



Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review



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ABSTRACT

Biochar is an incredibly rich source of carbon formed through biomass's thermal decomposition. There is a rise of interest in employing biochar derived from biomass in various disciplines to address the most significant environmental challenges. This article evaluated and presented the preparation, characterization, and, most importantly, the environmental application of biochar in a comprehensive way. Process parameters are primarily responsible for determining biomass production. The physicochemical properties of biochar vary according to the type of biomass used. The development of biochar utilizing a variety of different approaches has been discussed. Biochar is typically prepared through pyrolysis, gasification, or hydrothermal carbonization. Biochar has been used in various applications, including soil remediation and enhancement, carbon sequestration, organic solid waste composting, water and wastewater decontamination, catalyst and activator, electrode materials, and electrode modifier. In summary, biochar has a vast number of possible uses in environmental reduction and the mechanism by which its performances should be further investigated.

1. Introduction

Biochar is a porous carbonaceous solid material with a high degree of aromatization and high resistance to decomposition formed through the thermal breakdown of biomass from plants or animals that is thermally decomposed in the absence of oxygen (Rangabhashiyam and Balasubramanian, 2019). It has gained considerable interest in recent years due to its versatile use in various agricultural and industrial activities. Biochars exhibit a wide range of physicochemical characteristics, significantly impacting their wide variety of applications (Amalina et al., 2022). Recent data suggests that the material and process of biochar production significantly affect biochar properties, like elemental ingredient concentrations, density, porosity, and pH, all of which affect the biochar's applicability for diverse applications. It is utilized in waste treatment in various industries to eliminate organic and inorganic pollutants and multiple types of dyes and pigments from textiles (Enaime et al., 2020; Nidheesh et al., 2021; Sakhiya et al., 2020). It is used in agriculture to improve the soil's quality (Daful and Chandraratne, 2018; Food and Agriculture Organization of the United Nations, 2018). It lowers the rate of nutrient degradation in the soil, improving its quality. Biochar can be used as a power generation fuel due to its high carbon content

(Yaashikaa et al., 2020). Biomass has been identified as an auspicious source of renewable energy, minerals, and chemicals (Sadh et al., 2018).

Agricultural wastes, algae biomass, crop residues, animal wastes, activated sludge, energy crops, and digestate are the primary sources of biomass as a feedstock (Li et al., 2020; Raud et al., 2019). Many physical, thermochemical, and biochemical methods can be used to turn biomass into high-value products. Biochar is derived through thermochemical conversions of carbonaceous biomass at elevated temperatures (300–900 °C) and in limited oxygen conditions, including pyrolysis, gasification, torrefaction, and hydrothermal carbonization (HTC) (Nidheesh et al., 2021). Biochars have various physical, chemical, and mechanical characteristics that vary according to the raw material and pyrolysis circumstances (Kazemi et al., 2020). Its availability heavily influences selecting an appropriate feedstock in the territory where the biochar is most likely to be generated. This decreases transportation costs while also lowering the CO₂ emissions of biochar technologies. The generation of biochar derived from biomass is a consequence of the technology used and the process factors involved (Li et al., 2019). Recent research on biomass pyrolysis has found that the generation of biochar depends on several variables, especially the biomass type, its moisture content, particle size, and the reaction conditions (temperature, dura-

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Table 1
Organic dyes and chemical molecular structure for adsorptive removal by an adsorbent.

	Date Palm Rachis	Date Palm Leaflets	Empty Fruit Bunches	Date Palm Glaich	Plum Pulp	Orange peel	Hard Wood	Soft Wood	Rice straw	Wheat straw
Cellulose	40.40	34.87	38.44	22.22	45	54.1	45–50	35–40	25–35	30–35
Hemicellulose	33.08	19.84	24.65	20.44	41	49	20–25	20–25	20–30	26–32
Lignin	12.49	14.03	25.08	16.01	3	12	20–25	27–30	10–15	16–21

tion, heating rate) (Ge et al., 2021; Kumar et al., 2020) and the ambient (gas type and flow rate) (Leng et al., 2021), and other variables (catalyst, reactor type) (Sakhiya et al., 2020).

The aim of this study is to demonstrate the possibility of waste biomass converted into biochar, a valuable substance with numerous environmental employments. This paper discusses the raw materials used for the preparation, techniques, properties, and biochar application and a conclusion.

2. Raw materials for biochar production

Biochar is a porous solid substance made by a variety of biomass feedstocks. It has a negative surface functional group and a porous structure (Amalina et al., 2022). Biochars with various hemicellulose, cellulose, and lignin degrees can have a wide range of physicochemical properties (X. Liu et al., 2018; Singh et al., 2021). The primary materials used to make biochar include biomass, municipal wastes, crop residue, and animal manure. These materials are made from both lignocellulosic and non-lignocellulosic biomass. Lignocellulosic biomass is an excellent bioresource of plant and animal components, including agricultural and wood wastes, energy crops, and municipal solid waste (MSW) (Krishnan et al., 2021). Non-lignocellulosic biomasses such as sewage sludge, animal waste, algal, fur, and skeletal, amongst others, present significant hurdles to critical management and usage due to their complexity and diverse constituents (Amalina et al., 2020; Grobelak et al., 2019). (Li et al., 2020) provided an overview of non-lignocellulosic biomass features, thermochemical properties of significant components (carbon, oxygen, nitrogen, phosphorus, and metals), characterization techniques, conversion processes, and practical implementations of non-lignocellulosic biochar. Non-lignocellulosic biomass poses massive harm to the biological system than lignocellulosic biomass due to its higher concentrations of heavy metals and heteroatoms such as nitrogen, phosphorus, and sulphur (Senthil and Lee, 2020). Toxic metals in non-lignocellulosic biomass can be dissolved in water, resulting in contamination and accumulation in food chains (Zhou et al., 2020). The compositions of cellulose, hemicellulose and lignin in these biomass feedstocks are illustrated in Table 1.

3. Biochar preparation techniques

Biomass can be turned into renewable fuels through biochemical and thermochemical conversion techniques. The significant bioconversion processes include anaerobic/aerobic digestion, fermentation, and enzymatic or acid hydrolysis (Sadh et al., 2018). Bacteria or enzymes degrade biomass molecules into smaller ones during biochemical conversion. This process is considerably slower than thermochemical conversion but requires less external energy (Jones et al., 2018). In anaerobic digestion, bacteria gain oxygen from the substrate rather than from the atmosphere. Biogas, a combination of methane and carbon dioxide (CO₂), and biosolids are the by-products of anaerobic digestion (Ambaye et al., 2020; Zhang et al., 2020). Anaerobic bacteria digest only about 5%–10% of the feed into the digester. The digestate is composed of any indigestible material that remains. Aerobic digestion, colloquially referred to as composting, occurs in the presence of oxygen. It utilizes various microorganisms that consume oxygen from the air, resulting in CO₂, heat, and solid residue (Chiappero et al., 2020). Starch is metabolized to sucrose through fermentation employing acids or enzymes. Then, with the

