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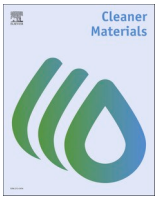

Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications

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ABSTRACT

Biochar is a carbon-rich product obtained from the thermochemical conversion of biomass. Utilizing biochar is essential for enhancing economic viability and maintaining the ecology effectively. This work reviews the techniques for producing biochar from various lignocellulosic biomass sources. Pyrolysis technology for converting lignocellulosic biomass into biochar has emerged as a frontier research domain for pollutants removal. The effects of biomass feedstock parameters, production techniques, reaction conditions (temperature, heating rate, etc.), activation, and functional group modification are compared on biochar's physical and chemical properties. This review also focused on environmental applications in several domains, such as agriculture and wastewater treatment. Considering the extensive availability of feedstock, excellent physical/chemical surface properties, and inexpensive cost, biochar has a remarkable potential for removing water pollutants efficiently. Studying the evolution properties of biochar by in-situ or post-modification is of great significance for improving the utilization value of lignocellulosic biomass. Biochar is a valuable resource, yet its application necessitates additional research into its properties and structure, as well as the development of techniques to modify those factors.

Introduction

Biomass as organic solid waste and renewable resource has garnered increased interest over the past few years. Biomass refers to the biological materials derived from living organisms or creatures with similar biological (Li et al., 2020; Senthil and Lee, 2020). Lignocellulosic biomass consists of carbohydrate polymers (hemicellulose and cellulose) and aromatic polymers (lignin) (Li et al., 2020; Yaashikaa et al., 2019; Yaashikaa et al., 2020), and it can be thermochemically converted into solid (biochar, tar), gas (syngas) and liquid (bio-oil) products (Jorge et al., 2021). Biochar is a porous carbonaceous solid material with a high degree of aromatization and high resistance to decomposition that is formed through the thermal breakdown of biomass from plant or animal waste in the absence of oxygen or under a limited oxygen atmosphere (Kumar et al., 2021; Yadav et al., 2022). However, numerous definitions of biochar may be found in the literature; accordingly, Rashidi and Yusup (Rashidi and Yusup, 2020) concluded that the term biochar remains undefined. Thus, the International Biochar Initiative (IBI) standardised biochar as "a solid material generated by thermochemically converting biomass in oxygen-limited conditions." As biochar and charcoal are formed from carbonaceous feedstock via the pyrolysis process, they have a similar production route. Nevertheless, biochar and charcoal can be distinguished by their beginning material and end application. Besides, European Biochar Foundation (EBF) reported biochar as "a porous, carbonaceous material that is produced by the pyrolysis of biomass and is used in such a way that the contained carbon serves as a long-term C sink or replaces fossil carbon in industrial production. It is not designed to be burned to generate electricity" (European Biochar Foundation (EBC), 2022). In addition to the primary element "carbon," biochar contains numerous supplemental factors that influence the action and function of materials. Biochar has a porous structure with large functional groups (rich in surface free radicals and surface charges) and a large surface area. It also contains minerals and trace metals (Esteves et al., 2020b, Tomczyk et al., 2020). Biochar is an electron acceptor and donor reservoir with pH buffering and cation exchange capacities (Sun et al., 2021a). These properties

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provide biochar with a high level of reactivity and are primarily influenced by the composition of the raw materials and production techniques (Fig. 1). Production techniques include slow or fast pyrolysis (Jesudoss et al., 2020), gasification (Gopinath et al., 2021), hydrothermal carbonization (Mbarki et al., 2019), torrefaction (Ge et al., 2021), and flash carbonization (Li et al., 2020), in addition to the regulation of the pyrolysis process and subsequent modification (Huang et al., 2021; Pan et al., 2021).

Due to its excellent physical and chemical characteristics, biochar is frequently employed in the removal of water contaminants (Amalina et al., 2022a), catalysis (Talaiekhozani et al., 2021), composting (Chen et al., 2019a,b), fermentation detoxication (Sadh et al., 2018), and electrochemical energy (Bolan et al., 2021; Mamaní et al., 2019; Waqas et al., 2018). Biomass source materials and numerous process parameters have significant effects on the physicochemical properties of biochar, hence directly determining its application (Amalina et al., 2022c). Biomass raw material's content and the thermochemical conversion conditions influence yield, physicochemical properties, and biochar quality. Biochar's physical and chemical properties can be enhanced through post-treatment (activation and modification)(Conte et al., 2021; Kameyama et al., 2019; Shamsollahi and Partovinia, 2019). In recent times, there has been a great deal of interest in optimising the pyrolysis conditions to increase the yield and quality of biochar; nevertheless, there has been a dearth of research into the design of biochar and the structure-application relationship between the physicochemical properties and applications of biochar.

The primary goal of this study was to demonstrate the potential of lignocellulosic biomass converted into biochar, a valuable substance with recent developments in biochar production techniques. Numerous environmental applications were reported based on understanding biochar's physicochemical properties.

Lignocellulosic biomass

Applying lignocellulosic biomass has attracted considerable interest due to its renewable properties, accessibility, and simplicity. Agriculture and forest are the primary sources of lignocellulosic biomass. The properties of biochar vary on the type and composition of the lignocellulosic feedstock used to produce biochar. The total carbon content of the biochar depends on the nature of lignocellulosic material, the thermochemical degradation process, and other factors. The essential components of lignocellulosic biomass are cellulose, hemicellulose, and lignin.

Cellulose

Cellulose is present in the plant cell wall and pure form in cotton fibres, composed of β–D-glucopyranosyl six-carbon ring sugar (Senthil and Lee, 2020; Yaashikaa et al., 2020). It supports the structure of the plant cell. Glucose dehydration produces the linear structure of cellulose. Microfibrils are formed when crystalline and non-crystalline phases intertwine (Bapat, 2020). The three hydroxyl groups of the pyranose ring interact to develop a crystalline structure. This offers cellulose stability and mechanical strength.

Hemicellulose

Hemicelluloses are polysaccharides with several branches surrounding celluloses (Hou et al., 2019). It works as a linkage between cellulose and lignin. Compared to cellulose, they are amorphous (not crystalline), and their composition and structure vary depending on the type of the lignocellulosic material (Ukanwa et al., 2019). Elements of hemicellulose include monomers which include glucose, mannose, arabinose, galactose, and others. The polymerisation degree is less than cellulose comprising 50–200 monomers (Raud et al., 2019).

Lignin

Lignin is an aromatic, branched, amorphous, heterogeneous, three-dimensionally cross-linked polymer strongly linked to cellulose and hemicellulose polymers (Contescu et al., 2018; Waters et al., 2017). Lignin is primarily found in the fibres' outer layer, which is crucial for sustaining structural rigidity. Roughly 40 % of lignin has been found in lignocellulosic biomass. Lignin works as a binding agent in the cell wall between cellulose and hemicellulose. 25 % lignin was reported in hardwoods and 33 % in softwoods, respectively (Contescu et al., 2018; Jorge et al., 2021; Rangabhashiyam and Balasubramanian, 2019). In addition to the chemical components, biomass contains inorganic components and extractives, particularly proteins, sugars, terpenes, gums, alkaloids, resins, lipids, saponins, etc. These substances can be extracted from biomass using either polar or nonpolar solvents. The inorganic components are depicted by ash (Cataldo et al., 2022; Daful and Chandraratne, 2018; Monterroso et al., 2020) .

Biochar production from lignocellulosic material

Biomass's thermochemical conversion forms biochar and other components, generally bio-oil, methane, carbon dioxide, hydrogen, etc (Hamzah et al., 2019; Othmani et al., 2021; Shahbaz et al., 2020). Typically, the biochar formed by thermochemical degradation has a high energy density (Leng et al., 2021). Biochar production from lignocellulosic biomass has attracted worldwide attention because of its accessibility and application on a broad scale. In general terms, lignocellulosic biomass can be categorised as follows: (i) agricultural residues (straw, sugarcane bagasse, husk, etc.) (Senthil and Lee, 2020; Ukanwa et al., 2019); (ii) forest residues (roots, wood chips, sawdust, etc.) (Bhardwaj et al., 2019; Venkatesh et al., 2022); and (iii) herbaceous biomass (switchgrass, elephant grass, etc.) (Conte et al., 2021; Kazemi et al., 2020). Various techniques for converting biomass to biochar include pyrolysis, hydrothermal carbonization, and gasification. In the absence of oxygen, biochar formed by pyrolysis undergoes thermal degradation. During this conversion, gaseous products such as CO_2, CO, H_2, CH_4, and moisture are emitted (Machrouhi et al., 2019; Yao, Ma, & Xiao, 2019). The biochar yield is determined by pyrolysis parameters

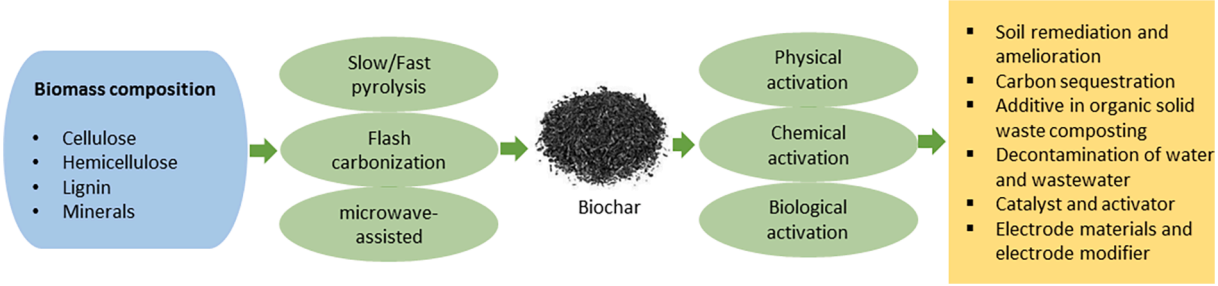

Fig. 1. Production and environmental application of biochar.

such as temperature, pressure, and heating rate. High furnace temperature, low pressure, and a rapid heating rate produce biochar with enhanced carbon content and a large surface area (Amalina et al., 2022a).

