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REVIEW

Optimizing biochar production: a review of recent progress in lignocellulosic biomass pyrolysis

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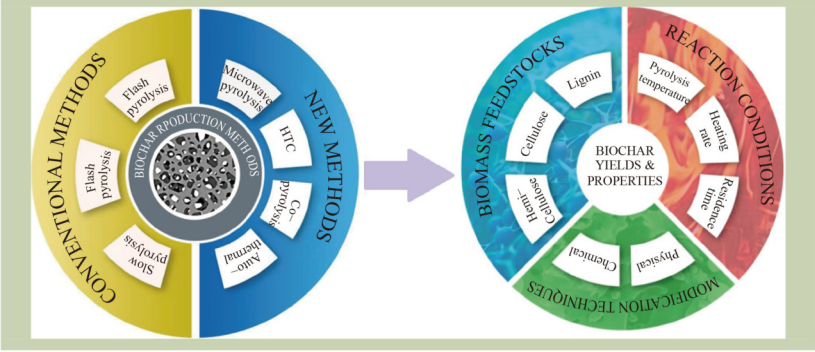
KEYWORDS

Biochar, lignocellulosic biomass, optimization, properties, pyrolysis, yield

HIGHLIGHTS

- The review provides an examination of recent advancements in optimizing biochar production from lignocellulosic biomass through pyrolysis, covering both conventional and new techniques.
- The study emphasizes the critical role of feedstock composition, pyrolysis conditions (temperature, heating rate, residence time), and modification methods in determining biochar yield and properties.
- Choosing renewable, readily available feedstocks is crucial for reducing dependence on finite resources and repurposing waste materials, thereby mitigating environmental impacts and enhancing sustainability.
- Key pyrolysis parameters, such as temperature and heating rate, must be carefully optimized to maximize biochar yield and quality while minimizing energy consumption and environmental footprint.
- Modification methods are essential for tailoring biochar properties to specific applications, overcoming limitations of pristine biochar, and improving its effectiveness, all while promoting resource efficiency and sustainability.

GRAPHICAL ABSTRACT



ABSTRACT

Biochar, a carbon-rich material produced by biomass pyrolysis, is valued for soil amendment, carbon sequestration and environmental remediation. Optimum biochar production depends on understanding key factors, including feedstock characteristics, pyrolysis conditions and modification methods. This review examines various pyrolysis techniques, ranging from well-established to new methods, assessing their mechanisms, strengths and limitations for large-scale production. It emphasizes the importance of feedstock selection, pyrolysis conditions and modification methods in affecting biochar yield and properties. By synthesizing current research findings, this review aims to provide insights into optimizing biochar production for sustainable utilization of lignocellulosic biomass resources.

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1 Introduction

Biochar is a stable, carbon-rich material produced from biomass through pyrolysis at 300–800 °C in an oxygen-limited environment[1]. During this process, the biochar undergoes structural modifications where the original surface structure is reorganized. This can lead to the formation of larger cavities from smaller pores, resulting in a more accessible pore network predominantly composed of macropores[2]. During pyrolysis, biomass decomposes in the absence of oxygen, releasing moisture and volatile compounds through dehydration, decarboxylation, evaporation and polymerization. Dehydration produces steam and hydrocarbons. Decarboxylation releases CO_2, yielding carbon-rich intermediates. Evaporation releases volatile organic compounds that can be used as syngas formation. Polymerization forms bio-oil. The solid residue left after pyrolysis is biochar[3]. Generally, pyrolysis involves the release of moisture and volatile compounds from biomass through reactions, resulting in the production of syngas, bio-oil and biochar.

Biomass (feedstock) selection for pyrolysis depends on availability, composition and desired products. Lignocellulosic biomass is favored for its abundance and renewability, containing cellulose, hemicellulose and lignin components[4]. Understanding the thermal degradation pathways of these components is crucial for biochar production. Hemicellulose, with simpler sugar units, decomposes at lower temperatures (220–315 °C), releasing volatile compounds[5]. Cellulose degradation occurs at slightly higher temperatures (315–400 °C), while lignin, with its complex aromatic structure, decomposes at even higher temperatures (350–500 °C), contributing to biochar formation[6]. The properties of biochar are closely tied to feedstock composition. Cellulose and hemicellulose-rich feedstocks produce biochar with lower fixed carbon and aromaticity but higher oxygen-containing functional groups, enhancing sorption and contaminant adsorption[7–9]. Conversely, lignin-rich biomass, produces biochar with higher porosity, surface area, aromaticity, stability and fixed carbon content suitable for soil improvement and environmental remediation[10,11].