aid of yeast, sugar is turned into ethanol or other substances. Before fermentation of lignocellulosic material, extensive pre-treatment (hydrolysis) is required to convert the cellulose and hemicellulose to simple sucrose. Hydrolysis can be accomplished using acids, enzymes, or hydrothermal energy (Alkurdi et al., 2019). The lignin is not oxidized and is instead synthesized thermochemically. Meanwhile, numerous thermochemical conversion techniques are available for biomass conversion to solid, liquid, and gaseous products. Thermal decomposition is a standard process for biochar production. Thermochemical methods, including pyrolysis, HTC, gasification, and torrefaction, are all important in biochar production (Amalina et al., 2022; Tang et al., 2019; Wang and Wang, 2019). Thermochemical conversion techniques, including combustion, gasification, and pyrolysis, employ extreme heat to break down the bonds of organic materials (Hassan et al., 2020). The yield of biochar is highly influenced by the pyrolysis method used. Slow pyrolysis without oxygen produces (30%) more charcoal than either fast pyrolysis (12%) or gasification (10%) (Enaime et al., 2020; Oliveira et al., 2017; Rangabhashiyam and Balasubramanian, 2019). Combustion is simply a method through which biomass is heated in the presence of oxygen. Chemically, it is the exothermic oxidation of material at high temperatures in the presence of oxygen to produce CO₂ and H₂O, also known as hot flue gas. The solid by-products of burning include char, containing specific organic carbon, and ash, which generally contains inorganic oxides and carbonates (Mamanf et al., 2019). Combustion temperatures are typically between 700 and 1400 °C. Combustion is not optimal for producing biochar since it converts most carbon in the biomass to CO₂. To avoid total combustion, gasification is conducted at temperatures more than 800 °C in a deficiency of oxygen (Zaker et al., 2019). Gasification is used to extract gaseous by-products of incomplete burning, especially carbon monoxide (CO), hydrogen (H₂), carbon dioxide (CO₂), nitrogen (N₂), and moisture (H₂O). Additionally, gasifiers are inefficient for producing biochar because they transform the bulk of the carbon in the biomass to CO and CO₂ (Umenweke et al., 2022).

3.1. Pyrolysis

Pyrolysis is a non-oxidative thermal breakdown process. It results in the formation of three unique product fractions: solid residue (biochar), condensable liquid (bio-oil), and non-condensable gaseous (syngas) (Rangabhashiyam and Balasubramanian, 2019; Senthil and Lee, 2020). When oxygen is eliminated from the mixture, combustion cannot occur; instead, pyrolysis. Temperatures during pyrolysis are typically around 300–700 °C. Pyrolysis seems to be the primarily favourable method to produce charcoal and bio-oil from biomass. Reduced pyrolysis temperatures and extended residence times result in a greater biochar yield. It is well known that prolonged reaction time promotes polymerization, leading to more biochar production. Moderate temperatures and short residence time typically result in more liquids (Yaashikaa et al., 2019). These thermochemical processes employ various operating conditions, including residence times ranging from < 1 s to hours, heating rates from < 11 °C/s to > 1000 °C/s, and temperatures between 300 and 700 °C or more (Santoso et al., 2020). Since each pyrolysis generates a varied proportion of the by-products, it is critical to choose the pyrolysis process to acquire a successful result carefully. Three pathways can be used to characterize the direct conversion of biomass during the pyrolysis process: char production, depolymerization, and fragmentation (Daful and Chandraratne, 2018; Rangabhashiyam and Balasubra-

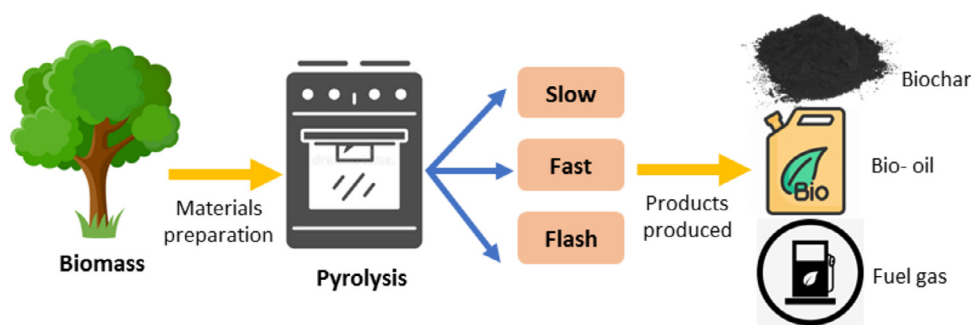


Fig. 1. General concept of the pyrolysis process.

manian, 2019; Yaashikaa et al., 2020). Char generation is often encouraged through intramolecular and intermolecular rearrangement events, which results in a residue with better thermal stability. This route is defined by forming benzene rings and their subsequent combination to form an aromatic polycyclic structure (Karimi et al., 2018). Generally, these rearrangement reactions result in the release of liquid or gases. Depolymerization is defined by the dissolution of polymer bonds followed by stabilizing processes that result in monomer, dimer, and trimer units. At ambient temperatures, such volatile compounds condense and are found in the liquid fraction. Fragmentation occurs when polymer and even monomer links are broken, resulting in generating gases and various organic liquids that are condensable at surrounding temperatures (Shiung et al., 2019).

Direct conversion gases and liquids are unstable at pyrolysis temperatures and can experience side reactions like cracking or recombination with sufficient residence time (Yu et al., 2019). Cracking reactions include dissociating volatile chemicals into molecules with a lower molecular weight. Recombination combines volatile compounds to form more significant molecular weight molecules that may not be volatile at pyrolysis temperatures (Dhyani and Bhaskar, 2018). Secondary char is also formed during recombination reactions. Primary char has the potential to perform as a catalyst in secondary reactions.

Fast pyrolysis produces a higher proportion of bio-oils due to the rapid heating rates and lower residence durations. On the other hand, slow pyrolysis produces a higher proportion of biochars due to the slower heating rates and longer residence durations. Primary and secondary reactions occur during the heat degradation of biomass, highlighting the essential distinction between fast and slow pyrolysis.

Pyrolysis involves a comparatively dry material, often less than 30% moisture content, though up to 10% moisture level is acceptable and ground to a variety of particle sizes due to the type of pyrolysis performed (Abdel-Shafy and Mansour, 2018; Akdeniz, 2019). Fig. 1 illustrates the general process of pyrolysis.

Fig. 2

A water holding capacity feedstock requires additional energy to accommodate the increased heat of vaporization as the biomass is heated to the pyrolysis temperature. In addition, because the gases and liquids produced during pyrolysis with high water content are diluted with steam, their calorific value is reduced. HTC techniques can be used to decompose wet biomass that contains at least 70% water. The most prevalent procedures are slow and fast pyrolysis, with slow pyrolysis being the best practical method for producing high-yield biochar, as shown in Table 2.