Hydrothermal carbonization is accomplished by dissolving biomass sources in water in a hermetically sealed system, which is then heated to 300 °C for approximately 16 h (Brown et al., 2020). The operation conditions and the presence of water produce biochar with a greater number of chemical functional groups. In addition, parameters such as temperature, pressure, and residence duration define the distinctive properties of biochar. Hydrothermal carbonization is spontaneous and exothermic; therefore, carbon existing in the original product is transferred to the final product (Mbarki et al., 2019; Selmi et al., 2018). Hydrochar is prevalent in oxygen functional groups, has a high cation exchange capacity, and requires additional energy to produce (Wei et al., 2021). Hydrochar has a smaller surface area, lower carbon stability, and fewer pores than biochar (Lei, 2018).

Pyrolytic conversion of lignocellulosic materials

Pyrolysis occurs by heating lignocellulosic material at high temperatures in the absence of oxygen. This is the first step in the gasification and combustion processes (Shafie et al., 2021). The final product of pyrolysis is biochar, a carbon-rich solid product. It is possible to obtain condensable and non-condensable volatile end products (Zaker et al., 2019). Fig. 2 illustrates the general process of pyrolysis. Cellulose, hemicellulose, and lignin, the constituents of lignocellulosic material, undergo diverse degradation routes to generate end products. Detailing the research of lignocellulosic biomass requires an assessment of the degradation of these components. These components undergo pyrolysis at the following temperatures: (i) cellulose, which is thermally stable due to its semi-crystalline chains, decomposes between 305 and 375 °C; (ii) hemicellulose, a polymer with branching and short side chains, decomposes between 200 and 350 °C; and (iii) lignin, phenolic structures breakdown at 250–500 °C (Hassan et al., 2020; Wei et al., 2021; Yaashikaa et al., 2019) .

The pyrolysis of the lignin component produces roughly 65 % more biochar than the pyrolysis of cellulose and hemicellulose, with their low liquid content of 0.5 %. The pyrolysis of cellulose and hemicellulose produced volatile chemicals, but the pyrolysis of lignin produced more solid biochar (Venkatesh et al., 2022). Numerous series and parallel processes such as dehydration, depolymerization, isomerization, and decarboxylation occur (Amalina et al., 2022a; (Lee et al., 2020). Different temperatures of biomass heating disrupt chemical bonds in the polymeric structure, releasing volatile compounds in the residue. This phase is known as the primary decomposition. The subsequent conversion of these volatile compounds is referred to as the secondary decomposition stage (Sakhiya et al., 2020). The pathway of lignocellulosic biomass degradation is depicted in Fig. 3.

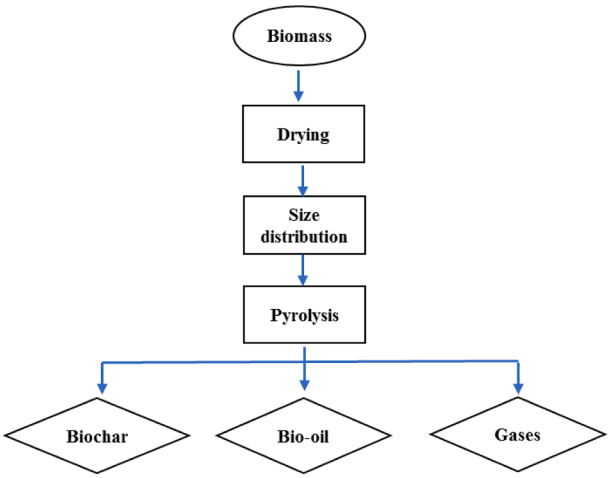

Fig. 2. General concept of the pyrolysis process.

At 200–500 °C, biomass degradation typically occurs during the primary decomposition process (Zamani et al., 2017). The pyrolysis of cellulose involves the initial conversion of cellulose into amorphous cellulose intermediates, followed by the conversion of irregular carbohydrates into aromatic carbon as the final product. Biochar is produced from biomass through intramolecular and intermolecular interactions (Goldberga et al., 2018). As the temperature rises, the hemicellulose components are converted into porous, smooth substances, decreasing functional groups (hydroxyl and methoxy groups). Secondary reactions of biochar, like cracking and polymerization, occur after the primary reaction, with polymerization being the primary cause of the secondary production (Li et al., 2020; Yaashikaa et al., 2020) .

Slow pyrolysis, fast pyrolysis, flash carbonation, and microwave-assisted pyrolysis can be distinguished based on the heating rate, residence time, and heating mode (Daful and Chandraratne, 2018; Iisa et al., 2019). Reza et al. (2020) summarise the types of biomass pyrolysis, their advantages and disadvantages, and the amount of biochar produced, as depicted in Fig. 4. Table 1 covers a variety of typical biomass pyrolysis processes and their corresponding biochar characteristics.

Slow pyrolysis has a temperature range of 400–600 °C, a prolonged residence time (several hours to several days), and a low heating rate. Ayaz et al. (2021) synthesised three forms of biochar from cow manure by slow pyrolysis. Subsequently, they characterized them, revealing distinct variances in morphology, surface area, pore structure, surface charge, and oxygen-containing functional groups. Slow pyrolysis, primarily used for biochar formation, is regarded as the optimal pyrolysis technique; the biochar yield is 30–60 %, and the specific surface area is 400 m^2/g.

Fast pyrolysis is typically conducted at temperatures between 450 and 600 °C, with a higher heating rate (200 °C/min) and a shorter residence time (a few seconds) than slow pyrolysis. This process occurs briefly; therefore, the impacts of heat and mass transfer, dynamics, and other factors significantly influence the product yield and process efficiency. Using a customized sedimentation tube reactor, Ha and Lee (2020) investigated fast pyrolysis behaviour and the product distribution of two typical coastal biomass fuels (artichokes and reeds). The results demonstrated that a fast-heating rate could overcome heat and mass transfer resistance and speed up the breakdown degradation of covalent bonds. These operating conditions for rapid pyrolysis were favourable to a low biochar yield (10–20 %). The short residence time may have contributed to the low calorific value and high oxygen content of biochar produced by rapid pyrolysis.

Flash carbonization is a more effective biochar manufacturing technology than conventional carbonization due to its high biochar yield (28–32 %) and short reaction time (30 min). In the operation of flash carbonization, the feedstock is initially packed into a packed bed reactor. The vessel is then pressurised to 1–2 bar using air, and its bottom is heated using a flame. The entire packed bed is heated for less than 30 min by the upward movement of the flame as air flows downstream (Li et al., 2020). Flash carbonization generally requires a specific level of pressure.

Microwave-assisted heating is an incredible alternative to traditional heating since it offers both external and internal heating. This enhances the rate of chemical reactions at lower temperatures, dramatically decreasing processing time and energy consumption. Studies have demonstrated that the chemical properties of biochar produced by microwave-assisted pyrolysis are more uniform than those of traditional pyrolysis. Talaiekhozani et al. (2021) fabricated mesoporous biochar with a high surface area and regulated aperture by activating the material and then pyrolyzing it in a microwave. The surface area of the nano-biochar produced by 600 W of microwave radiation was 357 m^2/g, with delicate and deep pores.

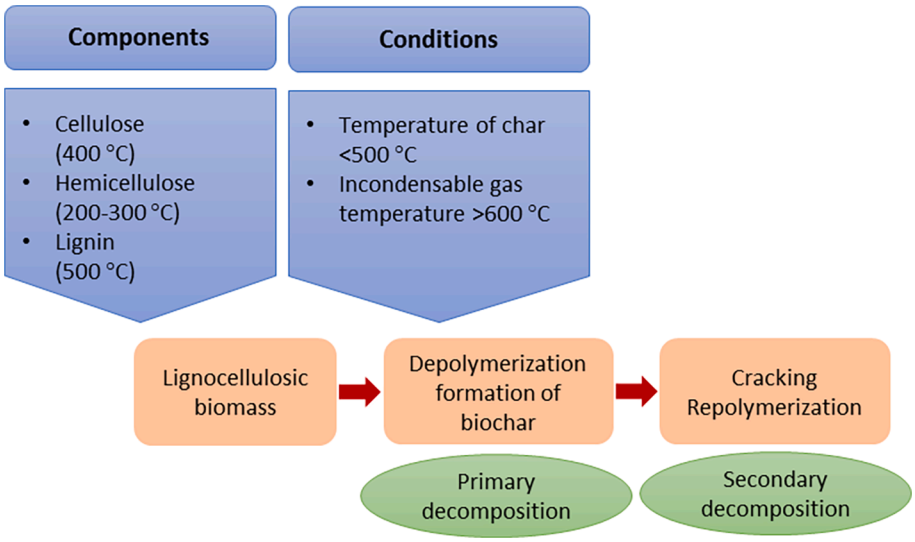

Fig. 3. Primary and secondary decomposition mechanism.