Biochar production has progresses from laboratory, pilot to commercial scales. At the laboratory scale, research focuses on understanding fundamental processes and optimizing production parameters using small-scale reactors to evaluate the effects of various conditions on biochar properties[1]. The pilot-scale bridges research with commercialization by expanding production to test economic feasibility and process efficiency, while addressing operational and environmental challenges[12]. At the commercial scale, biochar is produced industrially using large-scale reactors to meet market demands, with continuous operations and stringent adherence to quality and regulatory standards[13]. Recent advancements in biomass pyrolysis include both well-established and new techniques. Established methods are classified into slow, fast and flash pyrolysis. Slow pyrolysis, with a low heating rate (< 20 °C·min^{-1}) and long retention time (> 1 h) at 300–700 °C, primarily produces biochar. Fast pyrolysis uses rapid heating (> 200 °C·min^{-1}) and short residence times (< 10 min) at 400–800 °C, focusing on bio-oil. Flash pyrolysis involves extremely rapid heating (> 1000 °C·s^{-1}) at 900–1300 °C, requiring smaller feedstock particles for efficient processing[14].

New pyrolysis techniques enhance yield and quality by providing precise control over the process, addressing the limitations of established methods[15]. Key approaches include microwave-assisted pyrolysis, co-pyrolysis, hydrothermal carbonization and autothermal pyrolysis, each offering unique benefits for optimizing the processing of various biomass feedstocks. In microwave-assisted pyrolysis, microwave energy is primarily absorbed by the water content within the biomass, leading to rapid and localized heating. This indirect heating of the biomass through its water content allows for more efficient and controlled pyrolysis compared to earlier methods[16]. Unlike conventional heating, which heats from the surface inward, microwave-assisted pyrolysis directly converts electromagnetic energy into heat within the material, offering faster, more efficient heating and better control. This method improves reaction kinetics and product yields[17]. For example, microwave heating of gumwood at 600–800 °C achieved 23% and 26% higher energy and exergy rates, respectively, and increased char yields by 46% compared to established methods[18]. Hydrothermal carbonization (HTC) differs from pyrolysis by using water as the primary solvent and operating at lower temperatures. Unlike pyrolysis, which produces biochar, HTC forms hydrochar and has less flexibility in controlling reaction parameters due to its high-pressure, closed system[19]. Another new technique, co-pyrolysis, involves the simultaneous thermal decomposition of multiple biomass feedstocks or biomass with other materials such as plastics or waste tires. By blending different feedstocks, co-pyrolysis can synergistically enhance product yields and properties while diversifying the range of potential applications for the resulting pyrolysis products. For example, Liu et al.[20] found that co-pyrolysis of pinewood and polycarbonate at 900 °C in a fixed bed reactor increased H_2 by 33%, CO by 26% and total syngas yields by 19%, while improving overall energy efficiency from 42.9% to 48.6%. Autothermal pyrolysis, unlike current methods, use air for fluidization instead of nitrogen and generates thermal energy through the partial oxidation of

pyrolysis products. Polin et al.[21] showed that autothermal pyrolysis with maize stover increased throughput from 7.8 to 21.9 kg·h^{-1}, though it reduced light biochar and bio-oil yields by 18.5% and 4.7%, respectively, while heavy bio-oil yields remained stable.

Although numerous reviews have addressed both established and new biochar production techniques, they frequently overlook a detailed analysis of their strengths and limitations for large-scale production. Additionally, these reviews often fail to discuss critical factors required to achieve optimal biochar yield and properties. This gap means that while theoretical aspects are well-covered, practical considerations and real-world challenges in scaling up production and optimizing biochar quality may not be fully addressed. This gap highlights the need for comprehensive research into all aspects of biochar production, including feedstock selection, pyrolysis conditions and modification methods. Addressing these factors will help researchers better understand and refine production strategies, improving efficiency and tailoring biochar for various applications.

2 Data collection and data processing

The Web of Science (Clarivate, Philadelphia, PA, USA) is a leading global citation database covering science, arts and humanities. For the period from 2014 to 2024, articles were selected using the keyword "biochar production". The search, spanning from January 2014 to August 2024, yielded 4671 relevant research papers and reviews after excluding non-research materials such as conference calls and book reviews. The data, exported as complete records with references, includes data for authors, affiliations, titles, sources, abstracts, keywords and references.