Slow pyrolysis is defined by low heat (300–550 °C), slow heating rates (0.1–0.8 °C/s), and a prolonged contact time (5–30 min or even 25–35 h) (El-naggar et al., 2019). Slow pyrolysis maximizes biochar yields by stimulating secondary reactions, accomplished by extended vapour residence periods. Slow pyrolysis produces primary and secondary char (Kumar et al., 2021). Additionally, the slow heating rate combined with the medium pyrolysis heat favours biochar formation. The biochar yield depends upon the materials' features and the pyrolysis processes, particularly the temperature, heating rate, and pyrolysis reactor (Sonu et al., 2020) Mineral-rich biomass produces less biochar. Due to the systematic

development of secondary reactions, slow pyrolysis could be exothermic. Slow pyrolysis can absorb particles ranging in size from (5–50 mm) (Sakhiya et al., 2020).

In intermediate pyrolysis, the reaction is quicker than slow but slower than fast pyrolysis. It happens between 450 and 550 °C, is more rapid than slow pyrolysis, takes 10–30 s to complete, and produces less charcoal than slow pyrolysis (Ge et al., 2021; Sakhiya et al., 2020). Intermediate pyrolysis chemosynthesis at appropriate temperatures prevents the development of high molecular weight tars and results in a range of product properties (biochar, bio-oil, and gases). The size and shape of the biomass particles are less crucial in intermediate pyrolysis than in fast pyrolysis. It can process a broader range of biomass, from bigger particles to pellets and chips, as well as material containing nearly 40% (Mbarki et al., 2019).

Fast pyrolysis is characterized by extreme temps, rapid heating rates (10–1000 °C/s), and brief residence times (0.5–2 s) (Tomczyk et al., 2020). Fast pyrolysis avoids secondary reactions by utilizing short vapour residence times and maintaining high biomass heating rates. It maximizes bio-oil output (Mutsengerere et al., 2019). The distribution of by-products is determined by biomass composition, heating rate, and temperature. If the desired product is bio-oil, the optimal pyrolysis temperature range is 425–600 °C with a maximum heat of less than 650 °C. Nevertheless, if gas generation is the prime purpose, the peak temperature can reach 1000 °C (Ge et al., 2021). A finely ground biomass feedstock, often less than 1 mm, is necessary to produce exceptionally high heat transfer rates and, consequently, extremely high heating rates, alleviating mass and heat transfer constraints (Ravindran et al., 2018). Biochar yields are often deficient in fast pyrolysis because only primary carbon is produced. Due to the unavailability of secondary reactions, the overall rapid pyrolysis process is endothermic. Fast pyrolysis recommends biomass containing less than 10% moisture content by weight to reduce water in the final bio-oil. Additionally, a low moisture level enables the feed to be ground into sufficiently fine particles to allow quick heating and pyrolysis (Lee et al., 2020).

Flash pyrolysis seeks to optimize the production of bio-oil. It is defined via high temperatures, fast heating (> 1000 °C/s), and brief contact times (< 0.5 s). Flash pyrolysis produces primarily identical products to fast pyrolysis. It arises between 800 and 1000 °C (Gaurav et al., 2020). Typically, excellent biomass feed particles (< 0.2 mm) are required.

Microwave-assisted pyrolysis is a relatively recent innovation that was initially explored as an efficient process for recovering and converting energy from homogeneous waste (Ge et al., 2021). Since the 1990s, the practice of microwave processing in the thermal treatment of biomass has attracted significant interest (Wang et al., 2018). The microwave-assisted pyrolysis method is amongst the ultimate attractive alternatives for speeding up and optimizing chemical reactions. Due to the excellent heat transfer profile, chemical reactions are performed quickly and efficiently compared to other thermochemical processes (Yin et al., 2018). Microwave-assisted pyrolysis provides several benefits compared to traditional pyrolysis, including uniform heating altogether, a quick heating rate, volumetric and selective heating. Microwave heating simplifies the process with rapid on/off control and increases product and quality production (Xiang et al., 2020). It lim-

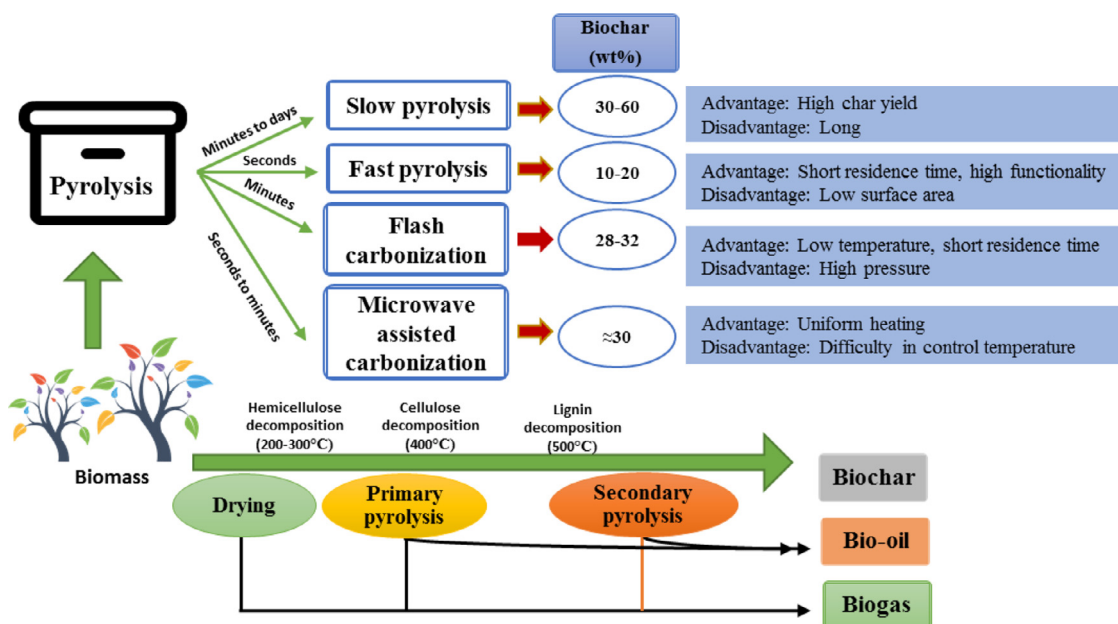


Fig. 2. The differences of pyrolysis process of biomass.

Table 2
Pyrolysis processes operating conditions and the by-product fractions.

Technique	Temperature(°C)	Residence time (s)	Heating rate(°C/s)	Biochar(%)	Bio-oil(%)	Syngas(%)	Ref.
Slow pyrolysis	300–550	hours to days	1–10	35	30	35	(Shahbaz et al., 2020)
Intermediate pyrolysis	450–550	10–20s	10–1000	25	50	25	(Daful and Chandraratne, 2018)
Fast pyrolysis	450–600	< 2s	10–1000	12	75	13	(Thomas et al., 2019)
Flash Pyrolysis	750–1000	0.5s	<1	–	–	–	
Microwave-Assisted Pyrolysis	400–800	–	>1000	–	–	–	(Zaker et al., 2019)
Gasification	> 800	10–20s	1–0.8	10	5	85	(Zaied et al., 2020)
Torrefaction	450–550	< 2 h	–	75	20	5	(Amalina et al., 2022)
Hydrothermal Carbonization	< 200	1–16 h	<1	35	30	35	(Brown et al., 2020)

its hazardous product development and pollution output, making the procedure environmentally sustainable (Venkatesh et al., 2022). Additional benefits include rapid heating efficiency due to in-situ heating, the capacity for handling wet biomass without drying, and the potential to pyrolyse enormous biological molecules. The downside of microwave-assisted pyrolysis is that it necessitates electricity (Ao et al., 2018; Ge et al., 2021), which is more expensive and of higher quality than the heat produced during conventional pyrolysis by the combustion of pyrolysis gases and vapours.

