components, depends on the gasifier type and operating conditions (Safarianbana, 2021). For instance, Baker et al. found tar yields of up to 12 wt% for some updraft gasifiers, and tar yields in the range of 4–15 wt%

for fluidized bed gasifiers, with the higher end observed at lower temperatures (600 °C) (Baker et al., 1988). Downdraft gasifiers operating at a relatively higher temperature of 900 °C tend to perform with a final tar yield less than 1 wt% (Antonopoulos et al., 2012; Baker et al., 1988). Generally, it can be said that the typical solid products yields of gasification and fast pyrolysis processes are significantly lower than of other technologies (Nartey and Zhao, 2014).

Torrefaction is a conventional thermal treatment technology of biomass in order to improve their physicochemical and thermochemical properties. Torrefaction is carried out typically at slow heating rates under atmospheric pressure, at temperatures from 200 °C to 300 °C, with relatively long residence time, and without or with limited oxygen supplies (Enaime et al., 2020; Zhang et al., 2019).

Hydrothermal carbonization is a technology that converts the carbohydrate components of biomass (from cellulose) to carbon-rich solids in water at low temperature and pressure (Titirici et al., 2007). This approach was introduced as a potential alternative to anaerobic digestion for treatment of some wastes and it could be appropriate for extraction of carbon from wet waste streams that otherwise would need a compulsory drying process before pyrolysis (Brownsort, 2009).

Microwave-assisted pyrolysis (MAP) is a promising technology to produce bio-energy products, including biochar, bio-oil and bio-gas. It is largely handled by the microwave power and it is performed under moderate temperature and residence time (Mutsengerere et al., 2019; Xiang et al., 2020). More details about each technology are discussed and explained in the next sections.

2.1. Slow pyrolysis

Pyrolysis is a flexible process that can produce several products including biochar, bio-oil, and syngas. The product mix can be optimized by varying the operating conditions and residence times (Li et al., 2020b; Rosales et al., 2017). During slow pyrolysis, biomass undergoes decomposition in absence of oxygen at a relatively moderate temperature (300–700 °C) and long residence time, which results in higher biochar yield as well as a low condensable liquid products yield due to an increase of the cracking reactions (Li et al., 2020b; Roy and Dias, 2017). Broadly, the quality of biochar is depending upon several factors like carbon content, pH value, specific surface area, porosity, and other components' content in the biochar. However, the carbon content in the char is the most significant parameter for the quality of biochar, and this can be considered that the biochar with more than 70% carbon content, proposes a high quality biochar (Yao et al., 2018). According to Table 2, biochar with higher quality (i.e. with high carbon content) can be achieved by running the pyrolysis under specific conditions including relatively high pyrolysis temperature, long vapor residence time and low heating rate. Hernandez-Mena et al. (2014) proposed a high quality biochar with 80% carbon content by applying slow pyrolysis of woody bamboo in a fixed bed reactor operating at temperature ranging from 300–600 °C and at a heating rate of 10 °C/min. Several researchers also obtained biochar, via slow pyrolysis of wood biomass at a high temperature (750–900 °C) and long residence time (more than 30 min), of a quality that can replace coal and coke in steelmaking (Jahanshahi et al., 2015; Mousa et al., 2016). In order to modify the biochar quality in slow pyrolysis approaches, a higher pyrolysis temperature is essential for removing volatile matter (VM) from biochar, thus increasing its fixed carbon (FC). Furthermore, the low heating rate favors adequate heat conduction which leads to higher carbon deposition and to increased biochar production (Veses et al., 2015).

Besides the mentioned operating parameters, other factors such as biomass particle size, type of feedstock, and pyrolysis atmosphere, influence the quality and yield of biochar directly. In other words, smaller particle size, and longer feedstock residence time, slower heating rate are beneficial for the reactions leading to the production of biochar (Yu et al., 2021). Moreover, the biomass feedstock is the critical parameter impacting the yield and quality of biochar. For instance, the yield of biochar achieved by employing pine wood slow pyrolysis at the fixed bed reactor is 89.8 wt% at an operating temperature of 300 °C, 17 °C/min heating rate and 600 s residence time. Compared to this, biochar yield of wheat straw slow pyrolysis is 94.8 wt% at similar operating conditions and pyrolyzer, confirming that wheat straw biomass is more efficient for biochar yield (Ronsse et al., 2013).

In addition to biochar, bio-oil and syngas are produced as other products or as by-products of slow pyrolysis. The vapors released from the biomass decomposed via slow pyrolysis contain condensable and non-condensable substances at a relatively high operating temperature. The condensable substances are categorized as bio-oil (liquid) containing mainly oxygenated organic compounds, like acids, esters, ketones and phenols (Setter et al., 2020), while the non-condensable substances are gases, mainly carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and light hydrocarbons (Boateng et al., 2015; Duku et al., 2011b). The chemicals in bio-oil can be extracted and utilized as value-added bio-products (Wang et al., 2014) and the product gas can be directly supplied to energy production plants for power and hot water/steam generation through the CHP process (Safarian et al., 2020a,f).

Earth pits and metal kilns have been used as fixed bed slow pyrolysis reactors for biochar production, in which biomass feedstocks are accumulated and heated in the sealed kiln for several hours to some days (Garcia-Perez et al., 2010). In these kinds of reactors, the solid reactants are not heated uniformly, and the gas-solid contact is poor in a fixed bed reactor. Moreover, kilns have been applied in traditional charcoal production and cannot recover bio-oil co-products from the system (Boateng et al., 2015).

Drum pyrolysers and rotary kilns are common continuous slow pyrolysis reactors used at a large scale in industries (Boateng et al., 2015). In a drum pyrolysis reactor, the biomass feedstocks are externally heated and moved over a horizontal cylindrical shell. As a first step, biomass is dried before entering the drum to assure high quality biochar and gas. The process takes some minutes for transport of biomass to the drum and the vapors residence time is long enough that most of them are cracked to non-condensable gases. However, some tar stays with the gas. Some of the gas product is burned in the firebox below the drum to satisfy the required heat for biomass pyrolysis. Rotary kilns are similar to drum pyrolysers except that the shell is oriented at an angle and rotated to allow gravity to move the biomass down the kiln. They also have similar solid residence time (5–30 min). Rotary kilns for biomass slow pyrolysis have been studied at low temperature (350 °C) and relatively high temperatures (600–900 °C). Klose and Wiest (Klose and Wiest, 1999) showed that the yields of bio-oil and syngas products can be controlled by varying the biomass feed rate and temperature in the rotary kilns but biochar yield remains relatively constant in the range of 20%–24%. This lack of control over the biochar yield indicates that large volume of rotary or drum kilns do not favor an interaction between pyrolysis vapors and biochar that would lead to additional biochar production (Boateng et al., 2015).

2.2. Fast pyrolysis

In contrast with slow pyrolysis, fast pyrolysis processes run at high temperature, high heating rate (around 1000 °C/s) and very short residence time (less than 2 s) (Qian et al., 2015). Through

Table 2
The yield and operating conditions through slow pyrolysis.

Biomass	Slow pyrolysis conditions			Biochar yield (%)	Carbon content of biochar (%)	Reactor type	Ref	Year
	Temperature (°C)	Heating rate (°C/min)	Residence time (min)					
Olive mill wastewater	500	5	60	34	84.7	Vertical tubular furnace	Haddad et al. (2021)	2021
Cow manure	300	7	30	84.1	–	Muffle furnace	Hossain et al. (2021)	2021
Rice husk	300	20	90	37.71	46	Fixed bed	Vieira et al. (2020)	2020
Coffee husk	350	0.5	30	39.82	69.96	Muffle furnace	Setter et al. (2020)	2020
Palm shell	500	10	60	35.5	60.12	Screw-fluidized bed	Qureshi et al. (2019)	2019
Walnut shell	500	15	60	30	77.97	Fixed bed	Gupta et al. (2019)	2019
Oil palm empty fruit bunches	300	–	–	68.6	–	–	Dahawi et al. (2019)	2019
Lignin	500	5	480	45.7	85.9	Batch reactor	Farrokh et al. (2018)	2018
Redcedar sapwood	500	6	30	30.9	85.8	Parr reactor (fluidized bed)	Yang et al. (2016)	2016
Redcedar heartwood	500	6	30	21	88.88	Parr reactor (fluidized bed)	Yang et al. (2016)	2016
Rubber wood	500	10	20	24.25	87.17	–	Halim and Swithenbank (2016)	2016
Woody bamboo	300	10	42	80	82.1	Fixed bed	Hernandez-Mena et al. (2014)	2014
Spirulina Sp. algae	500	10	60	32	45.3	Fixed bed	Chaiwong et al. (2013)	2013
Corn straw	550	30	Various	24	92.8	–	Delgado et al. (2013)	2013
Pine wood	300	17	10	89.8	54.1	Fixed bed	Ronsse et al. (2013)	2013
Wheat straw	300	17	10	94.8	50.3	Fixed bed	Ronsse et al. (2013)	2013