CiteSpace was used to analyze these 4671 papers, employing a one-year time slice and default settings to focus on keyword networks[22]. The map (Fig. 1) shows keyword frequencies, with larger nodes indicating higher frequencies. The colors denote various keyword groups and larger circles represent stronger connections between keywords[23]. "Biochar" emerges as the most frequently co-occurring keyword, underscoring its central role in the research. Other significant keywords include "bio-oil", "microalgae" and "plastic waste". The increase in publications on biochar pyrolysis since 2019, as shown in Fig. 1, highlights a marked rise in interest and advancements in the field, reflecting intensified research activity and ongoing improvements in biochar production processes.

3 Production of biochar

3.1 Lignocellulosic biomass feedstock

Biomass is a complex, biogenic organic-inorganic material from both natural and anthropogenic sources. It includes:

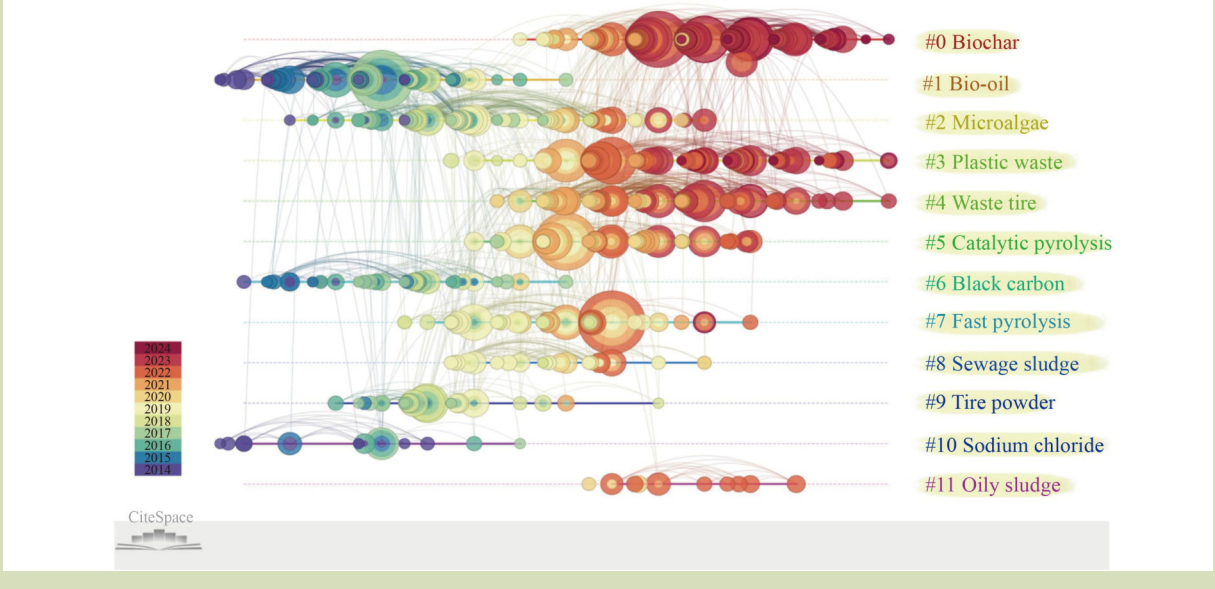

Fig. 1 Co-occurrence network of keywords in biochar production

(1) natural constituents from photosynthesis and food digestion, and (2) technogenic products from processing these natural materials. Biomass can be broadly classified based on biological diversity and source[24] (Fig. 2).

Biomass can also be classified into two main types: (1) lignocellulosic biomass, which is widely used for biochar production, and (2) non-lignocellulosic biomass[25,26]. Lignocellulosic biomass primarily composes cellulose, hemicellulose and lignin, as show in Fig. 3. Cellulose, hemicellulose and lignin are distributed in the cell wall as a skeleton, linking material and hard solids, respectively[27]. Cellulose is a linear polysaccharide of d-glucose units joined by β-1,4-glycosidic bonds whereas hemicellulose is a group of complex heteropolysaccharides comprised from various sugars (d-xylose, d-glucose, d-mannose, d-galactose, and l-arabinose) and sugar acids (d-glucuronic and d-galacturonic acids)[28]. Lignin is an amorphous heteropolymer consisting of phenylpropane units (coniferyl alcohol, sinapyl alcohol and coumaryl alcohol) joined together by different types of linkages[29]. Also, biomass usually contains a small amount of alkali and alkaline earth metals (i.e., K, Na, Ca and Mg) that can act as self-activators in pore formation of biochar during pyrolysis[30].