Pyrolysis of biomass includes the transfer of energy rather than heat. Electromagnetic energy is transformed into heat energy by conductive heat (Zhongzhe Liu et al., 2018). Also, energy is released within the biomass volume rather than from an external source. Unlike conventional pyrolysis, the temperature at the biomass's centre is higher than the surface and ambient of the material (Zaker et al., 2019), as shown in Fig. 3. The application of microwaves in a new method expedites the operation relatively. Furthermore, pyrolysis by microwave radiation does not involve biomass biodegradation or drying (Godwin et al., 2019). This strategy makes it possible to transfer homogeneous thermal energy internally into the feedstock running, respecting the functional groups of reactions. The resulting biochar has a higher surface area (a Bruner-Emmet-Teller, BET, up to 450–800 m²/g) and many functional groups than the conventional biochar (Naji and Tye, 2022).

The microwave biochar has unique physical and chemical properties and is very stable compared to the conventional user. Compared

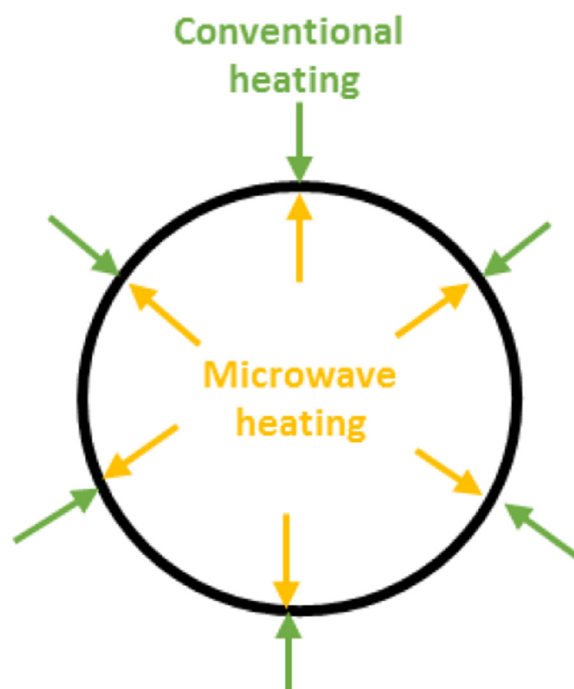


Fig. 3. Microwave and conventional heating nature.

Table 3
Microwave heating's advantages and disadvantages.

Benefits	Limitations	Ref.
Volumetric & selective heating	Poor microwave absorbing materials require more power	(Ge et al., 2021)
Economic with short time and high efficiency	Random heating (Creating hot and cold places)	(Wang et al., 2018)
Instant-on/off to control heat	Arc and plasma form due to the thermal runaway	(Shiung et al., 2019)
Environmentally friendly (Clean and silent)	More complicated reactor design	(Mutsengerere et al., 2019)

to previous heating, the feed was heated from the depth of the sample to the surface, thus allowing the heating process to occur at a rapid rate (Umenweke et al., 2022). Microwave heating causes heat circulation within the material where the electromagnetic waves interact with the dipoles (Mulyadi et al., 2019). This microwave heating mechanism shows a very efficient heating process by distributing heat and simplicity of heat control. This microwave heating mechanism shows a very efficient heating process by spreading and clarity of heat control. Microwave heating is quick and efficient energy heating, facilitates yield production, eliminates the need for liquid convection, facilitates thermal control, restores the energy and chemical value of waste products, and has the best biochar production quality and efficiency in terms of surface efficiency and cost-effectiveness (Cheng et al., 2021; Enaime et al., 2020). However, Table 3 summarizes the benefits and limitations of microwave heating in the context of pyrolysis.

3.1.2. Torrefaction

Torrefaction, a type of pyrolysis that occurs at a medium temperature, requires gradually heating the material to temperatures between 200 and 300 °C (< 11 °C/s) in the absence of air at atmospheric pressure (Manyà et al., 2020). Torrefaction eliminates excess water and volatiles and partially degrades biopolymers, cellulose, hemicelluloses, and lignin by releasing organic volatiles. It is more likely to produce solids than liquid or gaseous products. According to (Daful and Chandraratne, 2018), biochar should have a molar oxygen to carbon (O/C) ratio below 0.4. However, torrefied material typically has a more excellent O/C ratio than that specified by the European Commission for biochar. As a result, torrefied biomass is ineligible to be considered as biochar. Torrefied biomass possesses physical and chemical qualities that are intermediate between biomass feedstocks and char. Torrefaction is a pre-treatment procedure generally employed to remove moisture from biomass and densify it, hence lowering the price of mobilization and increasing the heating value of the biomass (Yadav et al., 2022; Zoroufchi et al., 2020). Additionally, torrefaction boosts the biomass material's hydrophobicity, grindability, and biodegradability compared to unmodified biomass resources. Torrefied biomass may be kept for an extended period without degrading. Torrefaction typically produces a mass yield of 70%–80% and an energy yield of 80%–90% (Enaime et al., 2020).

3.1.3. Hydrothermal carbonization

Most biomass materials are moist, with moisture concentrations up to 95 wt%. Biomass with a moisture content greater than 30% must be dried before pyrolysis (Ha and Lee, 2020). Hydrothermal carbonization (HTC) is a process that uses heat and pressure to synthesize biomass into carbonaceous biofuel in the presence of water. This is a potentially promising approach for converting wet biomass to biofuels without resorting to energy-intensive drying (He Zhang et al., 2018). Water is both a solvent as well as a reactive. While solid biomass containing liquid is heated at low temperatures (< 200 °C) in a closed chamber under autogenous pressure, an HTC process results in the formation of primary solids called hydrochar (Mbarki et al., 2019). Hydrothermal liquefaction (HTL) occurs at temperatures from 200 to 350 °C, turning the biomass

fuel mostly into a liquid product. Hydrothermal gasification (HTG) occurs around the critical temperature and pressure close to those of water (374 °C and 22.1 MPa), converting the biomass primarily into a gaseous medium (H₂, CO, CH₄, and CO₂). Hydrochar specifications include a more excellent H/C ratio than biochar specifications (Kumar et al., 2020; Liu et al., 2020; You et al., 2017).