a fast pyrolysis method, the biomass compounds are promptly decomposed to produce vapors and biochar. The condensable substances in the pyrolysis vapors are the main product of fast pyrolysis. This product is a dark-brown liquid and is called bio-oil (Choi et al., 2017). The yield of bio-oil is significantly sensitive to the heating rate and pyrolysis temperature. In general, the maximum bio-oil yield (50–75%wt) from biomass feedstock occurs at 500 °C and increased temperatures will decrease bio-oil yield due to rapid quenching of vapors (Li et al., 2020b). Harman-Ware et al. (2013) produced bio-oil with a yield of 55% by performing of fast pyrolysis of the green alga Scenedesmus at 500 °C and vapor residence time of 2 s, and Wang et al. (2013b) observed a 53% bio-oil yield with the fast pyrolysis of Chlorella vulgaris at a temperature of 500 °C .

Moreover, it has been found that higher pyrolysis temperatures reduce the biochar yield because of accelerating the release of gaseous volatiles. This impact also occurs when increasing the heating rate. It can be explained by the fact that through a high heating rate biomass is quickly heated and the volatile release speeds up (Zeng et al., 2015). Since the fast volatile release, the pyrolysis vapors have a low residence time in the high temperature zone, then the amount of carbon deposition decreases. For instance, Angın (2013) investigated the effect of pyrolysis temperature and heating rate on the biochar yield from fast pyrolysis of safflower seed press cake. She observed that the biochar yield of this system reduces approximately 3%–8% by varying the heating rate from 10 to 50 °C/min. Zhao et al. (2018) studied the impact of pyrolysis temperature (200–700 °C) and heating rate (1, 5, 10, 15, 20 °C/min), on biochar yield derived from rapeseed stem feedstock. Their results show that the yield of rapeseed stem biochar has a non-linear indirect, decreasing relationship with pyrolysis temperature. As the pyrolysis temperature increased from 200 to 300 °C, the biochar yield reduced sharply from 80% to 36%. However, when increasing the temperature from 300 to 700 °C the yield fell much more gradually. In addition, the rapeseed stem biochar yield showed a nonlinear impact with heating rate. Firstly, the yield increased as the heating rate increased from 1 to 5 °C/ min, but then decreased when increasing the heating rate from 5 to 20 °C/min, thus achieving an optimum yield at 5 °C/min. The biochar yield gained from poplar wood declined from 34.83 to 31.95 wt% at 400 °C by increasing the heating rate from 10 to 50 °C/min (Chen et al., 2016). Moreover, increasing the pressure can improve biochar yield because the residence time of vapors in biomass particles is prolonged which subsequently promotes char deposition (Tripathi et al., 2016). Wang et al. (2013a) found that the biochar yield increased from 24.9 to 27.5 wt% when the pyrolysis process of pine sawdust was performed in a high pressure and close fixed bed reactor. Pressure also modifies the quality of biochar (carbon content of biochar). Pyrolysis under high pressure results in biochar with high carbon content as well as biochar product with increased energy density (Antal and Grønli, 2003). Operating conditions of fast pyrolysis and the yield and quality of biochar are shown in Table 3, which vary widely depending upon the feedstock utilized.

In contrast to the negative effect of pyrolysis temperature on the biochar yield, higher pyrolysis temperature is favorable

Table 3
The yield and parameters through fast pyrolysis.

Biomass	Temperature (°C)	Biochar yield (%)	Carbon content (%)	Reactor type	Ref	Year
Waste wood	450	18.5	23.2	Fluidized bed	Zhou et al. (2021)	2021
Pig manure	450	25.2	21.2	Fluidized bed	Zhou et al. (2021)	2021
Guava seeds (agro-industrial waste)	350	62.24	–	Single-shot pyrolyzer	Silveira-Junior et al. (2021)	2021
Kanuka woodchips	450	16	–	Fluidized bed	Xin et al. (2021)	2021
Sawdust	550	12	68.43	Fluidized bed	Karmee et al. (2020)	2020
Ivory nut	500	15.8	69.6	Continuous lab-scale reactor	Ghysels et al. (2019)	2019
Wheat straw	500	26	56	Airtight twin-screw reactor	Funke et al. (2018)	2018
Brown macroalgae	375	56.08	30.67	Bubbling fluidized bed	Choi et al. (2017)	2017
Douglas fir	480	11.2	75.8	Bubbling fluidized bed	Wu et al. (2016)	2016
Rice husk	550	38.86	44.73	Fixed bed	Zhang and Xiong (2016)	2016
Yellow poplar	500	5.1	76.3	Fluidized bed	Hwang et al. (2015)	2015
Biomass pellets	500	24.91	86.23	Semi-continuous triple-screw reactor	Raclavská et al. (2015)	2015
Used tires	500	40	85.13	Semi-continuous triple-screw reactor	Raclavská et al. (2015)	2015
Rice husk	500	26	45.2	Conical spouted bed	Alvarez et al. (2015)	2015
Corn stalks	550	–	72.3	Fluidized bed	Wang et al. (2014)	2014

for the biochar quality (carbon content in biochar) due to an increased release of volatiles from the biomass feedstock (Zhao et al., 2018). For instance, Peng et al. (2012) reported that the carbon content of biochar attained from pine sawdust pyrolysis increased from 70.68 to 78.75% by increasing the pyrolysis temperature from 550 to 750 °C. The heating rate also has a similar impact on the biochar quality in fast pyrolysis processes, i.e. the biochar produced at a higher heating rate has a higher carbon content (Chen et al., 2016). The carbon content of biochar obtained from the pyrolysis of safflower seed press cake increased from 67.3 to 71.7% by increasing the heating rate from 10 to 50 °C/min (Angın, 2013).

In order to achieve a higher bio-oil yield in the fast pyrolysis process, different kinds of pyrolysis reactors have been developed, including bubbling fluidized bed, circulating fluidized bed, ablative, rotary cone, auger and screw reactors (Bridgwater, 2012; Qureshi et al., 2018). It should be noted that the biochar yield produced with fast pyrolysis in fluidized bed, rotary cone or ablative reactors is approximately 15 wt% (Bridgwater, 2012). However, this yield can increase to about 25 wt% by employing an auger/screw reactor (Raclavská et al., 2015).

2.3. Intermediate pyrolysis

Intermediate pyrolysis of biomass is another thermochemical conversion technology that sits between the slow and fast pyrolysis processes, operating at moderate temperature 300 to 500 °C, moderate heating rate (1–10 °C/s), short vapor residence time (a few seconds) and moderate feedstock residence time (1 to 15 min) (Ahmed et al., 2018). In contrast with fast pyrolysis, the bio-oil product from intermediate pyrolysis includes only a small amount of reactive tar, thus it can enter boilers and engines directly without any post-treatment for tar removing. However, Mahmood et al. (2013) reported that the acidity number of the bio-oil obtained via intermediate pyrolysis can be relatively high (e.g. 49 mgKOH/g for brewers spent grain based biochar) in comparison to bio-diesel (0.8 mgKOH/g) that indicating potential corrosion problems if considered directly as fuel for engine applications.