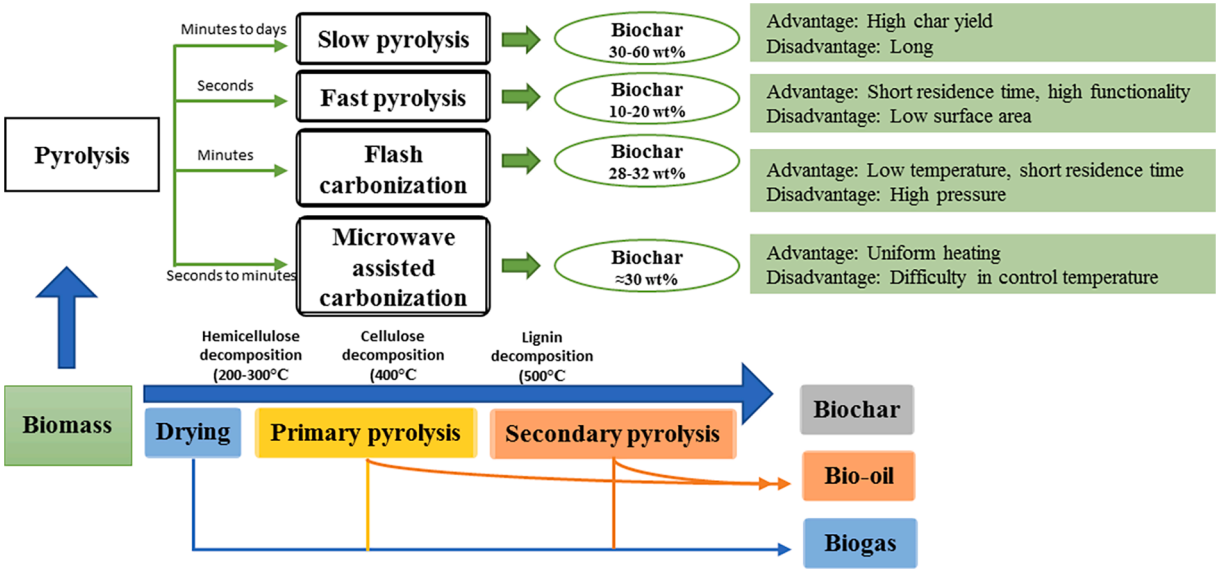

Fig. 4. Advantages and disadvantages of different types of biomass pyrolysis.

Factors influencing the pyrolytic conversion of lignocellulosic biomass

During the pyrolysis process, biochar characteristics are determined by the following parameters: feedstock, heating rate, temperature, and residence time. The vast majority of waste biomass can be directly converted into biochar using the pyrolysis technique if the resources are cost-effective and environmentally friendly. These properties are met by lignocellulosic biomass for its efficient biomass conversion.

Feedstock composition

The difference between the organic and inorganic components of biomass is contingent upon the nature, type, and environmental conditions of crop development (Conte et al., 2021; Diacono et al., 2019; Krishnan et al., 2021b). Moisture is crucial in selecting biochar type, as biomass with a high moisture content necessitates high conversion energy and temperature. Sometimes the carbon in biomass is heated to provide energy for the process, impacting the production of biochar and other products (Pallarés et al., 2018). Biomass containing more volatile compounds leads to bio-oil formation, whereas biomass having more carbon leads to biochar formation. The first phase in biomass decomposition is the removal of moisture, followed by the degradation of cellulose, hemicellulose, and lignin. High lignin content lignocellulosic biomass produces a high biochar yield (Santoso et al., 2020).

Heating rate

At a slower heating rate, particularly during secondary decomposition, biomass degradation is limited, hence boosting biochar yield. In contrast, the pyrolysis process at a high heating rate generates vast quantities of liquid, volatile compounds while minimising biochar yield. The pace of heating controls biochar's porosity and surface area (Ge et al., 2021; Shafie et al., 2021; Xu et al., 2020) .

Temperature

At higher temperatures, biomass is converted to gaseous, resulting in

Table 1
Operating conditions and biochar characteristics.

Types of pyrolysis	Biomass feedstocks	Temperature range °C	Heating rate °C/min	Residence time (min)	Reaction environment	Biochar yield (%)	BET surface area (m^2/g)	Applications	References
Slow pyrolysis	Tobacco petiole	300–700	10	30	N_2	33.3–53.7	0.42–7.51	adsorption-reduction removal of Cr(VI)	(Li et al., 2020)
	Palm kernel shell, empty fruit Bunch, etc.	500	10	60	N_2	35.14–79.16	–	–	(Kamyab et al., 2018)
	Halophyte grass	300,500,700	10	–	N_2	24–48	2.01–12.56	removal of iodine and methylene blue	(Irfan, 2017)
	Ulothrix zonata algae	400–800	15	120	N_2	46.2–22.6		adsorption of dyes	(Mishra et al., 2021)
	Phytoremediation plant	350–750	10	60	N_2	36.98–48.37	1.55–273.8	environmental acceptability assessment	(Hasanuzzaman et al., 2020)
	Fallen maple leaves	350–750	–	120	N_2	17–33	2.1–191.1	tetracycline removal	(Rasool et al., 2021)
Slow/fast pyrolysis	Beech wood	600–2000	5–450	6	Ar	6.5–14.0	7.9–127.8	–	(Danish and Ahmad, 2018)
Fast pyrolysis	Jerusalem artichoke stalks and reed	550–850	100, 300, 500	–	–	32.84–35.08		–	(Chiappero et al., 2020)
	Palm kernel shells	479–555	–	30–197	–	21.1–23.1	19.1–40.3	–	(Kamyab et al., 2018)
Flash carbonization	Rice straw	800–1200	1000	20	N_2	20.80–61.54	13.03–25.02 415.85 (Max.)		(Tsai and Jiang, 2018)
	Coconut husk	700–1000	103–104 /s	5 s	O_2 and steam	11.11–16.67	–	–	
Microwave-assisted	Prosopis juliflora biomass	300–600 W	–	–	–	–	–	adsorption of dyes	(Feng et al., 2021)

a decrease in biochar yield. On the biochar, the functional groups and carbon content are lost. The temperature during pyrolysis affects physicochemical parameters, including pH, surface area, carbon content, stability, surface charge, volatile content, etc (Ibrahim et al., 2021). Due to the gaseous compounds produced from biomass at high temperatures, biochar's surface area develops. Low-temperature biochar has the following characteristics: high polarity, acidic nature, low hydrophobicity, and aromaticity (Akdeniz, 2019; Leng et al., 2021). Typically, biomass degradation during pyrolysis occurs between 200 and 500 °C. During the process, hemicellulose may break down partially or entirely, followed by the total breakdown of cellulose and the partial decomposition of lignin (Esteves et al., 2020a, Gale et al., 2021).

Residence time

Conditions of low temperature and extended residence time are optimal for high biochar production (Bunce et al., 2018). Increasing the residence time for vapour facilitates the polymerisation of the biomass. On the contrary, if the biomass is given less residence time, polymerisation may not be complete, affecting biochar production (Ahmed et al., 2016; Liu et al., 2020d). In addition, residence time has a substantial effect on biochar properties such as porosity and surface area. Thus far, biochar yield has been increased by sustaining the biomass at 500–900 °C and a residence time of 2 h (Yao et al., 2019). In addition to temperature, feedstock, and heating rate, other influencing parameters, such as residence time's effect on biomass, are determined.

Advanced techniques for biochar characterization

Biochar characterization assesses its potential to absorb pollutants and for other applications. The structural and elemental study also helps anticipate biochar's environmental impact. The interaction between metals and biochar is pH-dependent, as i) the function of biochar varies with pH, and ii) the speciation of metal contaminant ions varies with pH. These biochar characteristics demonstrated its ability to operate as a highly effective adsorbent for eliminating most soil contaminants. The approaches for characterizing biochar are based on its structure, surface functional groups, and elemental analyses. Current advances in biochar characterization methods include Scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), Thermo-gravimetric analysis (TGA), Nuclear magnetic resonance spectroscopy (NMR), Brunauer-Emmett-Teller (BET), proximate and ultimate analysis, Raman spectroscopy, etc. Table 2 summarises the entire biochar characterization approaches that have been used. The characteristics of biochar are primarily determined by feedstock type, technology (process type, reactor design), and process conditions

Table 2
Detailed summary of biochar's characterization.

Characterization	Detailed analysis
Physical property	Surface area, pore volume and size (N_2 gas sorption)
	Particle size distribution (Laser sizing)
	Density (Mercury porosity, Pycnometer)
Chemical property	pH (pH meter)
	Electrical conductivity (Conductivity meter)
	Cation exchange capacity (Ion chromatography)
	Biochar compositions (CHNS, EDS, XPS)
	Metallic/ash contents (XRD, ICP, XRF)
	Proximate analysis (Muffle furnace, TGA)
	Surface functionality (FTIR, Raman)
	Surface acidity/alkalinity (Boehm titration)
	Surface aromaticity (13C NMR, Raman spectroscopy)
Surface structure & morphology	SEM/FESEM
	TEM
	Crystallinity (XRD, Raman)
Stability	TGA-DSC

(temperature, heating rate, residence time, pressure, carrier gas); consequently, the biochar's properties are highly variable.

Fourier transform infrared spectroscopy (FTIR)

Carboxylic (–COOH), hydroxyl (–OH), amine, amide, and lactonic groups are the essential functional groups present at the surface of biochar that enhance its sorption property. Biomass and temperature are the primary elements that impact the surface functional groups of biochar(Yaashikaa et al., 2020). Furthermore, when other properties like pH, surface area, and porosity are increased, biochar functional groups may be decreased. FTIR characterize the surface functional groups. The surface functional groups of biochar synthesised at various temperatures varied significantly. In addition to FTIR, NMR can be used to identify biochar surface and functional groups.