The proportions of cellulose, hemicellulose, and lignin in lignocellulosic feedstocks can vary widely based on several factors such as plant species, tissue type, maturity and

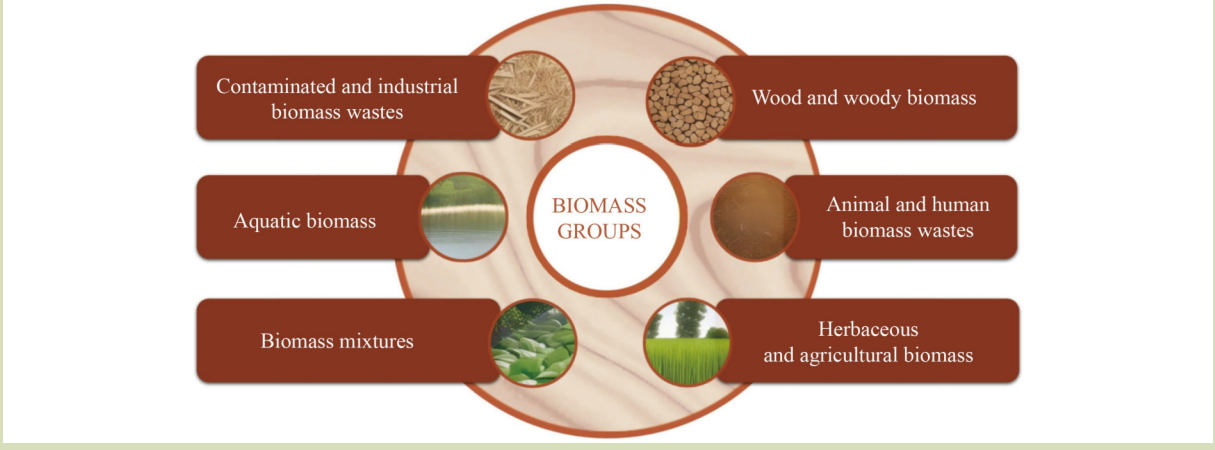

Fig. 2 General classification of biomass types based on biological diversity, source and origin.

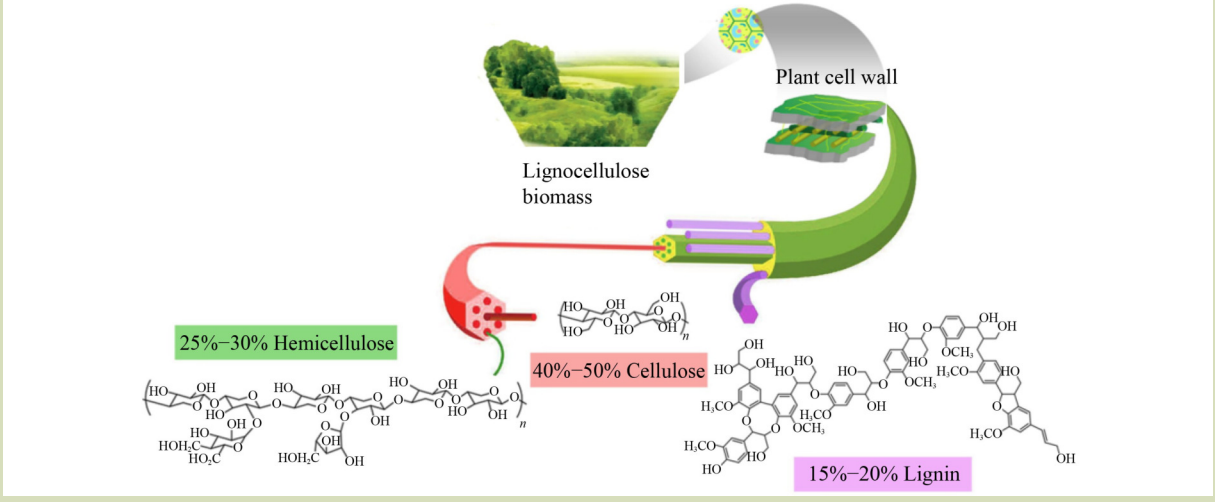

Fig. 3 The three components in lignocellulosic biomass.