Through this process, tars with high molecular weight, high quality bio-oil and dry char are produced that are suitable for agricultural applications and energy generation (Kazawadi et al., 2021). Moreover, a high-quality gas containing around 50% combustible gases (H_2, CH_4 and CO), with the rest mainly CO_2, is produced. This is related to the type of reactors which are employed. Usually, screw-based reactors are applied for the intermediate pyrolysis that do not need large amounts of nitrogen as inert gas as fluidizing medium (as it is used in fluidized beds for fast pyrolysis process). These inert gasses normally remain as a part of the pyrolysis gas product and cause dilution while reducing its quality and heating value (Tripathi et al., 2016). According to Liu et al. (2012) intermediate pyrolysis reactors can handle low-value feedstocks and high-ash wastes like sewage sludge that cannot be used in fast pyrolysis, since these reactors are relying on screw conveyors which are capable of handling a great variety of bulk materials from sluggish to free-flowing (Kazawadi et al., 2021; Yang et al., 2017). The schematic of screw-based intermediate pyrolyzer with indirect heating is shown in Fig. 3 (Yang et al., 2017). The pyrolysis system consists of a biomass feeder, an intermediate pyrolysis reactor, a gas-char combustor, a vapor condenser and liquid separation system. The screw feeder continuously feeds fresh biomass to the reactor. The core of screw pyrolysis reactor contains inner and outer screw which the inner one conveys the feedstock forward through the reactor, and the

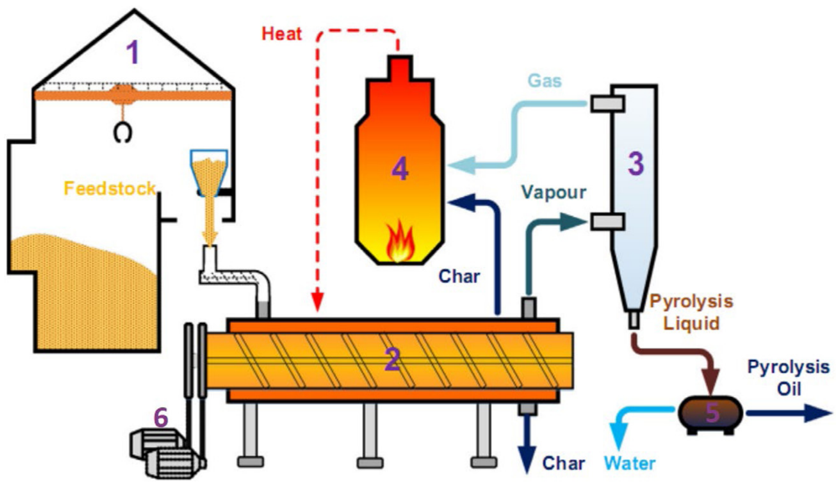

Fig. 3. Schematic diagram of screw-based intermediate pyrolyzer, 1: feeding system, 2: intermediate pyrolysis reactor, 3: condenser, 4: char-gas combustor, 5: liquid separator, 6: electric motors (Yang et al., 2017).

outer screw returns a portion of the biochar product backwards for heat exchange as well as enhancing cracking reactions of pyrolysis vapors. This results in the production of a much more amount of gases products and lower molecular weight condensable organic components and less heavy tars. Then the pyrolysis vapor leaves the reactor and condensed in a heat exchanger to form pyrolysis liquid and the non-condensable gases. Finally, the produced bio-oil is separated via utilizing a liquid separator and a mixture of gasses product and a fraction of biochar product are combusted to prepare the required heat for the pyrolysis process (Yang et al., 2014).

The fixed bed reactors have been also applied for intermediate pyrolysis system which are simple, reliable, and proven for fuels that are relatively uniform in size and have a low content of coal fines which can be integrated with a gas cooling and cleaning system, and it was commonly used for biocoal production. The fixed bed reactors generally function with high carbon preservation, low gas velocity, and low residue conveyed over a long solid residence time (Uddin et al., 2018). Fig. 4 shows the fixed bed reactor, which is considered simple, and includes the following basic units: biomass feeding, gas distribution, heating and cooling (Verma et al., 2012). Tinwala et al. (2015) researched agroindustrial biomasses and wastes on a fixed bench-scale pyrolyzer, identified distribution of bio-oil of 20.5–47.5% and biochar of 27.5%–40%, and concluded that bio-oil can replace furnace oil. Ahmed et al. (2018) studied the intermediate pyrolysis process of Acacia cincinnata and Acacia holosericea species in a fixed bed reactor at 500 °C to produce biochar, bio-oil and syngas products. They showed that biochar produced has high percentages of carbon and hydrogen contents with decent calorific values which makes them suitable for energy applications.

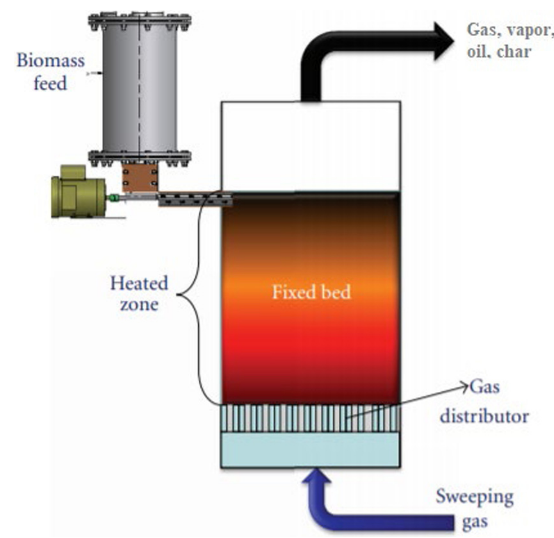

Fig. 4. Schematic of fixed bed pyrolyzer (Verma et al., 2012).

Biochar can be produced with higher yield and quality (e.g. with high carbon content) by considering the pyrolysis temperature, residence time and heating rate. For instance, Morgano et al. (2018) suggested a high quality biochar with 62% carbon content and 55.7% yield by employing intermediate pyrolysis of chicken manure in a screw pyrolysis reactor operating at 350 °C and at a 4.5 °C/min heating rate (Table 4). The effects of pyrolysis temperature and heating rate on the performance of intermediate pyrolysis processes for biochar production is similar to the slow and fast pyrolysis processes (Brownsort, 2009). It has been reported that higher pyrolysis temperatures as well as higher heating rates reduce the biochar yield and increase the biochar quality. Mohammed et al. (2017) studied the variation of yield and quality of biochar produced via pyrolysis of napier grass at a range of pyrolysis temperatures and heating rates. They observed that biochar yield of this system reduces around 4 and 5% by increasing the temperature from 600 to 750 °C and increasing the heating rate from 10 to 50 °C/min, respectively. Jung and Kim (2014) investigated the impact of pyrolysis temperature on the carbon content in the biochar derived from oak feedstock at a fixed heating rate. As the pyrolysis temperature increased from 500 to 800 °C, the carbon content in the biochar increased from 80.9% to 84.8%.

Furthermore, the input biomass to the process has a major impact on the yield and quality of biochar. Various types of biomass feedstocks with different physical and chemical properties have different impacts on the process outputs. For example, Mohammed et al. (2017) produced biochar with a yield of 19% from the intermediate pyrolysis of napier grass at 600 °C operating temperature and 50 °C/min heating rate. Compared to this, the biochar yield by the intermediate pyrolysis of bambara groundnut shell with lower amount of moisture content and volatiles, was 30% at similar operating temperature and heating rate (Mohammed et al., 2016) (Table 4).

Table 4
The yield and parameters through Intermediate pyrolysis.

Biomass	Intermediate pyrolysis conditions		Biochar yield (%)	Carbon content (%)	Reactor type	Ref	Year
	Temperature (°C)	Heating rate (°C/min)					
Chicken manure	350	4.5	55.7	61.9	Screw pyrolyzer	Morgano et al. (2018)	2018
Chicken manure	500	4.5	39.1	–	Screw pyrolyzer	Morgano et al. (2018)	2018
Acacia cincinnata tree	500	25	35.09	70.96	Fixed bed	Ahmed et al. (2018)	2018
Acacia holosericea tree	500	25	38.78	70.53	Fixed bed	Ahmed et al. (2018)	2018
Napier grass	600	10	23.2	–	Vertical fixed bed	Mohammed et al. (2017)	2017
Napier grass	750	10	19.6	–	Vertical fixed bed	Mohammed et al. (2017)	2017
Napier grass	600	50	19.2	79.8	Vertical fixed bed	Mohammed et al. (2017)	2017
Napier grass	750	50	18.8	85.8	Vertical fixed bed	Mohammed et al. (2017)	2017
Bambara groundnut shell	500	50	33	–	Vertical fixed bed	Mohammed et al. (2016)	2016
Bambara groundnut shell	600	50	30	84.7	Vertical fixed bed	Mohammed et al. (2016)	2016
Neem Seed	500	10	32	68.8	Fixed bed	Tinwala et al. (2015)	2015
Pigeon Pea husk	500	10	32.5	73.8	Fixed bed	Tinwala et al. (2015)	2015
Oak	500	10	–	80.9	Fixed bed	Jung and Kim (2014)	2014
Oak	800	10	–	84.8	Fixed bed	Jung and Kim (2014)	2014
Wood	450	20	28.5	75.6	Auger screw	Yang et al. (2014)	2014
Barely straw	450	20	30.2	74.8	Auger screw	Yang et al. (2014)	2014

2.4. Flash carbonization

Flash carbonization is a technology that involves partial combustion of packed biomass materials in a pressurized reactor under specific air supply. Char and gas are produced at high yields with no bio-oil or liquid product under these reaction conditions (Antal et al., 2003; Meyer et al., 2011). Through the flash carbonization process, biomass is quickly and efficiently converted into charcoal mainly. In this process, ignition occurs at an elevated pressure (around 1 MPa) in a packed bed of biomass. Due to the high pressure, the fire swiftly goes upward all over the bed, versus the downward flow of air, causing rapid conversion of biomass to charcoal (Ronsse et al., 2015).