FTIR spectroscopy is a vibrational technique used to investigate the surface functional groups of biochar. As the temperature increases, biochar in compositions and auxiliary arrangements have undergone tremendous changes. These adjustments were detectable by a non-destructive FTIR system. The spectra revealed a continuous loss of aromatic groups in the higher temperature range of 650–800 °C. In Diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), potassium bromide is employed to convert the sample into pellet form. The pellet sample is brought into contact with ATR (attenuated total reflectance) crystal, and functional groups are predicted using ATR-FTIR (Tong et al., 2020).

Scanning electron microscopy (SEM)

Typically, biochar with a large surface area and high porosity will have a high sorption capacity. During the pyrolysis process, the porous surface of biochar is developed when there is an increase in water loss during dehydration. According to the International Union of Pure and Applied Chemistry, biochar pores can be micro (less than2 nm), *meso* (2–50 nm), or macro (>50 nm) in size. Regardless of the pesticide molecules' polarity or charges, biochar with smaller pores cannot absorb them. Using SEM, the pore size of biochar can be characterized. Biochar sorption capacity is mainly determined by surface area, whereas biochar synthesis is primarily influenced by temperature. The surface area of treated and untreated raw materials may differ. In commerce, activated carbon has a greater surface area. Without an activation procedure, biochar has a limited surface area and is less porous (Amalina et al., 2022b). Activation is employed during biochar production to increase biochar's porosity and surface area. The activation process may involve both the physical and chemical activation processes.

SEM-identified surface structures of biochar. Images captured by a SEM of biochars revealed that various methods and temperatures dramatically modified the surface morphology of the initial particles; nonetheless, they largely retained their visible form. In particular, the development of pores in biochar tests with increasing temperature may result in a substantial enhancement of the pore characteristics of biochar. It is also possible that, as the pyrolysis temperature increases, the crystallinity of mineral components will increase, and highly desired aromatic structures will form in biochar (Amalina et al., 2022a). Biochar's microporous and mesoporous distributions, as well as their pore arrangement, are depicted in depth by SEM images. SEM can anticipate the surface morphology before and after the adsorption process. Utilizing SEM and EDX (Energy dispersive X-ray spectroscopy), the elemental composition of biochar is analyzed. Using SEM-EDX, the many components present on the surface of biochar can be determined. Most biochar application investigations have used SEM-EDX to determine the biochar surface after it has absorbed pollutants. The primary disadvantage of SEM-EDX is that it cannot detect organic pollutants.

X-ray diffraction (XRD)

The XRD technique is widely applicable for determining the crystallinity and structure of biochar. In XRD, the diffractogram has shown specific properties of nebulous material generated at temperatures above 350 °C and is dependable. The computerized XRD features a monochromator, a radiation source, and a stepping motor(Yaashikaa et al., 2020). The nanocrystal's crystalline nature resembles the sharp and robust XRD peaks. As time progresses, the particle diameter increases. Therefore, XRD patterns facilitate the production of high-quality, non-destructive biochar with a high sorption efficiency.

Thermo-gravimetric analysis (TGA)

The thermal analysis uses TGA to observe a material's physical and chemical properties as a function of a temperature increase. TGA is commonly used to characterize and evaluate the thermal behaviour of diverse samples. This thermogravimetric analysis aimed to determine the igniting properties of biochar and biomass mixtures. Moreover, the expected weighted average of each component was examined to determine whether the synergic activity occurred between the blend components. The results may aid in better comprehending the warm process and characteristics of the examples from a broad perspective and for evaluating tests (Mankge et al., 2022). During this operation, biochar is heated from ambient temperature to 1000 °C. Numerous researchers have reported various temperatures, including 10 to 20 °C/min, 10 K/min, and temperatures below 1000 °C.

Brunauer-Emmett-Teller analysis (BET)

BET analysis can be used to assess the surface area of biochar. The surface area research is crucial since this biochar property is primarily responsible for removing pollutants from soil and water. Comparing the crude examples to their biochar counterparts reveals a significant increase in the BET surface zone following pyrolysis. Most notably, the natural feedstocks lack micropores, but the pyrolysis process formed new micropores in the char. For both feedstock types, porosity results, including BET surface area and micropore region, improved as force level increased from 2100 to 2400 W, resulting in a faster rate of remaining unstable discharge and an increase in micropore development at higher heating rates (Garba, 2017). The release of a substantial amount of volatile matter produces biochar with high porosity, diverse pore structures, and low density.

Nuclear magnetic resonance spectroscopy (NMR)

Using the spectroscopic technique NMR, the structural composition of biochar may be studied. NMR employs strong, attractive field and radio frequency (RF) pulses to examine the structure of particles via the reverberation frequencies of specific atomic cores. To characterize biochars, solid-state techniques can be used to determine the available amount of carbon functional groups, the estimated level of aromatic ring formation, and the overall structure of char molecules. Using NMR spectroscopy, the aliphatic and aromatic hydrocarbon content can be determined. NMR can compare the stability and carbonization of different biochars(Yadav et al., 2022). The presence of ferromagnetic minerals in biochar can interfere with NMR signals, and biochar formed by high-temperature pyrolysis has a low signal-to-noise ratio. This is the principal disadvantage of NMR spectroscopy.

Raman spectroscopy

Raman scattering is one of the most important and widely used subatomic spectroscopy techniques. It depends on the vibrational advancements of atoms when electromagnetic radiation illuminates. Raman radiation is the light dispersion with a changed repetition of the

incident radiation due to an incident or the absorption of vibrational energy in the atom. Develop a method for assessing the degree of synthetic/nanostructural changes during biomass carbonization. This method can rapidly determine the heat treatment temperatures (HTTs) applied in producing a specific biochar sample. Raman spectroscopy is excellent for biochar characterization due to its high sensitivity, minimal sample preparation, and low interference, but its cost makes it less applicable(Bolan et al., 2021).

X-ray photon spectroscopy

The biochars were characterized using X-ray photoelectron spectroscopy (XPS) to elucidate the structure and arrangement of the biochars obtained at different temperatures and from the other feedstock. XPS can identify and quantify functional groups and fundamental biochar components. The modification of oxygen-containing functional groups relates to the short-term stability of biochar. XPS is also used to measure the elemental O/C molar ratio, which might be a proxy for biochar stability(Yaashikaa et al., 2020).

Biochar modification

Activation or modification can further improve the properties of biochar (Nidheesh et al., 2021). This can be accomplished by introducing new functional groups to biochar surface to develop biochar matrix composites or by biological modification. Table 3 provides instances of biochar formation using activation and modification techniques. These procedures involve treating steam, bases, acids, carbonaceous materials, metal oxides, organic compounds, clay minerals, and microorganisms (Ahmad et al., 2019; Mamane et al., 2020; Mishra et al., 2021) .

Physical activation can enhance biochar's pore structure and volume. In addition, surface chemical properties (polarity, functional groups, and hydrophobicity) are improved by physical activation, which does not require chemical reagents because it is a simple, non-expansive procedure. Biochar is mainly activated through steam and gas activation (Astuti et al., 2019). The oxygen in water molecules is exchanged with the carbon on the biochar surface to generate surface oxides and hydrogen during steam activation (Zhang et al., 2020a). During the gas activation process, volatile compounds are eliminated, and pores are expanded. Carbon content has been found to increase with time and temperature when CO_2 is utilised (Sakhiya et al., 2020).

Employing chemical reagents, biochar is treated to undergo chemical activation. Acids (HNO_3, HCl, H_2SO_4, and H_3PO_4), bases (NaOH, KOH, and K_2CO_3), and oxidants (H_2O_2 and $KMnO_4$) are typical reagents (Guo et al., 2020; Idrus and Hamad, 2022; Krishnan et al., 2021b). Compared to physical activation, the operating temperature and time required for chemical activation are comparatively low and short, but the economic expenditures are substantial. Among these chemical activation approaches, acid treatment can increase the pore characteristics of biochar, including the porosity and surface area, probably due to the acid's ability to remove surface contaminants. In addition, acid treatment can add or enhance the number of acidic functional groups on the surface of biochar (Liu et al., 2020b). H_3PO_4 can degrade aromatic and aliphatic structures of biomass and generate phosphate/polyphosphate cross bridges to inhibit contraction or shrinkage during pore development, for instance (Kalaiarasi et al., 2020). Due to its corrosiveness, oxidation with HNO_3 has been demonstrated to degrade the microporous wall, decreasing surface area (Hu et al., 2020). Like acid activation, alkali treatment can increase the surface alkalinity of biochar and modify its porous structure. For example, alkaline activation of biochar with NaOH and KOH can increase surface basicity and oxygen content. To facilitate

Table 3
Characteristics of biochar activated using physical, chemical and biological activation methods.