3.1.4. Gasification

Gasification is described as a thermochemical technology that converts heat from carbonaceous materials with a gasification agent such as air, oxygen, or steam in the ambient or at high pressures at temperatures above 750 °C into biochar and oxygen-deficient states. When air is used as the oxidizing medium, the resultant gas contains approximately 85% syngas, which include H₂, CO, CO₂, CH₄, N₂, and C₂H₂. It is disclosed that the steam gasification mode yields greater H₂ with a high heating value (Nidheesh et al., 2021). Typically, the gasification operation consists of four consecutive steps; drying, pyrolysis, partial oxidation, and reduction (Umenweke et al., 2022). Gasification can be classified into three main types of gas-solid contact mode: fixed bed, liquefied bed, and inlet flow. This method primarily produces syngas and a low char yield (Yaashikaa et al., 2020). Biochar yields are insufficiently significant under these conditions to consider gasification as a viable biochar production technology. Similarly, burning is not an appropriate method for producing biochar since, under ideal combustion circumstances, the biochar yield should be insignificant. The primary limitation of this method is the negligible amount of biochar produced by-product and the emission of greenhouse gases (GHG) (Nidheesh et al., 2021). Furthermore, the operating conditions for gasification vary to maximize energy from different carbonaceous feedstocks (Burk, 2017). It inevitably controls the gasification's operational settings (Zuber et al., 2019). Table 4 summarises the strengths and weaknesses of different biochar synthesis operations. In general, pyrolysis is the most efficient, sustainable, and preferable technique for producing biochar.

4. Biochar characteristics

The European Biochar Certificate specifies biochar as a "heterogeneous compound rich in aromatic carbon and minerals" (Li et al., 2020). It is synthesized through the controlled pyrolysis of sustainably harvested biomass using clean technology. It can be utilized for any application that does not need quick mineralization to CO₂ and can become a soil amendment. This distinction is made between biochar and other carbonaceous compounds, such as char and charcoal (Amalina et al., 2022). The biomass used to produce biochar must be renewable and sustainable. Biochar is meant for wastewater treatment, soil management, and carbon sequestration.

Plant biomass mainly comprises cellular lignocellulosic substance, the non-starch fibrous fraction of plant materials. As mentioned before, cellulose, hemicellulose, and lignin are the three primary components of lignocellulosic biomass (Dhyani and Bhaskar, 2018; Li et al., 2020). Cellulose is the primary element of the plant cell wall, as it provides a structural component. Hemicellulose and lignin are the second and third highly prevalent polymers in lignocellulosic biomass, respectively (Singh et al., 2021). These three polymers were primarily accountable for modifying physicochemical properties throughout the pyrolysis technique. The pyrolysis processes of these polymers vary chemically amongst biomass types. Cellulose and hemicellulose breakdown more rapidly than lignin across a shorter temperature range (Li et al., 2020). Additionally, biomass contains inorganic chemicals and organic extractives. Inorganic chemicals, which account for less than 10% of biomass by weight, are converted to ash during pyrolysis. The term "organic extractives" refers to the non-structural supports of biomass which can be recovered using either polar or nonpolar solutions. These comprise fatty acids, waxes, proteins, terpenes, simple sugars, gums, resins, and starches, as well as alkaloids, phenolics, pectins, glycosides, mucilages,

Table 4
The strengths and weaknesses of different biochar synthesis processes.

Biochar techniques	Advantages	Disadvantages	Ref.
Pyrolysis	Simple Low residence time High biochar yield Any organic feedstock can be utilized Large surface area, high conductivity, and the porous structure Environmental friendly	Necessitates dry feedstock feedstocks that have a moisture content of <30% It needs an inert environment Costly	(Ndirangu et al., 2019) (Daful and Chandraratne, 2018) (Xiang et al., 2020; Iisa et al., 2019; Yu et al., 2017)
HTC	Eliminates energy-intensive drying methods Suitable for biomasses with high moisture content The char formed has a high concentration of oxygen functional groups.	Low toxic substances and less C stability	(Pan et al., 2021; You et al., 2017)
Gasification	High syngas yield Short residence time Inexpensive	Low biochar yield	(Tang et al., 2019; Yaashikaa et al., 2019)

and saponins (Guo et al., 2018; Nyoo et al., 2021; Singh and Chandra, 2019). Further, biomass contains a significant amount of free and bound water.

Biochar's attributes are strongly influenced by the qualities of the raw materials and the pyrolysis conditions utilized to produce it (Kameyama et al., 2019). The pyrolysis temperature is the primary factor that controls the degree of devolatilization of the biomass. When biomass is heated up to 160 °C, the first constituent eliminated is free and bound water. Thermal biomass degradation begins with the volatilization of extractives at 220 °C (Huang et al., 2020). Hemicellulose is a minor stable polymer and degrades at temperatures between 220 and 315 °C. Cellulose is highly polymerized and shows increased thermal stability. It decomposes between 315 and 400 °C. Lignin is the most challenging element to pyrolyse due to its extensive decomposition temperature gradient of 160 to 900 °C (Kandanelli et al., 2018).

Carbon content, bulk density, carbon stability, volatile compound content, surface area, nutritional content, heavy metals, pH value, water and ash content, PAH, water holding capacity, porosity, elemental composition, cation exchange capacity (CEC), and electrical conductivity are all often measured quality characteristics for biochar (Ambaye et al., 2020; El-naggar et al., 2019). The quality of biochar depends entirely on the biomass sources and pyrolysis implementation. Pyrolysis parameters like heating rate, residence time, and temperature always affect biochar quality. The temperature at which biochar is pyrolyzed significantly affects its properties (Saadat et al., 2018; Tomczyk et al., 2020). As shown in Table 5, slow and fast pyrolysis yields biochars with different characteristics. It should also be noted that the biochar's characteristics may vary based on the feedstock utilized in its preparation, with some being more effective as soil amendments than others.

Certain quality factors are more critical than others, particularly in applying biochar. The pH, volatile chemical concentration, ash content, water holding capacity, bulk density, pore-volume, and surface area of biochar are critical quality characteristics in crop productivity (El-naggar et al., 2019). Carbon stability is an important performance criterion in the carbon sequestering and soil fertility enhancing processes. The soil's surface area and nutrient content are critical quality indicators in promoting soil fertility (Hu et al., 2020). The molar hydrogen to carbon (H/C) ratio constitutes an essential characterization measure for biochar since it indicates the material's degree of carbonization and stability. H/C ratios larger than 0.7 suggest poor quality biochar and pyrolysis limitations. The molar O/C ratio is significant for identifying and distinguishing biochar from other carbonization products. A value of O/C wider than 0.4 implies that the biochar is less stable (Talaiekhosani et al., 2021).

The molar ratios of H/C and O/C in lignocellulosic biomass are roughly 1.5 and 0.7, accordingly. Pyrolysis results in the devolatilization of biomass and the enrichment of the solid fraction with carbon. Hydrogen and oxygen are preferentially absorbed over carbon, and the H/C and O/C ratios tend to drop when biomass is converted into

biochar. The H/C and O/C ratios determine aromaticity and maturation (Gopinath et al., 2021).