environmental conditions[31]. Figure 4 shows the proximate and ultimate compositions of various lignocellulosic feedstocks, which are critical for designing biochar production processes. Hardwoods generally have higher lignin content than softwoods, while grasses contain more hemicellulose. This difference in composition reflects the diverse structural characteristics of different plant species and their environmental adaptation[4,32]. Also, agricultural residues such as wheat straw or maize cobs differ in composition from forestry residues such as wood chips or *Leucaena leucocephala* wood. Such differences in composition can arise from differences in plant anatomy, growth patterns and the specific conditions under which the biomass is produced and harvested[4,32].

3.2 Pyrolysis mechanisms

The thermal degradation of lignocellulosic components (hemicellulose, cellulose and lignin) in biochar production varies due to differences in their composition and structure. Hemicellulose and cellulose, composed of simpler sugar units, exhibit susceptibility to thermal decomposition at relatively lower temperatures, typically ranging from 220 to 315 °C and 315 to 400 °C, respectively[5]. Similar observations have been reported, indicating that hemicellulose has the lowest decomposition temperature and the widest decomposition range compared to cellulose and lignin[35]. During pyrolysis, both components undergo depolymerization and degradation reactions, such as dehydration, decarboxylation and fragmentation, resulting in the release of volatile compounds like water vapor, carbon dioxide, and organic acids[36]. As a result, cellulose and hemicellulose are useful for generating volatile products.

In contrast, lignin, with its complex aromatic polymer structure, is the primary precursor for biochar formation during pyrolysis. It has superior thermal stability compared to cellulose and hemicellulose, typically decomposing at 350–500 °C[6]. Given its cross-linked and aromatic nature, lignin does not fully decompose during pyrolysis. Instead, it partially decomposes and rearranges, forming carbonaceous residues that contribute to the solid fraction of biochar[36]. For example, the biochar yield from woody biomass is about 19 wt% at 900 °C for 64 min[37] whereas lignin can yield up to 45.7% biochar under similar conditions[38].

Figure 5 illustrates the degradation pathways of lignocellulosic components and organic extractives during pyrolysis, highlighting the production of various products and byproducts. Each component of lignocellulosic biomass degrades at different temperatures, resulting in distinct outputs. In the 50–100 °C range, biomass undergoes nonreactive drying, removing moisture and reducing porosity while preserving chemical constituents. At 120–150 °C, lignin softens, forming cohesive structures essential for later decomposition. In the 150–200 °C range, known as the reactive drying range, significant thermal transformations occur. This phase marks the initiation of the breakdown of hydrogen and