Activation method	Biomass feedstocks	Activation reagent	Activation conditions	BET surface area (m^2/g)	Pore volume (cm^3/g)	Ave. pore diameter (nm)	References
Physical activation	Rice straw	H_2O	T = 700 °C 1 h	363	0.164	1.81	(Akdeniz, 2019)
	Almond shell	Steam	T = 850 °C 30 min	601	0.375	–	(Ao et al., 2018)
	Coffee endocarp	CO_2	T = 700 °C 30 min	820	0.4	–	(Rattanapan et al., 2017)
			T = 700 °C 1 h	554	0.28	–	
			T = 700 °C 2 h	919	0.49	–	
		Steam	T = 700 °C 1 h	630	0.35	–	
	Sewage sludge	CO_2	T = 670 °C	12	0.01	–	(Ambaye et al., 2020)
		CO_2	T = 750 °C	62	0.03	–	
		CO_2	T = 800 °C	7	–	–	
	Posidonia oceanica (L.) fibers	Steam	T = 600 °C 20 min	375	0.056	13.03	
			T = 600 °C 2 h	496	0.086	13.26	
			T = 600 °C 5 h	615	0.160	13.09	
			T = 600 °C 12 h	313	0.707	17.16	
Chemical activation	Rice straw	KOH	T = 700 °C 2 h	772.3	0.422	2.185	(Akdeniz, 2019)
	Sewage sludge			782.6	0.606	3.096	
		H_3PO_4	T = 450 °C	6	–	–	(Ambaye et al., 2020)
		H_3PO_4	T = 450 °C	17	–	–	
		NaOH	T = 700 °C	689	0.29	–	
	Soybean oil cake	K_2CO_3	T = 600 °C 1 h	643.54	0.336	1.04	(Ao et al., 2018)
		K_2CO_3	T = 800 °C 1 h	1352.86	0.680	1.01	
		KOH	T = 600 °C 1 h	600.05	0.299	0.99	
		KOH	T = 800 °C 1 h	618.54	0.291	0.94	
	Safflower seed press cake	$ZnCl_2$	T = 600 °C 1 h	249.3	0.151	2.42	(Leng et al., 2021)
			T = 700 °C 1 h	491.9	0.249	2.02	
			T = 800 °C 1 h	772.0	0.358	1.85	
			T = 900 °C 1 h	801.5	0.393	1.96	
		5 M $ZnCl_2$	T = 900 °C 1 h	555	0.752	2.26	
Biological modification	Water hyacinths	Chlorella	Cultured	–	–	–	(Shokry et al., 2020)
	Softwood bark and aspen wood	biofilm: microbial community	Cultured	4–973	0.01–0.3	–	(Oliveira et al., 2017)

the subsequent activation, NaOH and KOH can also dissolve ash and condense organic materials (cellulose and lignin) (Gupta and Khatri, 2019; Leng et al., 2021; Sajjadi et al., 2019). K^+ may be introduced into the crystalline layer that forms the condensed carbon structure during activation to create potassium species such as K_2O and K_2CO_3. These organisms could spread into the biochar matrix, enlarging existing pores and generating new ones (Pallarés et al., 2018). NaOH is believed to be less corrosive and more cost-effective for carbon activation than KOH. At low temperatures, NaOH-modified biochar's surface area and micropores are lower than those of KOH-modified biochar (El-naggar et al., 2019). In conclusion, acid and essential treatments provide distinct physicochemical features to biochar that affect its further applications. For instance, acid-treated biochar promotes the absorption of inorganic matter, whereas alkali-treated biochar promotes the absorption of organic matter (Liu et al., 2020b). Table 3 demonstrates that chemical activation considerably impacts biochar pore formation. (i) impregnating or coating metal oxides on the surface of biochar (including magnetic modification) (Sarkar and Dey, 2021), graphene oxide (Mankge et al., 2022), and other carbonaceous structures (Sun et al., 2021b); (ii) employing complex organic compounds such as chitosan (Chen et al., 2019a); or (iii) amino functionalisation (Li et al., 2020). Chemical activation produces composites with ultimately new functional groups on the surfaces of the biochar or raw material, which did not exist previously. The incorporation of heteroatoms (N, P, and S) into the carbon framework is another approach for modifying biochar (Bedia et al., 2018).

For the biological pre-treatment of biochar, natural modification involves the utilization of microorganisms, notably bacteria or anaerobic digestion. For instance, the zeta potential on the surface of biochar formed by anaerobic digestion achieves a high negative value, resulting in improved cation adsorption by functional groups (Haziq et al., 2020b).

As explained above, the purpose of these treatments is to: (i) increase the surface area of biochar; (ii) improve the surface properties of biochar; or (iii) embed another material, such as organisms, with advantageous surface properties.

Environmental applications of biochar

There has been considerable interest in using biochar for various environmental applications, such as pollutant removal, carbon sequestration, soil remediation and amelioration. Biochar's unique properties make it an efficient, cost-effective, and ecologically friendly substance for removing various pollutants. Variability in physicochemical properties allows biochar to enhance its effectiveness in selected applications. Moreover, biochar has more comprehensive environmental applications due to its distinctive characteristics, such as high adsorption capacity, specific surface area, microporosity, and ion exchange capacity (Amalina et al., 2022d; (Oliveira et al., 2017). This variability and predominance of a particular reaction are governed by the biochar's specific physicochemical properties, which are attributable to the feedstock types and pyrolysis conditions employed in its preparation. These two criteria drastically influence the biochar's physicochemical properties, including its surface area, polarity, atomic ratio, pH, and elemental composition, as well as its overall surface property(Amin et al., 2016; Jha et al., 2021; Malyan et al., 2021). These criteria in biochar characteristics have substantial consequences for its appropriateness and effectiveness in treating specific contaminants.

Soil remediation and amelioration

Biochar has been utilised to remediate the soil contamination caused by organic contaminants and heavy metals. Biochar remediates soil primarily through adsorption (Alkharabsheh et al., 2021). Surface complexation, hydrogen binding, electrostatic attractions, acid-base interaction, and pi-pi interactions all contribute to the biochar adsorption mechanism (Sun et al., 2021a).

Carya tomentosa and *Carya illinoinensis*-derived biochar can successfully prevent the leaching of clomazone and bispyribac sodium from soil (Wang and Wang, 2019). In contrast, Schmidt et al. (2019) discovered that biochar addition did not influence glyphosate and chlorpyrifos leaching. This disparity may result from the various physicochemical properties of the contaminant in the issue. Significant elimination of polycyclic aromatic hydrocarbons (PAHs) was observed with the addition of biochar generated from sawdust and wheat straw. However, when sodium azide was added to the soil, PAH removal dropped considerably, indicating that biodegradation played a significant part in PAH decomposition. Adding biochar can increase soil microbial activity (Ali et al., 2017; Brickler et al., 2021; Sun et al., 2021a). High molecular weight PAHs were more resistant to biodegradation than low molecular weight PAHs, such as three and four-ring PAHs.

The reduction of several types of organic contaminants from soil by adding biochar is highlighted in Table 4. The removal of organic pollutants from the soil by biochar was affected by several variables, including the types of feedstocks, the dose applied, the specific contaminants, and their concentration.

Biochar may effectively absorb heavy metal ions in the soil and organic contaminants. The principal heavy metal adsorption mechanisms on biochar are surface complexation, precipitation, cation exchange, chemical reduction, and electrostatic attraction (Rangabhashiyam and Balasubramanian, 2019; Sajjadi et al., 2019).

The adsorption of Pb, Cd, Cr, Cu, and Zn by biochar generated from wheat straw was investigated. The biochar exhibited varying metal adsorption capacities. Pb had the most incredible absorption by biochar among the metals. In addition, when the metals coexisted, Cd ions adsorbing to the biochar were rapidly replaced by ions of other metals. The biochar formed from water hyacinth may successfully adsorb approximately 90 % of As(V) (Zhou et al., 2020); however, the biochar derived from rice straw demonstrated the maximum adsorption of Zn^{2+} (Gaurav et al., 2020). This disparity may be attributable to varying feedstock and experimental conditions. Several parameters, including pH, surface functional groups, porosity, surface charge, and mineral composition, can influence the adsorption capability of biochar, as discussed in earlier studies (Abegunde et al., 2020; Sizmur et al., 2017). When employing biochar as a remediation method, a flexible strategy should be developed based on the organic contaminants involved.

The removal of heavy metals in soil by biochar is presented in Table 5. Variable heavy metal removal efficiencies were shown in Table 5 for several biochars. The experimental conditions, particularly the types of biochar and the initial concentration of heavy metals, were vastly varied, making comparisons challenging. Due to the varying physiochemical features of various biochars, their adsorption capacities for inorganic and organic contaminants differed. Therefore, selecting feedstock was essential than adjusting pyrolysis temperature or biochar surface characteristics to remove pollutants (Mishra et al., 2021). In addition, biochar was modified to increase its ability to remove heavy metals (Lember et al., 2019). In addition to the modification techniques, heteroatom modification can substantially enhance the heavy metal adsorption ability. By producing HgS with poor solubility, sulfur-modified rice husk biochar enhanced the removal of Hg (Tang et al., 2019). Biochar mixed with zero-valent iron improved the adsorption of Cu and As and led to the highest ecological recovery of the soil bacterial population (Ahmed et al., 2020), which reflects well on the in-situ stabilisation of heavy metal-contaminated areas.

In addition to removing organic contaminants and heavy metals, biochar can neutralise acidic soil, boost cation exchange capacity, and improve soil fertility. Wang and Wang (2019) reported that after one month of treatment with soybean stover-derived biochar and oak-derived biochar, the soil's acidity increased by 2 units. With 5 % biochar, the cation exchange capacity was significantly increased. In addition, the soil improvement brought about by biochar facilitated the development of maize. In addition, the dose of biochar applied

Table 4
Adsorption of organic pollutants in soil by biochar.

Organic pollutants	Initial concentration (mg/kg)	Biomass feedstocks	Pyrolysis temperature (°C)	Applied dose (%)	Removal efficiency (%)	References
Dibutyl phthalate	100	Bamboo	650	1	87.5	(Wang et al., 2018a,b)
Phenanthrene	150	Conifer	600	0.5	100	(Conte et al., 2021)
Pentachlorophenol	150	Poplar	600	0.5	100	(Mahfooz et al., 2021)
Imidacloprid	–	Rice-straw	600	5	–	(Bartoli et al., 2020)
Imidacloprid	–	Wheat-straw	450	5	–	(Wang and Wang, 2019)
Diethyl phthalate	50	Bamboo	820	0.5	~90	(Wang et al., 2018a,b)
Carbamazepine	–	Wood	450	0.5	–	(Garba, 2017)
Sulfamethazine	–	Hardwood	600	2	–	(Oliveira et al., 2017)
Tylosin	50	Hardwood	850	10	66	(Wang and Wang, 2019)
Acetamiprid	250	Eucalyptus spp.	450	0.5	52.3	(Danish and Ahmad, 2018)
Pentachlorophenol	50	Rice-straw	–	2	96.2	(Cui et al., 2017)
Chlorpyrifos	50	Gossypium spp.	850	1	34	(Masciandaro et al., 2013)

Table 5
Stabilization of heavy metals in soil by biochar.