5. Biochar properties

The properties of biochar for both proximate and ultimate analysis show various properties of biochar. Significant physicochemical factors, especially porosity, surface area, and pH, affect its suitability for water and wastewater treatment (Kameyama et al., 2019). Carbon, hydrogen, sulfur, oxygen, and nitrogen are all constituents of biochar, as are minerals in the ash portion. Thus, biochar properties will vary according to the production conditions and the type of biomass employed. For instance, as biomass is thermally oxidized to make biochar, the intrinsic carbon is lost as CO₂, CO, CH₄, and other hydrocarbons (Zhongzhe Liu et al., 2018). Moreover, if biochar is synthesized at greater temperatures, cracking and devolatilization occur, resulting in larger pore holes within the biochar. Table 6 summarises the chemical compositions of biochars derived from various biomass sources.

Thus, biochar's comparative and final study might reveal its desirable properties. The lesser the O/C and H/C ratios, the more oxygen and hydrogen are lost during combustion (Hassan et al., 2020), resulting in a product with unique elemental carbon content. The International Biochar Initiative (IBI) specifies an optimum molar H/C ratio of 0.7 to differentiate biochar from unmodified or slightly modified biomass (Alkurdi et al., 2019)(Zhang et al., 2020). Thus, selecting appropriate working conditions and technologies is compulsory to generate superior-quality biochar. The pH of biochar made from various materials is approximately 10, and the microscopic surface structure of biochars varies between approximately 3m²/g for paddy husk biochar and about 500 m²/g for wood biochar (Senthil and Lee, 2020).

6. Environmental applications of biochar

Biochar, a much cheaper carbonaceous product, has gained traction as a cost-effective alternative to activated carbon for reducing the number of organic contaminants from aqueous solutions and a variety of inorganic contaminants (Thomas et al., 2019). Due to its exceptional capabilities, including high sorption capacity, large specific surface area, microporosity, and ion exchange capacity, biochar offers a broader range of environmental applications. Such variety and predominance of a particular reaction are governed by the biochar's unique physicochemical properties, which are influenced by the biomasses sources and pyrolysis techniques utilized in its development. These two parameters radically influenced the physical and chemical parameters of the biochar and hence the overall surface property (Gaurav et al., 2020; Nasrullah et al., 2022; Tomczyk et al., 2020). Such differences in biochar properties dramatically impact its feasibility and efficacy for remediating specific contaminants. Besides, biochar might be applied as a catalyst, wastewater treatment, composting, energy storage, carbon sequestration, and soil

Table 5
Physical and chemical properties of biochar synthesized from diverse feedstocks and temperatures.

Pyrolysis Method	Feedstock	Residence Time(h)	Temperature(°C)	pH	Surface Area(m ² /g)	Volume(cm ³ /g)	Ref.	
Slow pyrolysis	Pine wood	0.5 h	500	8.7	380	0.15	(Leng et al., 2021)	
	Wood bark	0.5 h	500	9.8	350	0.14	(Dhyani and Bhaskar, 2018)	
	Wood bark	2 h	500	10.9	67.5	0.054		
	Rice husk	2 h	500	7.99	230.91	–	(Kameyama et al., 2019)	
	Paper mill sludge	2 h	500	8.78	47.42	0.063	(Lu et al., 2020)	
	Manure	4 h	500	10.5	13.0	–	(Song et al., 2019)	
	Paper mill sludge	2 h	600	9.17	50.44	0.074	(Lu et al., 2020)	
	Rice straw	3 h	600	9.7	156.2	0.084	(Alkurdi et al., 2019)	
	Wheat straw	3 h	600	9.1	183.3	0.091		
	Herb residue	3 h	600	10.1	51.3	0.051	(Zhou et al., 2019)	
	Soybean stover	3 h	700	11.32	420.3	0.19	(Thomas et al., 2019)	
	Peanut shell	3 h	700	10.57	448.2	0.20		
	Fast pyrolysis	Pine wood	s	400	–	4.8	–	(Leng et al., 2021)
		Pine sawdust	3 s	400	4.2	6.2	0.011	(Lee et al., 2020)
Sawdust		s	400	6.35	83.90	0.012		
Pine wood		2 s	425	–	1.35	–	(Leng et al., 2021)	
Switchgrass		30 s	450	9.1	1.4	0.012	(Oliveira et al., 2017)	
Pine wood		2 s	500	–	175.4	–	(Leng et al., 2021)	
Sawdust		3 s	500	6.42	36.60	0.015	(Lee et al., 2020)	
Rice husk		acid	500	–	46.8	0.033	(Gopinath et al., 2021)	
Sawdust		(3 s	600	7.00	30.20	0.010	(Lee et al., 2020)	
Switchgrass		30 s	600	10.6	2.1	0.023	(Oliveira et al., 2017)	
Rice husk		alkali	500	–	117.8	0.073	(Gopinath et al., 2021)	
Sawdust		3 s	700	9.08	65.20	0.016	(Lee et al., 2020)	
Sawdust		3 s	800	9.31	330.00	0.048		
Switchgrass		30 s	800	11.2	17.2	0.032	(Oliveira et al., 2017)	
Microwave	Straw pellet	–	200	–	1.14	0.37	(Ge et al., 2021)	
	Willow chips	–	170	–	3.87	2.07		
	Corn stover	15 min	650	10.5	43.4	–	(Nidheesh et al., 2021)	
	Pine wood	15 min	650	7.85	52.1	–		
	Switchgrass	15 min	650	9.73	48.0	–	(Lei, 2018)	
	Sludge	10 min	700	–	110.80	0.07	(Zaker et al., 2019)	
	Peanut shell	–	200	6.40	4.93	0.018	(Ao et al., 2018)	
	Peanut shell	–	400	6.76	20.8	0.034		
	Peanut shell	–	600	7.78	587	0.289		

Table 6
Elemental analysis of biochar derived from various biomass sources.

	Date Palm Rachis	Date Palm Leaflets	Empty Fruit Bunches	Date Palm Gleich	Plum Pulp	Orange peel	Hard Wood	Soft Wood	Rice straw	Wheat straw
Ref.	(Hassan and Carr, 2021)	(Idrus and Hamad, 2022)	(Amalina et al., 2019)	(Amalina et al., 2020)	(Contescu et al., 2018)	(Lei, 2018)	(Ayaz et al., 2021)	(Singh and Chandra, 2019)	(Babiker et al., 2020)	(Qayyum et al., 2020)
Ash(%)	5.50	11.58	4.20	2.40	–	–	9.86	58.53	–	3.60
pH	–	–	–	–	–	–	7.18	4.85	–	5.92
C (%)	39.95	43.14	43.49	43.65	39.32	40.43	53.96	22.67	34.24	70.6
H (%)	7.19	7.49	7.51	7.59	4.75	4.83	1.83	1.31	3.31	3.50
N (%)	0.16	0.20	0.19	0.16	2.40	1.56	1.24	3.04	1.50	4.46
O (%)	52.70	52.70	52.73	52.74	53.30	52.90	42.98	72.99	37.6	15.8

Table 7
The benefits and constraints of multiples biochar applications.