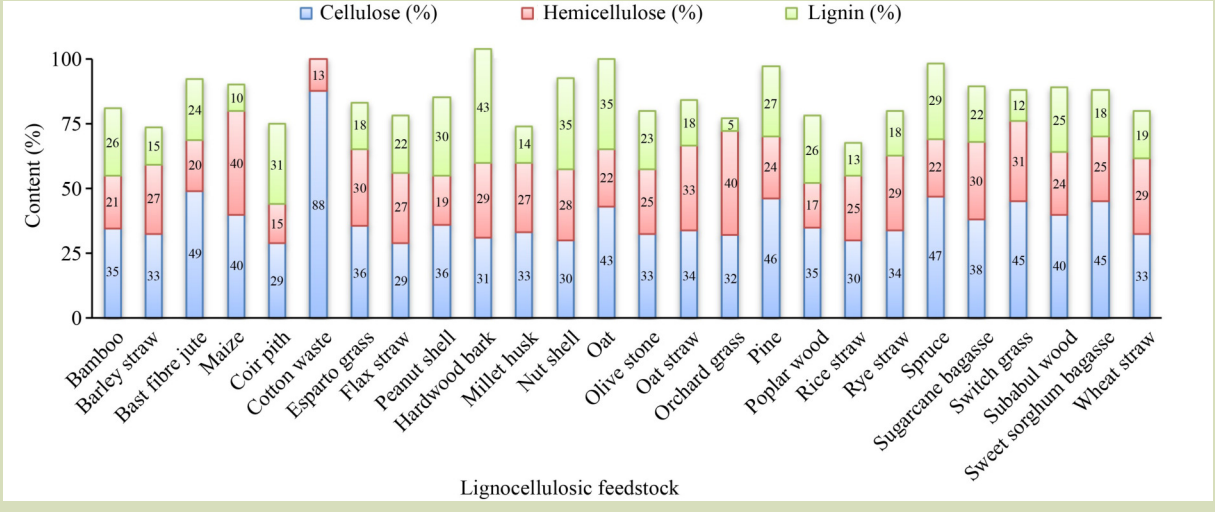

Fig. 4 Chemical composition of cellulose, hemicellulose and lignin in different lignocellulosic feedstock (data from published sources[4,32–34]). Sums of cellulose, hemicellulose and lignin do not equal 100% because the remainder includes non-structural carbohydrates (such as glucose, fructose and sucrose), as well as proteins, lipids and pectin.

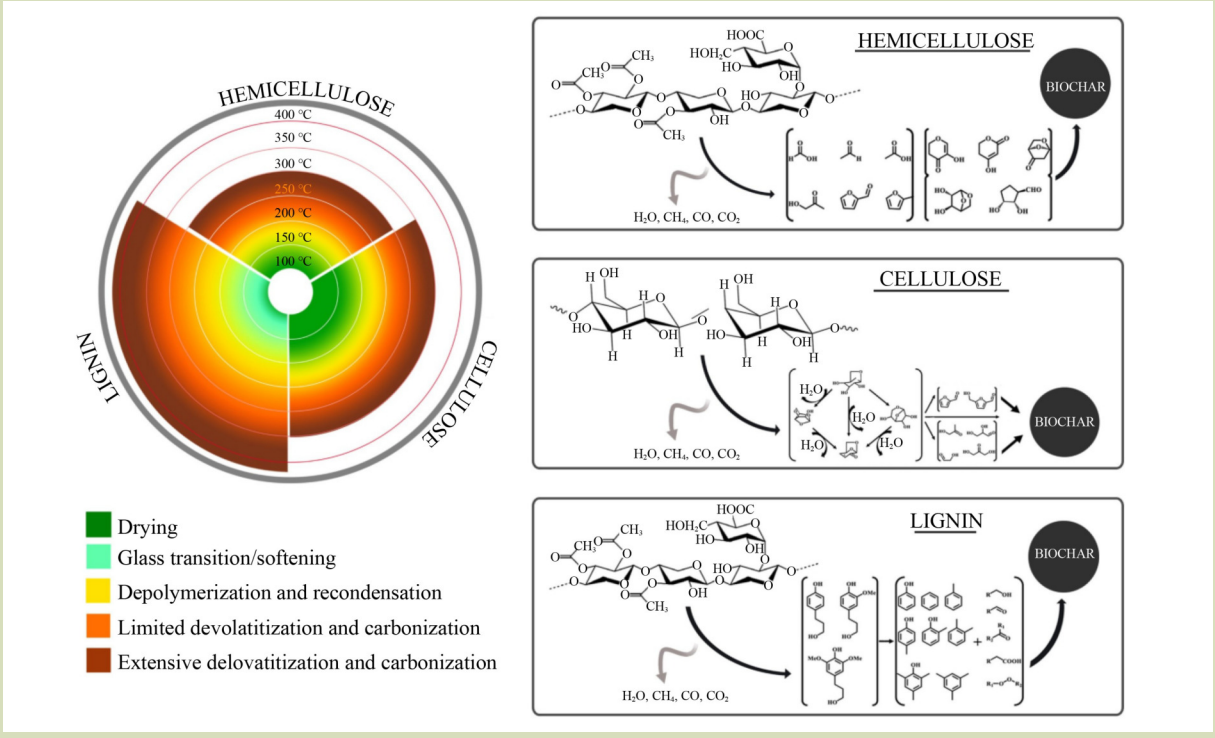

Fig. 5 Decomposition of hemicellulose, cellulose and lignin.

carbon bonds, releasing lipophilic extractives and volatile compounds, and causes the depolymerization of hemicellulose[39]. As a consequence, hemicellulose molecules fragment and transform into shortened, condensed polymers with solid structures.

As the temperature exceed 200–300 °C, cellulose undergoes carbonization and devolatilization, whereas lignin starts to carbonize and devolatilize at 300–500 °C[40]. These processes convert biomass into carbon-rich biochar and release volatile gases, resulting in a stable carbonaceous material.