Heavy ions	Initial concentration (mg/kg)	Biomass feedstocks	Pyrolysis Temperature (°C)	Applied dose (%)	Removal efficiency (%)	References
Cd^{2+}	1.4	Eucalyptus wood	500	2	80	(Danish and Ahmad, 2018)
Pb^{2+}	2463				93.7	
Zn^{2+}	1628				97.1	
Cu^{2+}	80				99.8	
Cd^{2+}	20	Rice straw	400	5	–	(Shamsollahi and Partovinia, 2019)
Cd^{2+}	~0.23	Bamboo	750	5	~56	(Shao et al., 2018)
Pb^{2+}	3.0				~66	
Cu^{2+}	3.5				~71	
Zn^{2+}	60				~21.7	
Cd^{2+}	~0.23	Rice straw	500	5	~50	(Shamsollahi and Partovinia, 2019)
Pb^{2+}	3.0				~93	
Cu^{2+}	3.5				~91	
Zn^{2+}	60				~67	
Pb^{2+}	1259.58	Pinecone	500	5	–	(Mishra et al., 2021)
As^{3+}	52.58				–	
Cd^{2+}	~0.53.09	Rice straw	500	20 t ha^{-1}	97.1	(Kaur et al., 2018)
Cd^{2+}			500	5	25.8	
Cu^{2+}	~33				97.3	
Pb^{2+}	~23				81.9	
Zn^{2+}	~440				62.2	
Cd^{2+}	2	Bamboo	750	2	–	(Dawood et al., 2017)
Cd^{2+}	5950	Tree bark	400	10	>99	(Ranasinghe et al., 2019)
Zn^{2+}	6650				>99	
Cu^{2+}	964	Pine bark	420	1	>99	(Dawood et al., 2017)
Ni^{2+}	–	Woody biomass, Gliricidia sepium	900	5	93	(Wang and Wang, 2019)
Cr^{2+}	–				97	
Mn^{4+}	–				92	
Zn^{2+}	2027	Sugar cane straw	700	5	54	(Bhardwaj et al., 2019)
Pb^{2+}	3688				50	
Cd^{2+}	6.4				56	
Cd^{2+}	50	Bamboo	400	1.5	87.4	
Pb^{2+}	696	Soybean stover	700	20	90	(Hassan et al., 2020)
Cd^{2+}	3.13	Wheat straw	550	40 t ha^{-1}	93.6	(Ringer, 2022)
Pb^{2+}	2	Rice straw	300	5	100	(Qin et al., 2020)
Cu^{2+}	1419	Cottonseed hull	800	20	–	(Tomczyk et al., 2020)
Pb^{2+}	14,847				–	
Zn^{2+}	205				–	

considerably impacted the growth of maize. It was discovered that maize grew best with 3 % biochar.

The addition of biochar can enhance the fertility of the soil. According to Ao et al. (2018), biochar derived from woody biomass has varying effects on various crops. Biochar from a woody biomass enhanced radish biomass, not wheat or soybeans. Biochar generated from bamboo improved maize production and growth (Wang et al., 2018a).

The improvement of soil fertility due to the addition of biochar may be attributed to the following factors: (i) the increase in water-holding capacity (Ringer, 2022); (ii) the increase in soil aggregates stability (Ayaz et al., 2021); (iii) the alleviation of soil compaction; and (iv) the decrease of soil bulk density and increase in porosity (Venkatesh et al., 2022).

Although adding biochar reduced bulk density, it improved porosity, which may provide more available water. The factors above may enhance root growth, enhancing crop growth and yields. However, the primary explanation for the increase in soil fertility must be further investigated based on soil and feedstock types. Recent research revealed that the dose of organo-mineral biochar applied significantly impacted ginger yield and nutrient cycling. A high dose of organo-mineral biochar boosted the availability of soil P and K and enhanced the economic value of ginger (Ringer, 2022). In addition, aged biochar exhibited features distinct from those of fresh biochar. The mineralisation rate of biochar

was greater than that of raw biochar. In addition, biochar exhibits more microbial and enzymatic activity (Negawo et al., 2017), indicating that aged biochar can perform better in environmental applications.

Carbon sequestration

Reducing the amount of carbon dioxide emitted into the atmosphere has become more critical considering climate change. As a significant carbon sink, soil plays a vital role in the global carbon cycle, directly impacting climate change (Pan et al., 2021). Carbon sequestration has been a method to reduce soil carbon dioxide emissions. Due to its highly condensed aromatic structure, biochar is often resistant to biodegradation (Shimabuku et al., 2016). Therefore, biochar is expected to impact soil carbon sequestration positively.

Numerous researches have been performed to examine the impact of biochar on soil carbon sequestration. However, there has been no consistent effect because both increased and decreased carbon dioxide emissions have been recorded (McHarg et al., 2022; Pan et al., 2021; Venkatesh et al., 2022). For example, the addition of carbon produced from fire to soil accelerated soil organic carbon turnover (El-naggar et al., 2019). However, adding biochar from wood sawdust to soil decreased carbon mineralisation, resulting in increased carbon sequestration (Abdulrahman et al., 2020). Feng et al. (2021) demonstrated that biochar's carbon sequestration was attributable to biochar-generated carbon rather than carbon produced from soil organic matter.

Daful and Chandraratne (2018) conducted a meta-analysis of decomposition and priming effects on published studies. After adding biochar, the mineralisation of soil organic matter was shown to be greater in low fertility soils than in high fertility soils. Similarly, carbon mineralisation was more remarkable in soils with low organic carbon concentration than in soils with high organic carbon content (Pan et al., 2021). Moreover, the incubation period strongly impacted the priming effect of biochar (Tomczyk et al., 2020).

Carbon in biochar can be separated into liable and insoluble carbon (Yaashikaa et al., 2020). When biochar is introduced to soil, soil microorganisms may quickly consume utilisable carbon, resulting in an initial rise in carbon mineralisation. This explained why the addition of biochar enhanced carbon mineralisation. Biochar contains far more refractory carbon than labile carbon (Ukanwa et al., 2019). Carbon resistance to decomposition can persist for an extended period in soil. Thus, the carbon input from adding biochar exceeds the carbon output from the mineralisation of liable carbon.

In general, the effect of adding biochar to carbon sequestration remained yet undefined. It is crucial to explore the relationship between the development of biochar and the kind of feedstock since the priming effect changes depending on the feedstock and pyrolysis conditions. Since pyrolysis circumstances significantly impact the physiochemical properties of biochar, it is also essential to investigate the relationship between pyrolysis conditions and the carbon sequestration effect of biochar. In addition, soil components should be assessed while examining biochar-induced carbon sequestration.

Catalyst and activator

Biochar may also act as a catalyst. It was employed as a catalyst in the production of biodiesel. For instance, hardwood biochar exhibited intense activity for the esterification of free fatty acids following sulfonation and smudging (Cheng and Li, 2018). In addition, biodiesel has a high acid density. Wang and Wang (2019) revealed that biochar generated from Douglas fir was substantially esterification active, which can lower fatty acid content. In addition, the catalyst could be reused 10 times without losing its catalytic activity. Due to its hydrophobicity and high acidity, sulfonic acid-functionalized hydrophobic mesoporous biochar increased the catalytic activity and stability in the alkylation reaction of 2-methylfuran with cyclopentanone, according to the most recent study (Zhang et al., 2018). In addition, biochar as a carrier inhibited the lipase produced by *Pseudomonas* sp. ISTPL3 boosts biodiesel production (Cao et al., 2017).

Sulphate radicals-based advanced oxidation processes have garnered significant interest in water and wastewater treatment. Persulfate could be activated effectively to produce sulphate radicals. Common ways of activation include heat, UV light, metal ions, and metal oxides (Waqas et al., 2018). Metal ions and metal oxides were extensively researched among the activated procedures. While metal ion activation can lead to secondary water contamination, metal oxide activation has limited persulfate activation stability. Carbon materials such as graphene were utilised as carriers to transfer metal ions to reduce the pollution generated by metal ions and enhance the stability of metal oxides.

The compound of carbon materials and metal oxides displayed improved persulfate activation capacity but lacked long-term stability (Li et al., 2022). Currently, most research uses carbon materials as a carrier to increase the stability of metal oxides, but the significance of carbon materials in activating persulfate has been overlooked. Recent interest in carbon materials as persulfate activators has increased due to benefits such as no secondary emissions and inexpensive costs.

Carbon materials activate persulfate in the following ways: (i) oxygen-containing functional groups on the surface of carbonaceous materials (Hassan and Carr, 2021); (ii) faulty structure in the carbonaceous materials (Senthil and Lee, 2020); and (iii) electron transmission mediator between persulfate and targeted pollutants (Mustapha et al., 2019).

Therefore, the contribution of carbon-based materials to persulfate activation must be addressed when carbon-based materials containing metal oxides are utilised as the persulfate catalyst.