Applications	Aim	Benefits	Drawbacks	Ref.
Catalyst	Assist in the catalysis of direct reactions.	Low cost, a more significant proportion of functional groups, and a large surface area.	Reduce the efficiency.	(Enaime et al., 2020)
Energy storage	Utilization of materials as electrode materials.	Economical, extremely porous, and has a wide surface area.	Poor performance.	(Thomas et al., 2019)
Soil amendment	Increasing the fertility and quality of soils, as well as carbon sequestration.	Low cost, reduces GHG emissions, aids in retaining nutrients and water, and regulates nutrient loss.	Heavy metal and poly aromatic hydrocarbon contamination remain.	(El-naggar et al., 2019; Irfan, 2017)
Adsorbents	Organic and inorganic contaminants are removed from the soil and aquatic systems.	The minimal cost and increased oxygen groups in biochar improve the sorption of contaminants.	Pollutant degradation effectiveness is limited, and heavy metals retain in soil.	(Hassan and Carr, 2021; Haziq et al., 2020; Talaiekhazani et al., 2021)
Composting	Enhancing the microbial population's structure and carbon mineralization.	Porous reduces GHG, has a large surface area and retains nutrients.	There is a possibility that heavy metals and other toxins will infiltrate the soil.	(Diacono et al., 2019)

Table 8
Adsorption of organic and inorganic pollutants and the efficiency of pollutants removed utilizing selected biomass.

Contaminant	Adsorbate	Adsorbent	Biochar dosage(%)	Removal efficiency(%)	Ref.
Organic	Poly aromatic hydrocarbons	Shrub	10	32	(Shamsollahi and Partovinia, 2019)
		Paper mill waste	5	37.9	(Diacono et al., 2019)
	Polychlorinated dibenzo-p-dioxins	Wood chips	1	40	(Bhormick et al., 2018)
		Maize Stover	1	52.3	(Runtti, 2016)
					52.3
	Perfluoro octane sulfonate	Sallow	0.12	41	(Yang et al., 2016)
		Maize straw	0.12	70	(Irfan, 2017)
	Atrazine	Ecological waste	1	19	(Naik et al., 2019)
	Carbofuran	Wood chips	1	51	(Abo Omar and Abdallah, 2019)
	Trifluralin	Wheat straw	1	13	(Danish and Ahmad, 2018)
	Simazine	Ecological waste	2	95	(Hamzah et al., 2019)
	Phenanthrene	Wood	0.1–5	50	(Bedia et al., 2018)
	Pentachlorophenol	Rice straw	2	96	(Liu et al., 2020)
	Trichloroethylene	Peanut shells	0.03	70	(Wu et al., 2019)
	Isoproturon	Soybean Stover Wood	0.03	67	(Zhang et al., 2020)
2			49.8	(Yin et al., 2018)	
Contaminant	Adsorbate	Adsorbent	Biochar dosage (%)	Removal efficiency (%)	Ref.
Inorganic	Cd ²⁺	Rice straw	20	97.1	(Milke et al., 2020)
		Tree bark	10	>99	(Santoso et al., 2020)
		Sludge	40	93.6	
			8	99.9	
	Pb ²⁺	Rice straw	5	100	(Kandanelli et al., 2018)
		Chicken manure	5	93.5	(Zhang et al., 2020)
		Soybean	20	90	(Yin et al., 2018)
		Stover Sugarcane straw	5	50	(Naik et al., 2019)
	Zn ²⁺	Sludge	5	51.2	(Grobela et al., 2019)
	Cr	Sugar beet tailings	0.8	88.5	(Naik et al., 2019)
	As	Shrub	47	0	(Liu et al., 2020)
	U	Switchgrass	0.5	90	(Gwenzi et al., 2017)

amendment. Table 7 summarises the benefits and constraints of multiple biochar uses.

5.1. Adsorbent

The environmental application of biochar is one of its principal implementations. Biochar has garnered considerable interest in wastewater treatment (Xiang et al., 2020). Recent publications demonstrate that biochar is a super effective, ecologically friendly, low-cost adsorbent. Biochar properties are crucial for removing pollutants, frequently influenced by the pyrolysis temperature and feedstock source (Tanveer et al., 2018). For instance, completely carbonized biochar synthesized at a temperature of over 500 °C exhibits a stronger attraction for organic contaminants due to its large surface area, microporosity, hydrophobicity, and carbon-to-nitrogen (C/N) ratio, pH, and low dissolved organics. Besides that, slightly carbonized biochar obtained at a lower pyrolysis temperature of less than 500 °C incorporates a relatively high concentration of dissolved organic carbon and functional groups containing oxygen, as well as a poor porosity and C/N ratio, providing the potential again for removal of residual contaminants (Jawad et al., 2019; Kazemi et al., 2020). Biochar derived from forest biomass and farming wastes has a greater surface area than biochar produced from municipal solid waste and livestock manure. Other variables include pH (due to the pyrolysis process), contact time, application rate, and contaminant type that affect biochar's removal rate (Amalina et al., 2022).

Significant exploration has been undertaken on using biochar to remove various industrial organic and inorganic chemicals (Alkurdi et al., 2019; Enaime et al., 2020), as illustrated in Table 8.

5.2. Wastewater treatment

Biochar is a porous solid with a large surface area, making it an attractive alternative for wastewater treatment (Enaime et al., 2020). Biochar was shown to be an excellent medium for absorbing nutrients from effluent and might be used in the soil as a modification. Biochar is credited with continually increasing pollutants removal from wastewater along with its porosity and adsorption tendencies, which enable toxic substances to aggregate on its surfaces, resulting in a pristine discharge and nutrient-dense biochar (Shokry et al., 2020). Carbonized materials and crude biomass are increasingly being used in wastewater treatment (Nyoo et al., 2021). Numerous researchers conducted a meta-analysis to consider biochar and activated carbon's ecological and economic implications in the evacuation of harmful pollutants. The test found that biochar evacuates more efficiently than activated coal. It is thus demonstrated that, while the large surface area of activated carbon favours toxin adsorption via pore filling, many components, particularly surface functional groups, that facilitate biochar's removal execution (Gwenzi et al., 2017). As seen by biochar's lower greenhouse gas emissions, synthesizing activated carbon has a significant natural effect. Similarly, the production of activated carbon (97 MJ/kg) takes a more surprising amount of energy than the production of biochar (6.1 MJ/kg) (Kohtowski et al., 2017). Thus, biochar may be more effective than activated carbon at removing hazardous pollutants from wastewater when considering GHG emissions, energy demand, and associated costs.

Table 9
Biochar application in biofuel production.