3.3 Pyrolysis technologies

Pyrolysis is the process of heating lignocellulosic material at high temperatures without oxygen, serving as the initial stage for gasification and combustion[41]. During pyrolysis, heat is externally generated and transferred to the biomass in a reactor via conduction, convection and thermal radiation[42]. Pyrolysis produces biochar, a carbon-rich solid material, along with condensable and non-condensable volatile byproducts[43].

Recent advancements in biomass pyrolysis can be broadly categorized into established and new techniques (Fig. 6). Established pyrolysis methods are typically divided into three main types based on heating rate, residence time and heating mode: (1) slow pyrolysis, (2) fast pyrolysis, and (3) flash pyrolysis. Fast and flash pyrolysis, with high heating rates and short vapor residence times, favor liquid yields (bio-oil), whereas slow pyrolysis, with longer residence times, primarily produces solid yields (biochar)[44,45]. Newer pyrolysis techniques, however, are designed to overcome the limitations

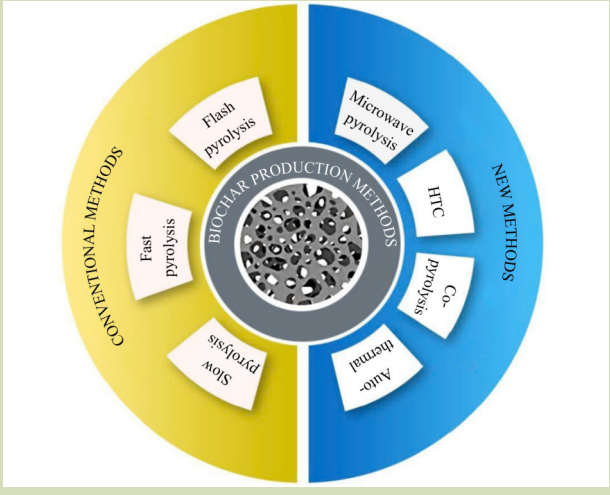

Fig. 6 Biomass pyrolysis methods.

of these current methods, with a focus on improving both the yield and quality of products and achieving more precise process control[15]. These new techniques, such as microwave-assisted pyrolysis, co-pyrolysis, hydrothermal carbonization and autothermal pyrolysis, each offer distinct benefits for optimizing the pyrolysis process[46]. Details on their scalability, efficiency, environmental impact and operating conditions are summarized in Table 1.

Established pyrolysis methods

Slow pyrolysis of lignocellulosic biomass involves gradual heating at 5–20 °C·min^{-1} to 300–700 °C in an oxygen-limited environment with extended vapor residence times from minutes to days. This method enables precise control over biomass conversion into high-quality biochar with increased carbon content and stability, minimizing gas and bio-oil production. Compared to fast and flash pyrolysis, slow pyrolysis effectively reduces heat and mass transfer limitations, enhances biochar yield, and promotes the formation of stable carbon structures. One study showed that slow pyrolysis biochar typically has a higher carbon content (around 69.6% by weight) compared to fast pyrolysis biochar (about 49.3% by weight), improving stability and reducing microbial

Table 1 Established and new pyrolysis processes, along with their respective strengths and limitations