As a carbon product, biochar has many functional groups that could activate persulfate. However, few investigations have been into the activation of persulfate by biochar to remove organic pollutants. According to our most recent study, biomass-derived biochar may activate peroxymonosulfate to create sulphate radicals. Nidheesh et al. (2021) found that magnetic nitrogen-doped biomass-derived biochar may activate persulfate for tetracycline hydrochloride decomposition. In addition, iron compounds, doped nitrogen, and graphitic carbon were responsible for persulfate activation, demonstrating biochar's contribution to persulfate activation. According to Enaime et al. (2020), biochar generated from pine needles can activate persulfate for the decomposition of polychlorinated biphenyl. Devi and Saroha (2016) discovered that biochar produced from biomass may successfully activate persulfate for 4-chlorophenol degradation. In 100 min, the removal efficiency of 4-chlorophenol reached 92.3 %. Biochar can activate persulfate; however, the resulting reactive species vary. This was because of the many activation mechanisms.

During pyrolysis, biochar may have a faulty structure, contributing to persulfate activation. In addition, persistent free radicals, such as semiquinones and phenoxyl, can contribute to persulfate activation. The metal ions in the sewage sludge's biochar could also contribute to persulfate activation (Amalina et al., 2020b). Different modes of activation led to the establishment of distinct reactive species. Two forms of persulfate have been identified: peroxydisulfate and peroxymonosulfate. Due to its specific molecular structures, biochar exhibited varying activation capacities for peroxydisulfate and peroxymonosulfate.

During persulfate activation, sulphate radicals, hydroxyl radicals, superoxide radicals, and singlet oxygen are produced as reactive species (Li et al., 2022). The oxidising capacity of these reactive species differs from that of organic contaminants. Therefore, the potential of persulfate to degrade organic pollutants may vary. The feedstock type significantly influences carbon, hydrogen, oxygen, and nitrogen quantities. Similarly, the preparation conditions can affect the carbon, hydrogen, oxygen, and nitrogen ratio.

Moreover, its modification methods can affect biochar's surface characteristics and electron density. Therefore, feedstock sources, preparation conditions, and modification techniques can influence the activation capability of biochar by changing its physiochemical

characteristics. Few investigations have identified the primary factor influencing the types of reactive species generated during the persulfate activation process. Future research should investigate the relationship between biochar characteristics and the types of reactive species generated during persulfate activation.

Biochar containing metal ions could accelerate the decomposition of polychlorinated biphenyl (Oliveira et al., 2017). However, emphasis must be paid to the metal biochar composite's stability, and biochar's contribution to persulfate activation must be re-evaluated. To promote the use of biochar in activating persulfate, however, additional research into the activation mechanism of persulfate by biochar is required. To examine the activation process of persulfate by biochar in depth, it is necessary to combine experimental results, analytical methods, and theoretical calculations such as density functional theory.

Biochar can be utilised as a catalyst for persulfate activation and in microbial fuel cells (Patwardhan et al., 2022). As a catalyst, biomass-derived biochar effectively increased power output (500 mWm^{-2}), comparable to Pt/C (Tang et al., 2019). Sonu et al. (2020) revealed that corncob-derived biochar synthesised at 650 °C as a catalyst produced 458.85 mWm^{-2} of electricity. The mechanism of biochar as a catalyst in microbial fuel cells was determined to be the enhancement of electron transfer brought about by the high graphite and pyridinic nitrogen levels of biochar generated from corncobs. The electrochemical properties of biochar are closely connected to its electron transfer capacity. Consequently, future research should study the correlation between the electrochemical characteristics of biochar and electron transfer.

Additive in organic solid waste composting

The constant accumulation of solid waste negatively impacted the sustainable development of human society, a topic that has generated considerable concern. Organic waste constitutes around 50 % of all substantial trash (Abdel-Shafy and Mansour, 2018). Efficiently treating organic solid waste is crucial for the effectively disposal of solid waste (Abdel-Shafy and Mansour, 2018). Composting as a waste treatment method has garnered significant attention due to its inherent benefits, such as low cost (Akdeniz, 2019).

Composting is an organism-based process. During the process, the raw material's organic matter encountered biological degradation (Amalina et al., 2020a; Sadh et al., 2018). The presence of biochar directly affects microbes, influencing the composting process (Lu et al., 2020). Numerous researches have investigated the effect of biochar addition on organic waste composting.

Biochar has the following effects on microorganisms during the decomposition of organic solid waste: (i) to offer a habitat for microorganisms; (ii) to provide optimal growing circumstances for microorganisms; and (iii) to increase microbial diversity. Due to the beneficial effect of biochar addition on composting, it has been determined that biochar addition hastened the degradation of organic solid waste. The development of biochar addition to composting is presented in Table 6.

The inclusion of biochar has a beneficial impact on composting in general. However, the priming effect might be ignored in poor fertility, alkaline, temperate soil (Sadh et al., 2018). Thus, the varieties of soil influence the efficacy of biochar in composting. Furthermore, the types and dosage of biochar, as well as the types of soil, have significant effects on the composting of organic solid waste. Therefore, an application strategy for biochar should be developed depending on the characteristics of composting organic solid waste and soil.

In addition, it was discovered that a bacterial consortium combined with biochar could stimulate microbial activity to accelerate degradation, increase the richness and modify the specific selection of bacterial community (Lee et al., 2020). This provides a method for effectively enhancing microbial activity and accelerating the degradation of organic solid waste.

Decontamination of water and wastewater

Numerous studies have demonstrated that biochar can remove organic and inorganic contaminants from water and wastewater through adsorption (Amalina et al., 2022a). Antibiotics are becoming pervasive environmental organic pollutants (Madikizela, 2021). It was established that biomass-derived biochar is a cost-effective and reusable antibacterial drug adsorbent (Amalina et al., 2019; Jaroniec et al., 2020). Table 7 summarised the decontamination of suspended contaminants from water by biochar via sorption.

The physiochemical properties of specified pollutants and the varieties of biochar influence the adsorption of contaminants by biochar in water. For instance, biochar synthesised from non-woody biomass may

Table 6
Effect of biochar addition on the composing performance.

Biomass feedstocks	Pyrolysis temperature (°C)	Applied dosage	Performance	References
Peanut shell	350	0.75 % biochar and 0.75 % compost (w%)	Stimulate the productivity of sesbania, seashore mallow, and total biomass.	(Sakhiya et al., 2020)
Rice husk	500	24 g compost þ 16 g biochar in 400 g soil	Substantially increase organic carbon and water-extract organic carbon; reduce the availability of Cd and Zn; enhance the availability of Cu.	(Akdeniz, 2019)
Acacia	350–450	2 t ha^{-1} biochar, 10 t ha^{-1} compost and 92 kg N ha^{-1}	Enhance grain yields and N uptake.	(Olasehinde et al., 2018)
Acacia green waste	550	47 t ha^{-1} biochar and 10 t ha^{-1} compost		
Logs	550	2.5 t ha^{-1} biochar and 25 t ha^{-1} compost	Enhance microbial affluence; modify microbial structure; boost macroporosity and bioturbation Enhance soil organic carbon, soil nutrient status, soil water content, and maize production.	(Bolan et al., 2021)
Hardwood, coniferous wood	750	8 t ha^{-1} biochar and 55 t ha^{-1} compost	There is no immediate economic utility for vines growing in alkaline, low-fertility, temperate soil.	(Wang and Wang, 2019)
Wood	500–600	0.3 kg compost and 0.27 kg biochar	Enhance the humification of sludge organics and improve their oxygen absorption.	(Gaurav et al., 2020)
Beech wood	350–450	100 mg/kg biochar and 100 mg/kg compost	Improve plant height, total organic carbon content, and total N content; reduce ammonium.	(Danish and Ahmad, 2018)
Residues of charcoal production	–	20 mg ha^{-1} biochar and 32.5 mg ha^{-1}	Enhance the soil's organic matter content, nutrient levels, and capacity for water storage.	(Waqas et al., 2018)
Quercus serrate	400–600	10 % biochar and 90 % compost	Change the structure of the microbial community.	(Wang and Wang, 2019)
Hardwood coniferous wood	750	8 t ha^{-1} biochar and 63 t ha^{-1} compost	Raise the number and activity of microorganisms without effect on the available Cu.	(Wang and Wang, 2019)

Table 7
Removal of organic contaminations from water and wastewater.

Adsorbates	Initial concentration (mg/L)	Biomass feedstocks	Pyrolysis temperature (°C)	Applied dose (g/L)	Removal efficiency (%)	Reference
Norfloxacin	10	Corn stalks	500	4	97.62	(Mbarki et al., 2019)
Sulfamethoxazole	20.3	Pinus radiata sawdust	650	2	100	(Wang and Wang, 2019)
Methylene blue	50	Mangosteen peel	800	3	80	(Machrouhi et al., 2019) (Nyoo et al., 2021)
salicylic acid	500	Waste Douglas fir	900–1000	0.4	100	(Burk, 2017)
4-nitroaniline benzoic acid		Corn straw				(Kameyama et al., 2019; Wang and Wang, 2019)
Atrazine	30		500	4	100	
Sulfamethoxazole	1	Wood	850	40 mg/L	20–30	Zhu et al., 2018)
Polychlorinated biphenyls	1	Corn straw	700	50 mg/L	n.a.	(Kameyama et al., 2019)
Tetracycline	5	Rice-husk	500	0.4	~90	(Wang et al., 2018a,b)
Trichloroethylene	20	Soybean stover	700	0.3	~55	(Thomas et al., 2019) (Wu et al., 2019)
		Peanut shell			~55	
Tetracycline	1000	Rice husk	500	5	–	
Methyl violet	816.06	Canola straw	350	8	–	(Gwenzi et al., 2017)
Phenanthrene	1	Soybean Stalk	700	0.33	99.5	(Liu et al., 2020c)

remove 20.3 mg/L of sulfamethoxazole (Weber and Quicker, 2018); however, biochar made from wood had a much lower removal effectiveness of sulfamethoxazole (20 to 30 %) (Tripathi et al., 2016). The biochar obtained from an organic farm had the lowest sulfamethoxazole removal effectiveness (6 %) (Leng et al., 2019). Various pyrolysis temperatures resulted in different tetracycline removal efficiencies for biochar generated from rice husk (Palansooriya et al., 2019). When the pyrolysis temperature was 800 °C and the initial concentration of tetracycline was 200 mg/L, the elimination efficiency ranged from 26 % to 60 %. The reduction efficiency reached approximately 90 % when the pyrolysis temperature was 500 °C and the initial concentration of tetracycline was 5 mg/L.