The charcoal yield, fixed carbon yield and energy conversion efficiency are the important indicators for performance study of the flash carbonization. These indicators are calculated as follows (Antal et al., 2003; Nunoura et al., 2006):

$$\text{Fixed carbon yield, } y_{fc} = y_{biochar}\left(\frac{\%fc}{100 - \%feed\ ash}\right) \tag{2}$$

$$\text{Energy conversion efficiency, } \eta_{biochar} = y_{biochar}\left(\frac{HHV_{biochar}}{HHV_{biomass}}\right) \tag{3}$$

The charcoal yield provides a quick conception of the flash carbonization efficiency; for its calculation, m_{char} and $m_{biomass}$, the dry mass flow rate of charcoal and feedstock, are required (Antal et al., 2003; Budai et al., 2016; Nunoura et al., 2006). However, y_{char} does not consider the chemical composition of the charcoal product, hence, the fixed carbon yield (y_{fC}) also needs to be calculated. In Eq. (2), $\%f_C$ and %feed ash are the values of fixed carbon content in the charcoal and ash in the feedstock, both in percent. This indicator shows the efficiency of the conversion from the ash-free feedstock to fixed carbon included in the charcoal product (Legarra et al., 2018). Theoretically, the maximum of the fixed-carbon yield can be predicted based on the elemental analysis of the biomass feedstock. Generally, the theoretical limit of y_{fC} is calculated as the mass fraction of solid carbon present at equilibrium when the elements C, H, and O with known molar fractions are allowed to react at a fixed temperature and pressure. Applying this method, the theoretical limits of y_{fC} at 400 °C and 1 MPa for corncob and macshell, with 43.2% and 52.2% carbon content, are 28% and 37%, respectively (Nunoura et al., 2006). Eq. (3) denotes the energy conversion efficiency in which $HHV_{biomass}$ and HHV_{char} are the higher heating value (HHV) of biomass feedstock and charcoal product, respectively. HHV_{char} can be determined by testing the charcoal product in a lab. Eq. (4) was considered for HHV_{char} calculation in various works (Nunoura et al., 2006), where %VM and %char ash are the volatiles and ash content in the charcoal which are directly measured in the proximate analysis.

$$HHV_{char} = 35.10 - 0.1784 \times \%VM - 0.4292 \times \%char\ ash (R^2 = 0.974) \tag{4}$$

Table 5
Operating conditions and indicators through flash carbonization.

Biomass	Flash carbonization conditions		Proximate analysis of charcoal product (%)			HHV_{char} (MJ/kg)	y_{char} (%)	y_{fc} (%)	η_{char} (%)	Ref	Year
	Temperature (°C)	Pressure (MPa)	FC	VM	Ash						
Spruce	300	0.1	52.2	45.7	2	28.9	57.3	29.9	–	Legarra Arizaleta (2018), Legarra et al. (2018, 2019)	2018 & 2019
Spruce	400	0.1	66.3	32.3	1.5	30.7	48.6	32.3	–	Legarra Arizaleta (2018), Legarra et al. (2018, 2019)	2018 & 2019
Oak	300	0.1	57.4	38.6	3.6	28.2	51.59	29.6	–	Legarra Arizaleta (2018), Legarra et al. (2018, 2019)	2018 & 2019
Cellulose	300	0.1	71.8	28	0.2	31.1	39.5	28.4	–	Legarra Arizaleta (2018), Legarra et al. (2018, 2019)	2018 & 2019
Birch	300	0.1	57.4	40.7	1.8	30.1	52.7	30.3	–	Legarra Arizaleta (2018), Legarra et al. (2018, 2019)	2018 & 2019
Birch	400	0.1	73.2	25	1.9	33	42.4	31	–	(Legarra Arizaleta, 2018; Legarra et al., 2018, 2019)	2018 & 2019
Corncob	300	0.791	89.6	7.2	3.3	32.4	27.7	25.2	51.6	(Nunoura et al., 2006)	2006
Corncob	300	1.14	83.4	14.8	1.9	31.6	34.6	29.3	62.9	(Nunoura et al., 2006)	2006
Macshell	300	1.14	90.9	8.3	0.8	33.3	35	32	56.3	(Nunoura et al., 2006)	2006
Macshell	300	2.17	75.5	24	0.5	30.6	41.9	31.8	61.9	(Nunoura et al., 2006)	2006
Leucaena wood	400	1	72.5	24.7	2.9	30	40	29.7	66.3	(Antal et al., 2003)	2003
Oak wood	400	1	79.5	20	0.5	31.4	35.1	28	62.2	(Antal et al., 2003)	2003
Corncob	400	1	83.7	13.6	2.7	31.3	31.3	28	59.5	(Antal et al., 2003)	2003
Macadamia nut shell	400	1	89.3	9.8	0.9	33.3	34.5	30.9	55.5	(Antal et al., 2003)	2003

Broadly speaking, proximate analysis of charcoal represents the charcoal compositions with regard to moisture, ash, volatile matter (VM), and fixed carbon (FC). The VM is specified as the amount of organic materials (dry, ash-free) that remains after carbonization to a certain threshold temperature, which is, for instance, 950 °C according to American Society for Testing and Materials standard for charcoal analysis (ASTM-D1762-84, 2007). It can be also obtained by the weight difference between the dry, ash-free charcoal and the FC, containing all organic material that is able to volatilize at 950 °C (Ronsse et al., 2015).

By increasing the temperature in the carbonization process, the fixed carbon content in the charcoal product increases significantly. In parallel, increased temperature has a negative impact on the volatiles content in the produced charcoal. Despite the fact that a higher VM content in charcoal causes reduction in its ignition and combustion temperature and it comes with higher smoke through the combustion, charcoals with low VM content are more difficult to ignite but have a clean (smoke-free) combustion.

It should be noted that an increase in carbonization temperature leads to improvement of charcoal quality due to increased fixed carbon yield and energy conversion efficiency while the overall charcoal yield is reduced. It has been concluded that the increase of FC content is a result of the reduction in the charcoal mass instead of additional carbon-fixing reactions (Ronsse et al., 2013). Moreover, ash content increases gradually at higher temperatures. Reduced charcoal yields also translate to higher ash contents (Cordero et al., 2001) (Table 5). Cordero et al. (2001) investigated the effect of temperature on proximate analysis of the resulting charcoals from oak and pine. They reported the FC, VM and ash contents in the charcoal produced from oak carbonization are in the range of 32%–85%, 67–12.5% and 1–2.5%, respectively, by increasing temperature from 300 to 600 °C. These ranges were 34%–84%, 63%–12% and 3%–4%, respectively, for the charcoal from pine carbonization. Legarra Arizaleta (2018), Legarra et al. (2019) studied the influence of temperature on the proximate analysis and performance of flash carbonization derived by several biomass feedstocks (Table 5). They showed that the charcoal yield reduces from 57.3% to 48.6% for the carbonization process fed by spruce when increasing the temperature from 300 to 400 °C and a fixed pressure of 0.1 MPa. In these conditions, the fixed carbon yield also increases from 29.2% to 32.3%.