Precursor	Biochar catalyst	Product yield (%)	Ref.
Canola oil	Forest plants	44	(Sakhiya et al., 2020)
Waste vegetable oil	Hardwood	81.5–88	(Talebian-Kiakalaieh et al., 2013)
Canola oil			
Palmitic	Peanut hull	70	(Karimi et al., 2018)
Stearic acid			(Drahansky et al., 2019)
Soybean oil			
Oleic acid	Commercial biochar	48	(Zuber et al., 2019)
Canola oil			
Waste cooking oil	Paddy husk	88	(Kazemi et al., 2020)
Sunflower oil	Palm kernel shell	99	(Amalina et al., 2019; Haziq et al., 2020)

5.3. Catalyst

Biochar's distinctive chemical structure, which contains a high surface area and specific surface functional groups, is simply generated via activation or functionalization and exhibits tremendous promise for application as a flexible catalyst or catalytic support in a wide variety of chemical reactions (Esteves et al., 2020). By oxidation, biochar may be simply separated from catalysts to extract precious metals. Thus, utilizing biochar as a catalyst will increase its use and assist in forming new catalysts. The biochar synthesized carbon-encapsulated iron nanoparticles, and its catalytic activity was assessed to convert synthesis gas to liquid hydrocarbons (Zhongzhe Liu et al., 2018). It was discovered that CO reduction was roughly 95% and liquid hydrocarbon specificity was as high as 68%. Likewise, biochar treated with potassium hydroxide (KOH) and sulfonated with fuming sulfuric acid (H_2SO_4) exhibits great isomerization in biodiesel generation (Zoroufchi et al., 2020). Catalysts have been critical in developing technology to convert traditional carbonaceous feedstocks and renewable carbonaceous feedstocks into natural worth products, equally fuels and chemicals (Zhang et al., 2018). The global catalyst market is expected to reach around \$34.3 billion by 2024 (The Global Catalyst Market, 2018), with catalytic technologies accounting for more than 35% of global domestic product (GDP) and over 95% of industrial products produced by catalytic reactions. Considering biochar's porous structure and high carbon content, it is a possible substitute for solid carbon-based catalysts, with several potential disadvantages, including high cost and being environmentally unfriendly. Numerous modifications, such as acid/base treatment or carbonization, might be given to the biochar to enhance its surface chemistry, making it an attractive option for catalytic processes (Esteves et al., 2020; Nasrullah et al., 2019). Waste biomass has become a more prominent renewable feedstock for producing fuels and platform chemicals. The impact of biochar as a catalyst on biofuel generation is shown in Table 9.

5.4. Energy storage and supercapacitors

Energy storage is critical to meet consumer needs for electrical and technological products. Supercapacitors are energy storage devices that support their rapid charge and discharge capabilities, high power density, and long cycle life. In contrast, rechargeable batteries have a high energy density and a low rate of charge/discharge (Nasrullah et al., 2017; Senthil and Lee, 2020). Further, lithium-ion batteries are utilized to store energy. The electrode materials determine the energy storage system's performance. These electrode products have a large surface area and a porous structure, which allow the active sites required for the oxidization. Carbon nanotubes, activated carbon, and graphene (Mankge et al., 2022; Mohamad et al., 2022) are extensively performed electrode materials. Due to the high cost of these carbon materials, their usage is limited. With this disadvantage, biochar as an electrode attracts interest (Gupta and Khatri, 2019). Like carbon material, biochar has a large surface area, is much more porous, and is inexpensive. Biochar is

an excellent electrode material for microbial fuel cells and supercapacitors (Thomas et al., 2019).

5.5. Carbon sequestration

Climate change has raised the urgency of reducing CO_2 emissions into the atmosphere. Soil is critical in the carbon cycle, which directly affects global warming. Carbon sequestration is feasible to lower CO_2 emissions through soil carbon sequestration (Talaiekhosani et al., 2021; Zaied et al., 2020). Since biochar is barely resistant to microbial breakdown due to an aromatic structure, it benefits soil carbon sequestration (Brown et al., 2020). Numerous publications have been published on biochar's ability to sequester carbon. However, no optimal data were recorded due to both excellent and negative impacts. Carbon emissions increased and were reduced in both directions (Bunce et al., 2018). Mineralization of organic matter in soil was more pronounced in poor fertile soils than in excellent fertile soils and soils with a high carbon content than in low carbon content soils (Jean et al., 2019; Nasrullah et al., 2020). Biochar has two forms of carbon: liable and recalcitrant carbon. Microbes readily consume available carbon after biochar application, resulting in more significant carbon mineralization during the first stage. Thus, biochar treatment resulted in the restoration of carbon mineralization (Jones et al., 2018). By comparison, recalcitrant carbon persists in the soil for a relatively long period. Thus, the amount of carbon fixed due to biochar application exceeds the amount emitted through relevant carbon mineralization. The effect of biochar on carbon sequestration is currently undetermined. The result varies depending on the type of biomass and pyrolytic circumstances. Since pyrolysis circumstances strongly affect biochar's physicochemical features, it is critical to establish a link between reaction circumstances and biochar's effect on carbon sequestration (Lu et al., 2020).

5.6. Animal feed

Besides soil improvement and carbon sequestration, biochar can be applied in animal feed and other animal husbandry aspects (Amalina et al., 2019). Current study findings by (Chiappero et al., 2020) indicate that by adding biochar to the animal diet may provide some essential benefits, including improved digestive process, enhanced immunity, decreased chronic botulism, higher feed intake and energy efficiency, enhanced growth rates, and reduced methane output (Masrom et al., 2018). Furthermore, as stated by (Schmidt et al., 2019), biochar as a feed ingredient can boost animal health, feed performance, and livestock productivity while reducing nutrient losses and greenhouse gas emissions and improving manure quality and hence soil fertility. When used in conjunction with other excellent farming practices, biochar can significantly enhance animal husbandry's sustainability performance. Numerous research on biochar feed additives also revealed that positive benefits on different metrics, including growth, digestion, feed efficiency, toxin adsorption, blood levels, meat quality, and/or emissions, were observed in many studies and across all farm

animal species (Amalina et al., 2020; Kumar et al., 2020). However, a considerable portion of the studies reported non-significant results. Most notably, none of the articles identified evidence of substantial adverse effects on animal health.

6. Conclusions

The article discusses biochar, a biomass waste-derived material, its physical and chemical properties, and its proximate analysis. The study outlines probable biomass wastes for biochar production. Numerous methods for producing biochar were explored. These are pyrolysis, torrefaction, HTC, slow, intermediate, fast, flash, and microwave-assisted pyrolysis. Biochars exhibit various physiochemical properties that significantly impact their vast range of applications. Biochars have a range of physical, chemical, and mechanical properties depending on the materials and pyrolysis preparations. The materials and operations of production have a considerable effect on the characteristics of biochar, including the concentrations of essential elements, density, porosity, and pH, all which affect the biochar's suitability for diverse applications. The slow pyrolysis method seems to be the most appropriate for producing biochar. Biochar's most prominent applications are also highlighted, notably in removing organic contaminants and heavy metals from wastewater. Biochar is primarily used as an adsorbent, a catalyst, and a support material for catalysts. The performance of biochar is discussed for various uses, along with numerous quality factors.

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Declaration of Competing Interests

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.

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