The temperature of pyrolysis had a significant effect on the adsorption capacity of biochar. In addition to pyrolysis temperature, other variables, such as pyrolysis time, can modify the physiochemical characteristics of biochar, which in turn affects its adsorption capability.

Heavy metal pollution is a significant environmental remediation concern. Adsorption efficiently removes heavy metals from aquatic environments (Haziq et al., 2020a; Nasrullah et al., 2020). The reduction of heavy metal ions by biochar is outlined in Table 8. Like removing organic pollutants by biochar, eliminating heavy metals by biochar depends on the types of heavy metals and feedstocks. Biochar exhibited a reduced removal capability for Cd^{2+} and As^{5+} compared to other common heavy metals such as Pb^{2+} and Zn^{2+}.

The pyrolysis temperature considerably altered the biochar's adsorption capability. For example, the biochar produced from corn straw exhibited varying Cu^{2+} adsorption capacities. At a pyrolysis temperature of 800 °C, 1 g/L of biochar was necessary to remove 1 mM of Cu2 +. At 400 °C, 20 g/L of biochar was required to remove 20 mg/L of Cu^{2+}. The water hyacinth-derived biochar demonstrated distinct adsorption capacities for Cd^{2+} and Pb^{2+}, demonstrating that the adsorption capacities of biochar varied depending on the specific heavy metals. It is observed that the functional groups have a noticeable effect on the adsorption capacity of biochar treated with functional groups. For

Table 8
Removal of metals and metalloids from water and wastewater.

Adsorbates	Initial concentration (mg/L)	Biomass feedstocks	Pyrolysis temperature	Applied dose (g/L)	Removal efficiency (%)	Reference
Cu^{2+}	1 mM	Corn straws	800	1	97	(Kazemi et al., 2020)
Cd^{2+}	1 mM				88.1	
Cd^{2+}	20	Rape straw	600	1.25	100	(Yaashikaa et al., 2019)
Cd^{2+}	50	Mangosteen peel	800	3	80	(Machrouhi et al., 2019) (Nyoo et al., 2021)
Cd^{2+}	20	Corn straw	400	20	99.24	(Mbarki et al., 2019)
Pb^{2+}	20				98.62	
Pb^{2+}	400	Celery	500	5	97.7	(Dawood et al., 2017)
Pb^{2+}	100	Sugar cane bagasse			100	(Bhardwaj et al., 2019)
Pb^{2+}		Orange peel	~500	1	~80	
					30–40	
Cr^{6+}	200	Peanut hull	450–650	2	10–70	(Wu et al., 2019)
Cd^{2+}	100	Wheat straw	650–700	0.2 g	100	(Zhou et al., 2020)
Cu^{2+}	100				100	
Zn^{2+}	100				100	
As^{5+}	50	Pinewood	600	2.5	~35	(Zoroufchi et al., 2020)
Cd^{2+}	30	Hickory wood	600	2	95.9	(Ahmed et al., 2020)
Cu^{2+}	30				93.2	
Pb^{2+}	100				98.5	
As^{5+}	50	Pinewood	600	2.5	~35	(Zoroufchi et al., 2020)
Cr^{6+}	0.16	Rice husk			89	(Wang et al., 2018a,b)
Cr^{6+}	100		450–500	1	~100	
Cu^{2+}	1 mM	Hardwood	450	1	6.2	(Zhu et al., 2018)
Cu^{2+}	1 mM	Corn straw	600	10	95	(Kazemi et al., 2020)
Zn^{2+}	1 mM				90	

instance, the amino-modified biochar markedly increased the adsorption of Cu(II) via strong complexation (Vigneshwaran et al., 2021). Zhang et al. (2020a,b) discovered that biochar synthesised at a high temperature effectively removed Cr (VI).

Concerning heavy metals and organic pollutants, the most recent research indicates that biomass-derived biochar can effectively remove ammonium by monolayer chemical adsorption (Alkurdi et al., 2019). This suggests that competition adsorption occurred when biochar was used as adsorbents to remove heavy metals and organic pollutants in the presence of ammonium.

In addition to adsorption, biochar can promote bacteria, facilitating the elimination of organic matter. Wang and Wang (2019) discovered that the proportion of Archaea was significantly higher in the presence of biochar generated from fruitwood, reducing the stress of ammonia and acids on microorganisms, and enhancing their activity. In addition, the inclusion of biochar increased the removal of tetrabromobisphenol A by redox-active moieties and quickened the transformation of tetrabromobisphenol A that had been adsorbed (Liu et al., 2020a). It is highlighted to highlight the recycling and reusing of biochar should be considered when it is used for water and wastewater treatment. The magnetic modification of the biochar enables the biochar to be recycled. The magnetic properties of biochar generated from maize stalks and treated with a combination of $ZnCl_2$ and $FeCl_3$ increased dramatically (Alkharabsheh et al., 2021).

Based on the above findings, biochar reduced specific contaminants in batch trials. In practice, however, numerous contaminants coexist in the water and wastewater. It is possible for competitive adsorption to occur, resulting in conflicting laboratory results. Moreover, actual flow conditions may influence biochar's ability to absorb contaminants. Therefore, additional research should imitate the laboratory's virtual environment and study biochar's efficacy in removing pollutants.

Electrode materials and electrode modifier

The supercapacitor as an energy storage device has attracted considerable interest due to its high-power density, long cycle life, and rapid charging and discharging capacity (Mohamad et al., 2022). The optimal electrode materials must have a large surface area and a porous structure to provide sufficient active sites for electrochemical oxidation.

As electrode materials, common carbon materials, including granular activated carbon, graphite granule, graphene, and carbon nanotubes, can be utilised (Nasrullah et al., 2022). However, the high cost of typical carbon materials limits their utilisation. Biochar has comparable surface areas and porous structures to the primary carbon materials listed above. Moreover, its price is substantially lower. For instance, on average, the costs of granular activated carbon or graphite granule electrodes range between 500 and 2500 US$ per ton. In contrast, the price per tonne of biochar is 51,381 US$ (Bhattacharjee et al., 2020). Therefore, biochar could serve as an electrode material replacement.

Previous research has established the viability of biochar as a supercapacitor electrode material (Krishnan et al., 2021a; Nasrullah et al., 2020; Sarkar and Dey, 2021). For example, biochar generated from woody biomass was employed as electrode material, exhibiting a rapid charging-discharging behaviour and a capacitance of approximately 14F/g (Nidheesh et al., 2021). Prior to its application, biochar was activated to increase its capacitance. As discussed previously, acid treatment can raise the surface oxygen-containing functional groups, enhancing the pseudo capacitance resulting from redox reactions of carbonyl-surface oxygen-containing functional groups (Zhu et al., 2022). The capacitance of biochar generated from woody biomass improved from 14 to 115F/g when treated with nitric acid. Furthermore, biochar demonstrated excellent stability over 5000 cycles (Thomas et al., 2019).

Biochar can also be utilised as electrode material in microbial fuel cells (Lohri et al., 2017). The power output of biochar generated from wood was comparable to that of activated carbon (674 mWm^{-2}) and graphite (566 mWm^{-2}). However, biochar is less expensive than activated carbon and graphite. In addition to being an electrode material, biochar can also serve as an electrode modifier. As a modification of glassy carbon electrode, biochar generated from lignin enhanced the separation capacity and sensitivity of electroanalytical procedures for comparable organic substances (Jaroniec et al., 2020).

The peak currents of hydroquinone and catechol at the biochar-modified electrode were three and fivefold greater than those at the unmodified electrode. Large surface area and pore diameter were responsible for the improved performance. Wang and Wang (2019) discovered that algal-derived biochar anode generated a more significant bio current than graphite plate anode. Not only is the efficacy of biochar as an electrode material dependent on its surface area, but also on its functional groups. Considering the various forms of biochar, it is vital to research the electrode performance of different biochar types.

Conclusions

The growing interest in biochar applications has paved the path for converting lignocellulosic feedstock into biochar. As the primary product of pyrolysis, biochar is significantly impacted by the biomass feedstock and pyrolysis parameters. Compared to cellulose, hemicellulose, and lignin, biomass with a high lignin content results in more biochar formation. During the biochar formation process, temperature, time, and heating rate influence most. The modification of biochar by physical, chemical, and biological modes has resulted in the synthesis of biochar with an increased number of functional groups and surface area. The detailed characterization of biochar before any applications is essential for determining the relationship between nature and operating conditions and biochar's physiochemical properties, assessing biochar's suitability for specific applications, and determining the presence of contaminants and ecotoxicology properties. This paper also provided a comprehensive overview of biochar, focusing on its environmental applications. Conversion of conventional lignocellulosic biomass to biochar offers feedstocks treatment options contributing to ecological sustainability. In addition, biochar's low-cost feedstock and simple production technique enhance its practical utilisation. Biochar preparation, activation/modification, and reprocessing should be synergistically optimized for economic and ecological efficiency. Biochar is an alternative to commercially activated carbon for pollutant removal.

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.

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