2.5. Gasification

Gasification is a thermochemical conversion process that is run at 600–1500 °C for conversion of various kinds of biomass to syngas. The product gas can be utilized as a chemical feedstock or consumed as a fuel for cooking or for generation power and heat in different sectors. The gasification process includes the

Table 6
The yield and parameters through gasification.

Biomass	Temperature (°C)	ER	Biochar yield (%)	Carbon content (%)	Reactor type	Ref	Year
Miscanthus	600	–	25.53	92.9	Tube furnace	Tian et al. (2021)	2021
Dealcoholized marc of grape	1200	–	15	52.97	Lab-scale drop-tube	Hernández et al. (2020)	2020
Miscanthus	600	–	–	71.54	Tube furnace	Tian et al. (2020)	2020
Elephant grass	300	–	14.29	–	Updraft	Adeniyi et al. (2019)	2019
Sawdust	500	0.1	20.9	–	Downdraft	Tauqir et al. (2019)	2019
Sawdust	700	0.2	1.45	–	Downdraft	Tauqir et al. (2019)	2019
Coconut shells	750	–	–	87.7	Semi continuous lab-scale fluidized bed	Romero Millán et al. (2019)	2019
Bamboo guadua	750	–	–	69.7	Semi continuous lab-scale fluidized bed	Romero Millán et al. (2019)	2019
Oil palm shells	750	–	–	87	Semi continuous lab-scale fluidized bed	Romero Millán et al. (2019)	2019
Wood chips	650	–	–	68.63	Downdraft	Benedetti et al. (2018)	2018
Pellets	650	–	–	83.39	Rising co-current	Benedetti et al. (2018)	2018
Rice hulls	650	Air flow: 8 L/min	39	–	Top-lit updraft	Yuan et al. (2018)	2018
Wood chips	650	Air flow: 8 L/min	27	–	Top-lit updraft	Yuan et al. (2018)	2018

steps of drying, decomposition (pyrolysis), oxidation (combustion), reduction (char gasification), and cracking (Safarian et al., 2020b, 2019b). Biochar is an unwanted by-product of gasification processes. However, its production under various operating conditions has been analyzed by several researchers. It is because of that the char is necessary to provide heat within the gasifiers. The reduction reactions occurring inside the gasifier are endothermic, and the energy required for these reactions can be provided by the combustion of total or a fraction of char produced from the system.

The value and the quality of the biochar produced via biomass gasification are influenced by various gasification process parameters such as gasifier temperature, pressure, air equivalence ratio (air equivalence ratio (ER) is the ratio of the air enters in the system to the stoichiometric demanded air), the biomass characteristics and the gasifying agent. The carbon content in the biomass feedstock has a positive impact on the quality of the biochar obtained from biomass gasification (Safarian et al., 2020d). In addition, the ER affects the biochar production most significantly in comparison to other process parameters, and its optimum value is depending on feedstock properties (Benedetti et al., 2018). For example, it lies between 0.2–0.3 for timber and wood wastes (Safarian et al., 2020c,e). Indeed, by increasing the ER, an extra amount of oxygen is supplied to the system that leads to biomass combustion and increase in gasification temperature, which affects the quality of the produced biochar as shown in Table 6.

Parametric analysis of biomass gasification for biochar production has widely been done in recent years. Tauqir et al. (2019) showed that increasing various operating parameters including temperature, ER and moisture content has a negative impact on biochar production via sawdust gasification. For instance, they found that biochar production decreased from 4.3 to 1.3 kg/h with increasing ER from 0.1 to 0.45 at fixed gasifier temperature of 500 °C. Muvhiiwa et al. (2019) studied the effect of temperature and oxidizing agent on biochar carbon content. They showed that biochar carbon content declines from 89 to 80% at 700 °C and from 93 to 86% at 900 °C when the oxygen flow rate is increased from 0.15 to 0.6 kg/h. These researchers confirm that an increase in ER in gasification processes decreases both biochar yield and carbon content in biochar. At a low ER, biomass gasification acts like pyrolysis, whilst at a higher ER value the extra amount of oxygen reacts with the fuel completely and causes biomass combustion. Then the production of both syngas and biochar are reduced. Therefore, it is important to find the proper span of ER for each kind of biomass gasification (Safarian et al., 2021c).

Two different types of fixed bed (updraft, downdraft, crossdraft) and fluidized bed (bubbling, circulating) reactors have been developed for biomass gasifiers. The fixed bed gasifiers include a bed filled with solid fuel particles where the gasifying agent is rising, descending, or flowing horizontally through the reactor. However, the fluidized bed reactors are generally cylindrical columns including particles through the fluid flows. As the main advantage of fluidized beds, the fluid velocity is relatively high to suspend the particles through the whole column, creating a broad contact area with the fluid (Warnecke, 2000). In contrast with ER, varying the type of gasifier reactor has a small impact on the yield and quality of biochar (Benedetti et al., 2018; Hernández et al., 2020). In spite of that, top-lit updraft gasifiers applied by several researchers had a higher biochar yield in comparison to other

Table 7
Operating conditions and indicators through torrefaction.

Biomass	Torrefaction conditions			Mass yield (%)	Energy yield (%)	Carbon content (%)	HHV (MJ/kg)	Energy density	Reactor type	Ref	Year
	Temperature (°C)	Heating rate (°C/min)	Residence time (min)								
Fruit peel waste	210–300	18	60	88–49	82–78	64.1 (at 300 °C)	22–27.5	1.12–1.59	Batch reactor	Lin et al. (2021)	2021
Cassava rhizome	200–300	10	30	92–52.5	94–68	46.5–61.1	18.5–24.5	1.01–1.3	Horizontal tube furnace	Nakason et al. (2021)	2021
Ground coffee residue	200–300	10	60	76–38	87–48	63.3–74	27.8–31.1	1.14–1.26	Horizontal furnace	Pathomrotsakun et al. (2020)	2020
Microalgae	160–170	20	10	56–45	68–59	54.7–57.4	23.5–25.5	1.2–1.3	–	Yu et al. (2020)	2020
Wood pellets	200–300	5	60	96.2–48.2	97.6–65.9	–	18.4–24.8	1.01–1.36	Horizontal tube furnace	Arriola et al. (2020)	2020
Pellets	200–250	5	15	90.1–38.2	93.6–49.8	52.2–66.6	20.7–25	1.04–1.3	Lab-scale fluidized bed	Brachi et al. (2019b)	2019
Olive pomace pellets	200–250	5	15	79.9–53	94.5–68.4	57.3–63.6	24.4–26.1	1.18–1.29	Lab-scale fluidized bed	Brachi et al. (2019b)	2019
Rice straw	200–300	–	30	94.3–70.4	98.5–84.4	45–50.9	17.3–19.8	1.04–1.19	Bench-scale nitrogen reactor	Kai et al. (2019)	2019
Bamboo	210–300	10	30	95.3–59.9	97.3–75.1	48.5–61.2	19.2–23.1	1.02–1.25	Tube furnace	Ma et al. (2019)	2019
Orange peel residues	200–250	–	15	49.3–33.3	64.4–51.9	59.8–70	22.3–26.9	1.21–1.49	Fluidized bed	Brachi et al. (2019a)	2019
Medicine residue	200–300	–	60	93.1–55.7	93.8–74.6	55.2–69.7	–	1–1.33	Tube furnace	Zhang et al. (2018b)	2018
Spent coffee grounds	200–300	–	60	94.5–55.4	97.5–75.8	54.8–70.9	–	1.03–1.36	Tube furnace	Zhang et al. (2018b)	2018
Sugarcane bagasse	200–300	–	60	85–28	90–44	46.8–68	17.1–25	1.05–1.5	Cylinder tube furnace	Chen et al. (2017)	2017
Oil palm frond	200–300	10	60	95–50	99.9–71.2	42.8–56.6	17.7–25.1	1.05–1.42	Horizontal tube furnace	Matali et al. (2016)	2016
Tomato peel residues	200–285	5	30	90.6–74.9	92.9–89.3	59.5–66.4	26.2–30	1.03–1.19	Fluidized bed	Brachi et al. (2016)	2016

types. For example, Yuan et al. (2018), reported 39% for biochar yield produced from the gasification of rice husks operated at 650 °C.

2.6. Torrefaction

Another thermochemical technology for char production is torrefaction that is introduced as a kind of mild pyrolysis operated in inert atmosphere and at temperatures from 200 to 300 °C. Although the conditions through the torrefaction process are strongly dependent on the type of biomass feedstock, the whole process is run from 10 to 180 min at a low heating rate, less than 20 °C/min (Mamvura and Danha, 2020). The main aim of this technology is to produce solid char fuel comprising 90% of the initial energy content, a torrefied char with energy densification around 1.3 need to be obtained (Van der Stelt et al., 2011). However, through this process, on average 30 wt% of the products yield are reactive and combustible volatile substances which are known as syngas or torrefied vapor (Ma et al., 2019). The product volatiles are generally burned in a combustion chamber to cover the required energy for the torrefaction process.

Mass yield, calorific value, energy density and energy yield of the torrefied char product are the critical indicators for evaluation of the torrefaction performance which are calculated as follows (Matali et al., 2016):

$$Mass\ \text{yield},\ M_y(wt\%) = 100 \times \frac{m_{char}}{m_{biomass}} \tag{5}$$

$$\text{Energy yield},\ E_y(\%) = M_y \times \frac{HHV_{char}}{HHV_{biomass}} \tag{6}$$

$$\text{Energy density},\ E_d = \frac{E_y}{M_y} \tag{7}$$

where, M_y, E_y and E_d present mass yield, energy yield and energy density, respectively. m_{char} is mass of torrefied char, $m_{biomass}$ is mass of input biomass, both in kg and HHV_{char} and $\text{HHV}_{biomass}$ are high heating values of torrefied char and input biomass, in MJ/kg.

To produce torrefied char with high energy density, low temperature and long residence time are necessary factors through the process, which leads to improvement in yield, quality and energy yield of the torrefied char (see Table 7). By observing these matters, biomass can be converted to char with a yield in the range of 60%–80% and its calorific value could approach that of coal (around 22 MJ/kg) (Phanphanich and Mani, 2011). Chen et al. (2017) found that the biochar produced with sugarcane bagasse torrefaction at 275 °C for 60 min or at 300 °C for 30 min or longer is a suitable fuel for replacement of coal due to it possesses calorific value in a comparable level to coal, but the energy yield from the torrefaction at 300 °C is too low that is not recommended.

Obviously, the properties of biomass feedstocks such as moisture content, calorific value, ash and volatiles content, have a significant impact on the quality of torrefied char (Medic et al., 2010). However, among them, the moisture content plays the most significant role since it mainly determines the required energy for the torrefaction process (Van der Stelt et al., 2011).

Benavente et al. (2015) studied the energy demand for wet and dry torrefaction processes of wet agro-industrial wastes. They reported that wet torrefaction, up to 50% moisture, could be more energy-efficient process in comparison with the dry alternative, and the mechanical dewatering process of wet biomass is the critical parameter for making it higher energy-efficient option.

Although the residence time is a key factor for the quality of product char, torrefaction temperature has much more impact on the process performance compared to residence time (Kai et al., 2019). As seen in Table 7, by increasing torrefaction temperatures for various types of biomass materials, the char product has higher carbon content. Moreover, several researchers investigated the effect of oxidative and inert atmospheres on the torrefaction performance. Both mass and energy yields of the product char from oxidative torrefaction are worse than that of the non-oxidative treatment (Brachi et al., 2019b). However, providing an inert gas like nitrogen as a carrier gas to the process makes torrefaction economically infeasible for large-scale applications. This matter is much more important when the fluidized bed is applied to deliver a solid product with a uniform quality, which is difficult to achieve in other torrefaction reactors (Brachi et al., 2019a, 2018, 2019b, 2016).

2.7. Hydrothermal carbonization

Hydrothermal carbonization (HTC) is the conversion of wet feedstock or biomass with high moisture content at a temperature range of 100–300 °C to biochar (referred as hydrochar) without pre-drying (Xiang et al., 2020). HTC of biomass is studied as heating of wet biomass at elevated pressure (2–10 MPa) in a closed vessel for several hours. The existence of water in the process speeds up the biomass carbonization and effectively influences the product distribution because the moisture content in the biomass acts as a reaction medium and as a reactant in the process. Water is a great reaction agent because it is an oxidized substance that is has does not have a high heating value. In contrast to HTC, presence of water in biomass has a negative impact on the pyrolysis process, because more energy is needed for evaporation. Hence, HTC can handle various biomass feedstocks along with the overall process economy. It also eliminates the required energy needed for removing the moisture content in the raw biomass feedstocks (Nizamuddin et al., 2017).

A list of recent works on HTC of various types of biomass at different operating conditions is shown in Table 8. This process yields mainly hydrochar, some bio-oil, and a small amount of gaseous products (Kambo et al., 2018). The nature and distribution of the products are strongly depending on the feedstock type and process temperature. However, the impact of reaction time and the biomass to water ratio cannot be ignored (Nizamuddin et al., 2016). Typically, moderate temperatures favor high bio-oil yield, high temperatures are proper for syngas generation whereas low temperatures are preferred for char production (Heidari et al., 2021; Miliotti et al., 2020). By increasing the temperature, the solid production goes down gradually, while the liquid and gaseous products increase. The temperature ranges for solid, liquid and gas products are from 150 to 200 °C, from 250 to 350 °C and above 350 °C, respectively (Nizamuddin et al., 2017) (Table 8). Heidari et al. (2021) indicated that the hydrochar yields are high at temperatures of less than 200 °C and an increase in temperature to an intermediate value of 200–250 °C reduces the amount of hydrochar product. Several studies have been carried out to evaluate the effects of temperature and residence time on the output distribution from the various HTC processes using different biomass feedstocks (Heidari et al., 2021; Kambo et al., 2018; Li et al., 2020a; Merzari et al., 2018; Miliotti et al., 2020; Nizamuddin et al., 2016; Peng et al., 2016; Tasca et al., 2019; Wang et al., 2019). It can be observed from Table 8 that regardless of the type of biomass used by the process, the hydrochar yield decreases as temperature and residence time increase and most studies come to the same conclusion that the optimum temperature and residence time for HTC of biomass are 180 °C and 30 min, respectively.

Peng et al. (2016) conducted an investigation into the critical impact of temperature on sewage sludge biomass at fixed and varying residence times. They found that the hydrochar yield decreases rapidly from 66.2% to 56.2% by an increase in temperature from 180 to 260 °C. In addition, Miliotti et al. (2020) demonstrated that the carbon content in the hydrochar is also influenced by temperature. They investigated the effect of temperature on the yield and quality of hydrochar produced from HTC of maize silage. It was found that the carbon content in the hydrochar product increases with increasing temperature while the hydrogen and oxygen content decreases. Carbon content in the hydrochar product increased from 49.7% to 62.8% with increased temperature from 200 to 250 °C while its yield decreased from 72.6% to 62.9%. Nizamuddin et al. (2016) carried out a parametric analysis of HTC fed by palm shell for hydrochar production. They evaluated the effects of various operating conditions like temperature, residence time and biomass to water ratio (BWR) on the yield and quality of hydrochar product. The higher hydrochar yield was observed at the higher BWR at a range of temperatures (180–260 °C) and residence times (30–120 min). However, their results showed also that HTC is more sensitive to the process temperature when compared to the residence time and BWR. On the one hand, hydrochar yield decreased 82% when increasing temperature from 180 to 260 °C at 30 min residence time and 1.6 wt% BWR. On the other hand, it decreased by 17% and 20.4% when increasing residence time from 30 to 120 min and reducing BWR from 1.6 to 1.1 wt%, respectively.

2.8. Microwave assisted pyrolysis (MAP)

Recently, microwave heating systems have been considered and studied by several researchers as an attractive and replaceable method for conventional heating reactors due to their benefits. Microwave pyrolysis is a more controllable single-stage system, cost and energy effective biochar production technique with rapid heating rates that lead to acceleration of reactions, higher yields and selectivity of the target components can be attained in shorter reaction times compared to those achieved by applying the conventional approaches. Microwave and conventional systems are different in view of heat generation. In conventional heating alternatives, the heating source is placed out of the bed, and it is accomplished by convection and conduction methods. Then, a temperature gradient is created from the outside to the inner core of the bed based on the heat transferring until a steady state condition is established (Mubarak et al., 2016). However, in microwave systems, the heat is generated in the bulk of the feedstock which makes penetration of microwaves through it resulting in the conversion of microwave energy to heat. In fact, in MAP, heat is generated by molecular motion caused via the movement of ionic and dipolar species. Then, the molecular level heating goes toward a rapid and homogeneous temperature promotion throughout the reactor (Huang et al., 2016).

In spite of several advantages of MAP, it has some critical challenges regarding difficulties in usage of microwave itself as well as in materials that are processed. These problems are related to the ability of a material to convert microwave energy into heat relying on the dielectric properties. Dielectric heating is a volumetric way by which heat is produced in the inner part of the material via selective absorption of electromagnetic energy. However, not all materials (e.g. transparent materials) can

Table 8
The yield and parameters through hydrothermal carbonization.

Biomass	Hydrothermal carbonization conditions			Hydrochar yield (%)	Carbon content (%)	Reactor type	Ref	Year
	Temperature (°C)	Biomass to water ratio (wt%)	Residence time (min)					
Pine wood	180	1.2	30	79.5	–	Batch reactor	Heidari et al. (2021)	2021
Pine wood	180	1.2	180	67	–	Batch reactor	Heidari et al. (2021)	2021
Pine wood	250	1.2	30	48.8	–	Batch reactor	Heidari et al. (2021)	2021
Bamboo sawdust	200	–	420	–	54.2	Hydrothermal reactor	Li et al. (2020a)	2020
Maize silage	200	1.1	30	72.6	49.7	Micro reactor test bench	Miliotti et al. (2020)	2020
Maize silage	250	1.1	180	62.9	62.8	Micro reactor test bench	Miliotti et al. (2020)	2020
Soybean protein	180	–	120	21	61.2	–	Wang et al. (2019)	2019
Soybean protein	260	–	120	17.5	71.2	–	Wang et al. (2019)	2019
Municipal solid waste	180	1.1	180	54.2	48.7	Bench-scale reactor	Merzari et al. (2018)	2018
Municipal solid waste	220	1.1	180	50.9	50.4	Bench-scale reactor	Merzari et al. (2018)	2018
Miscanthus	260	1.16	30	55	–	Bench top reactor	Kambo et al. (2018)	2018
Palm shell	180	1.6	30	70.6	59.6	Batch reactor	Nizamuddin et al. (2016)	2016
Palm shell	260	1.1	30	38.7	63.7	Batch reactor	Nizamuddin et al. (2016)	2016
Palm shell	180	1.1	30	58.6	–	Batch reactor	Nizamuddin et al. (2016)	2016
Palm shell	180	1.6	120	60.3	–	Batch reactor	Nizamuddin et al. (2016)	2016
Sewage sludge	260	–	30	56.2	24.3	–	Peng et al. (2016)	2016
Sewage sludge	260	–	480	66.2	24.1	–	Peng et al. (2016)	2016
Sewage sludge	180	–	30	66.2	21.2	–	Peng et al. (2016)	2016

easily be heated by this method. For example, feedstocks with high moisture content are more suitable for microwave heating than dry materials. Addition of absorbers to transparent materials could also be helpful for increasing the reaction temperature. Another problem is the difficulty of measuring temperature in the microwave reactor and non-uniform heating behavior that cause thermal damage in processed materials. In addition, this process requires more health and safety precautions due to harmful microwave leakages for humans (Ethaib et al., 2020). Several studies on microwave pyrolysis of biomass have been carried out to analyze the effects of various factors on the yield distribution and characteristics of the main products. The impacts of process parameters like microwave power (Kostas et al., 2020), mass flow rate of feedstock (Huang et al., 2015), temperature (Liew et al., 2018; Wallace et al., 2019), microwave absorber (Hossain et al., 2017; Shukla et al., 2019), type of feedstock (Ge et al., 2021; Suriapparao and Vinu, 2021), type of catalyst (Mong et al., 2020), heating rate (Hossain et al., 2016; Sahoo and Remya, 2020), particle size (Hossain et al., 2016) and residence time (Fodah et al., 2021; Liew et al., 2018) on the yield and quality of biochar product have been investigated. The main results of several recent studies on MAP for biochar production and the considered effective operating conditions are listed in Table 9. As can be observed, the yields and quality of biochar produced vary significantly. This can be attributed to the variation in biomass type, input weight, particle size, microwave power value, temperature, residence time, reactor type, and heating rate. Among these parameters, the effects of reaction temperature, microwave power and residence time are the most important parameters (Huang et al., 2016; Nizamuddin et al., 2018).

Table 9
Yield and parameters through microwave pyrolysis for biochar production.

Biomass	Microwave pyrolysis conditions			Biochar yield (%)	Carbon content (%)	Reactor type	Ref	Year
	Temperature (°C)	Power (watt)	Residence time (min)					
Groundnut shell	600	450	12	15.3	–	–	Suriapparao and Vinu (2021)	2021
Bagasse	600	450	12	19.6	–	–	Suriapparao and Vinu (2021)	2021
Mixed wood sawdust	600	450	12	24	–	–	Suriapparao and Vinu (2021)	2021
Corn stover	250	300	15	46	67.5	Batch cylindrical quartz reactor	Fodah et al. (2021)	2020
Corn stover	250	900	15	28	–	Batch cylindrical quartz reactor	Fodah et al. (2021)	2020
Softwood chips	348.4	2100	60	40	80	Single batch reactor	Wallace et al. (2019)	2019
Softwood chips	659.8	2700	60	24	77.5	Single batch reactor	Wallace et al. (2019)	2019
Hemp stalk	398.8	2100	60	37	78.2	Single batch reactor	Wallace et al. (2019)	2019
Hemp stalk	604.2	2700	60	27	78.5	Single batch reactor	Wallace et al. (2019)	2019
Oil palm waste	950	700	10	38	79	–	Liew et al. (2018)	2018
Oil palm fiber	450	900	7	31.2	–	HAMiab-C1500 microwave muffle reactor	Hossain et al. (2017)	2017
Oil palm fiber	450	400	13	48.2	–	HAMiab-C1500 microwave muffle reactor	Hossain et al. (2017)	2017
Oil palm fiber	700	400	21	30.4	–	HAMiab-C1500 microwave muffle reactor	Hossain et al. (2017)	2017
Oil palm fiber	700	900	11	17.5	–	HAMiab-C1500 microwave muffle reactor	Hossain et al. (2017)	2017

It has been confirmed by several studies that an increase in microwave power causes reduction in biochar yield (Sahoo and Remya, 2020). It was reported in the study carried out by Fodah et al. (2021) that at 300 W microwave pyrolysis of corn stover, the biochar yield is about 46%, while by increasing this parameter from 300 to 900 W, the solid yield degrades to 28%. Hossain et al. (2017) evaluated the influence of microwave power on biochar and syngas yields and observed that lower microwave power favors biochar yield and is a hindrance to the gaseous yield. It was reported that the biochar yield at a microwave power of 400 W is 48.2 wt%, which further reduces to 31.2 wt% at 900 W of microwave power. The lower biochar production at higher microwave power is explained by the fact that higher microwave power leads to higher heating rates and higher heating rates cause an increase in thermal cracking, resulting in an increase in syngas yield and reduction in biochar yield (Hossain et al., 2016).

The temperature within the microwave pyrolysis process is the most significant parameter affecting the products distribution. Wallace et al. (2019) reported a notable change in the yield and quality of biochar product through the microwave pyrolysis of softwood chips and hemp stalk feedstocks by altering the temperature and microwave power, simultaneously. It was observed that at lower temperature, higher biochar with higher carbon content is produced whereas when temperature increases, the biochar yield decreases and its quality almost does not change. Regarding softwood chips, the biochar yield reduced from 40% to 24% by varying of temperature and microwave power from 348.4 to 459.8 °C and 2100 to 2700 watt, respectively. Hossain et al. (2016) analyzed the temperature impact on product distribution of pyrolysis of oil palm fiber. Similar results were found; an increase in temperature leads to an improvement of the syngas formation but degradation in the biochar product. Wang et al. (2009) studied biochar production by employing both conventional and microwave heating systems from pine sawdust and compared them in terms of temperature effect on biochar yield. They found that the biochar yield decreases by increasing the temperature from 400 to 700 °C and no significant change in biochar yield occurred after 700 °C. Comparing the biochar yield obtained from the conventional pyrolysis at the same temperatures, it was found that the biochar yield of conventional approaches is greater than of microwave pyrolysis. This can be explained by the fact that there is a heterogeneous and endothermic reaction between CO_2 and char during the microwave pyrolysis which eventually leads to a decrease in the biochar yield. Furthermore, the heating rate within a microwave reactor is generally higher than that in a conventional pyrolyzer. Hence, the biochar could absorb the microwave energy and increase the pyrolysis process, resulting in a biochar reduction (Nizamuddin et al., 2016).

3. Conclusions and discussion

In this work various sustainable technologies for biochar production from the viewpoint of process performance were reviewed. Different technologies (i.e. slow pyrolysis, fast pyrolysis, Intermediate pyrolysis, torrefaction, microwave, gasification, flash carbonization, and hydrothermal carbonization) were reviewed with regards to the biochar yield and quality. They were compared and investigated with regards to factors such as products types and distribution. Then the proper biomass feedstocks that can be fed to these technologies and the practical operating conditions for each system were highlighted. Then, the effect of the critical operating parameters like temperature and heating rate on the yield as well as the quality of the biochar product were studied.

The yield and quality of products achieved by the thermochemical conversion processes of biomass show great variation because of differences in feedstock, operating conditions and applied technology. The main conclusions of this review are as follows:

(1) Process parameters need to be optimized for a better yield of biochar. First step for the biochar production is feedstock selection. The critical factor that influence on the biochar production is moisture content in the biomass. Biomass with low moisture content is proper for biochar production since by using high moisture biomass, it leads to the tar formation which subsequently reduces the char production. In addition, most of the energy supplied to the process is consumed in removing the moisture instead of increasing the temperature if wet biomass is applied. Biomass having more that 10% moisture content is not suitable for pyrolysis and for a more char yield, use of dry biomass is advisable.

(2) Typically, wood and woody biomass and herbaceous and agricultural biomass can be fed to various biochar production technologies but aquatic biomass with high moisture content can be only fed to gasification and hydrothermal carbonization alternatives. Gasification is able process a wide range of feedstocks but it yields mostly syngas (more than 80%). However, biochar can be produced from lignocellulosic biomass with slow pyrolysis, fast pyrolysis, intermediate pyrolysis and microwave assisted pyrolysis. Animal and human waste biomass are best processed via torrefaction and flash carbonization technologies for the production of mainly charcoal and small amounts of synthetic gas.

(3) The most successful technology for high-yielding biochar production is slow pyrolysis which achieves a biochar yield in the range of 25–50 wt% and it can also reach to more than 70%, depending on the feedstock, reactor type and operating conditions. In contrast with slow pyrolysis, fast pyrolysis gives higher bio-oil yields (50–75 wt%) and the biochar yield is generally 12 wt% of the total feedstock. Moreover, intermediate pyrolysis is between fast and slow pyrolysis and results in a good distribution of products and hence can be used in the coproduction of biochar, bio-oil, and gas. Among the several process parameters, temperature and heating rate are the most significant parameters that control the pyrolysis yield in these three technologies. The biochar yield decreases by increasing the temperature and heating rate. However, low temperature does not allow that the pyrolysis reactions take place, completely and also at high temperature, the biochar formed during the pyrolysis reactions goes further decomposed to liquid and non-condensable gases which lower the biochar yield. Hence, it is so important to operate the pyrolysis process at optimum temperate depending upon the biomass feedstock. Moreover, higher heating rate causes a rapid transfer of heat to the biomass and results in a quick decomposition of biomass into volatile maters while at low heating rate leads to the char production. It is also important to say that versus the negative effect of pyrolysis temperature on the biochar yield, higher pyrolysis temperature and heating rate are favorable for the biochar quality (carbon content in biochar) due to increase in releasing of volatiles from the biomass feedstock and deposition of carbon.

(4) Through the flash carbonization, biomass is converted to charcoal (generally 30–50 wt%) and gas product; then the produced charcoal is used mainly as co-fired with coal in coal fired power plants for different industries like cement kiln as well as for water filtration and adsorption of contaminants. The charcoal yield, fixed carbon yield and energy conversion efficiency have been applied as the important indicators for performance study of the flash carbonization. By increasing the process temperature, the fixed carbon content in the charcoal product increases significantly. Ash content in the charcoal also increases gradually at higher temperatures. However, increased temperature has a negative impact on the volatiles content in the charcoal that makes it more difficult to ignite but have a clean (smoke-free) combustion. Increase in carbonization temperature also leads to improvement of charcoal quality due to increased fixed carbon yield and energy conversion efficiency while the overall charcoal yield reduces.

(5) Gasification is applied for treatment of various kinds of organic materials like municipal solid wastes and hydrocarbons like coal into mainly syngas (around 85 wt%) and small biochar (around 10 wt%). Biochar is an unwanted product of gasification but it is necessary for the process to provide heat within the gasifiers. Char combustion produces heat that supports most of endothermic gasification reactions, as well as the energy required by the drying and pyrolysis parts. The equivalence ratio (ER) has the most important effect on the biochar production in comparison to other process parameters, and its optimum value is depending on feedstock properties. For example, it is in the range of 0.2–0.4 for wood and woody biomass. An increase in ER in gasification decreases both biochar yield and carbon content in biochar. At a low ER, biomass gasification acts like pyrolysis, whilst at a higher ER value the extra amount of oxygen reacts with the fuel completely and causes biomass combustion. Then the production of both syngas and biochar are reduced. In contrast with ER, varying the type of gasifier reactor has a small impact on the yield and quality of biochar. In spite of that, top-lit updraft gasifiers had a higher biochar yield in comparison to other types. For example, 39 wt% of biochar yield reported from the gasification of rice husks operated at 650 °C by using top-lit updraft gasifier.

(6) Through the torrefaction process, biomass is converted to char with a yield in the range of 60–80 wt% and calorific value close that of coal (around 22 MJ/kg) that can be used for heat and power generation. Moreover, through this process, averagely 30 wt% of the products yield are combustible volatile materials/torrefied vapor that are generally burned in a combustion chamber to cover the required energy for the torrefaction process. The charcoal mass yield, energy yield and energy density have been employed as the significant indicators for performance study of the torrefaction process. To produce torrefied char with high energy density, low temperature and long residence time are necessary factors through the process, which leads to improvement in yield, quality and energy yield of the torrefied char. Moreover, oxidative agent can have an critical impact on the torrefaction performance. Both mass and energy yields of the product char from oxidative torrefaction are worse than that of the non-oxidative treatment. However, providing an inert gas like nitrogen as a carrier gas to the process makes torrefaction economically infeasible for large-scale applications.

(7) Wet feedstocks like aquatic biomass and animal wastes can be processed in Hydrothermal carbonization (HTC) and convert to hydrochar. In HTC, complex drying and costly separation step are saved because in HTC the need for feed drying is eliminated. It is also easy to separate solid product through filtration from the mixture and the product char is useful to serve as a fuel or chemical. This process yields mainly hydrochar (averagely 60–80 wt%), some bio-oil (0–20 wt%), and a small amount of gaseous products (0–5 wt%). By increasing the temperature, the solid production goes down gradually, while the liquid and gaseous products increase. The temperature ranges for solid, liquid and gas products are from 150 to 200 °C, from 250 to 350 °C and above 350 °C, respectively. Moreover, regardless of the type of biomass used by the process, the hydrochar yield decreases as temperature and residence time increase and most studies come to the same conclusion that the optimum temperature and residence time for HTC of biomass are 180 °C and 30 min, respectively.

(8) Microwave-assisted pyrolysis (MAP) is performed under moderate temperature and residence time and almost half of lignocellulosic biomass can be converted into char product. Among various parameters affecting on the MAP performance, microwave power and reaction temperature are the most important factors. It has been confirmed that lower microwave power favors biochar yield. Indeed, higher microwave power leads to higher heating rates and higher heating rates cause an increase in thermal cracking, resulting in an increase in syngas yield and reduction in biochar yield. At lower temperature, higher biochar with higher carbon content is also produced whereas when temperature increases, the biochar yield decreases and its quality almost does not change. In general, the biochar yield of conventional pyrolysis approaches is greater than of microwave pyrolysis because there is a heterogeneous and endothermic reaction between CO_2 and char during the MAP that leads to a decrease in the biochar yield. Furthermore, the heating rate within a microwave reactor is higher than that in a conventional pyrolyzer. Hence, the biochar could absorb the microwave energy and increase the pyrolysis process, resulting in a biochar reduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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