Pyrolysis method	Conditions & yield	Scalability, efficiency, environmental impact, limitations and barriers*	Reference
Slow pyrolysis	Temp: 300–700 °C; Heating rate: 1–10 °C·min^{-1}; Residence time: > 1 h; Bio-oil: ~30%; Biochar: ~35%; Gases: ~35%	Adaptable to various scales; High biochar yield, efficient carbonization; Low emissions if designed properly, but high energy use, long processing times, feedstock quality variability; High costs, infrastructure investment, feedstock consistency	[47–54]
Fast pyrolysis	Temp: 400–800 °C; Heating rate: 20–200 °C·min^{-1}; Residence time: < 10 min; Bio-oil: ~50%; Biochar: ~20%; Gases: ~30%	Scalable from small to large; High bio-oil yield, rapid decomposition; Sustainable but high energy consumption, advanced combustion required; Lower biochar yield, feedstock consistency, heat transfer challenges	[55–62]
Flash pyrolysis	Temp: 900–1300 °C; Heating rate: > 1000 °C·s^{-1}; Residence time: < 10 s; Bio-oil: ~75%; Biochar: ~12%; Gases: ~13%	Suitable for various scales; Efficient conversion, minimal by-products; Reduces dependence on non-renewables, bio-oil needs refining; Expensive equipment, complex by-product separation, high capital cost	[63–71]
Microwave pyrolysis	Temp: 300–600 °C; Heating rate: 15–30 min; Bio-oil: ~15%; Biochar: ~50%; Gases: ~35%	Scalable from laboratory to industrial; Fast heating, efficient biochar production; Reduced energy consumption, higher product quality; Low yield, expensive equipment, scaling issues, uniform heating challenges	[72–83]
Co-pyrolysis	Temp: 300–1200 °C; Heating rate and residence time vary; Bio-oil: ~32%; Biochar: ~40%; Gases: ~28%	Adaptable scalability; Enhances biochar yield with mixed feedstocks; Reduces waste and emissions; Feedstock variability, complex equipment; Scaling challenges, quality control, by-product separation	[84–95]
Hydrothermal carbonization	Temp: 220–240 °C; Pressure: 2–10 MPa; Residence time: 1–72 h; Bio-oil: ~25%; Hydrochar: ~65%; Gases: ~10%	Mostly batch systems, pilot scale; High carbon conversion, low energy use; Reduces waste, mitigates GHG; Longer processing, feedstock variability; Scale-up challenges, reactor design issues	[96–102]
Autothermal pyrolysis	Pre-heat temp: ~450 °C, Heating rate: ~10 °C·min^{-1}, Residence time: ~10 min; Bio-oil: ~50%; Biochar: ~30%; Gases: ~20%	Flexible scalability; Self-sustained thermal process, energy-efficient; Lower carbon footprint, promotes circular economy; Complex reactor design, supplemental energy needs, energy balance and scaling challenges	[103–107]

Note: *A detailed analysis of scalability, efficiency, environmental impact, limitations, and barriers of each established and new pyrolysis processes is provided in the Table S1 of the Supplementary Materials.

degradation[50]. In another study, slow pyrolysis yielded more biochar (41%–44% by weight) compared to fast pyrolysis. The latter, characterized by high heating rates and shorter processing times, results in lower biochar yields (21%–4% by weight)[61]. Meanwhile, flash pyrolysis efficiently converts biomass into bio-oil with low water content and high conversion rates up to 70% by using very short residence times of less than 10 s[63]. This rapid process requires finely ground biomass particles (105–250 μm) for effective heat transfer[64]. Compared to slow and fast pyrolysis, flash pyrolysis faces challenges including cooling rates that can affect product quality, potential impurities in the bio-oil, high energy consumption and equipment degradation from corrosive feedstocks.

Numerous pyrolysis reactor types have been designed to convert biomass feedstocks into bio-oil, biochar and gas products. The yields of each product depend on the specific configuration and operational conditions of each reactor. Pyrolysis reactors can be operated in batch, semi-batch and continuous modes. Typically, reactors used for slow pyrolysis include cylindrical fixed-bed, batch, rotatory kiln and packed bed. The bubbling fluidized bed, circulating fluidized bed, transported bed, rotating cone, vortex, ablative and auger reactor are examples that are typical for either fast or flash pyrolysis[69]. Regardless of the reactor type, the external heat is generated by either the burning biomass, electric heaters or gas burners and transferred directly or indirectly to the biomass within a furnace[108].

New pyrolysis methods

Emerging pyrolysis techniques for biochar production involve new methods to enhance biochar yield, quality and properties. These techniques often incorporate modifications to traditional pyrolysis processes, including adjustments to temperature, heating rates, residence times and reactor configurations, and may use catalysts or additives. The overarching goal is to maximize the efficiency and sustainability of biochar production while minimizing environmental impact and resource consumption.

Co-pyrolysis uses two or more feedstocks to improve biomass pyrolysis through synergistic interactions among radicals, which influence processes like depolymerization, hydrogen transfer and isomerization. The success of co-pyrolysis depends on the interplay between feedstocks, affecting efficiency and product quality based on factors such as biomass type, blending ratio, reactor type, temperature and the presence of catalysts[86,87]. Unlike established pyrolysis, co-pyrolysis does not require equipment changes but does require careful material preparation. Different biomass components, such as cellulose, hemicellulose and lignin, affect pyrolysis outcomes, as illustrated by how blending these materials can alter yields of sugars and other compounds compared to native biomass[109].

Also, the blending ratio of different biomasses can alter the overall yield and composition of the pyrolysis products (Fig. 7). Co-pyrolysis of palm kernel shell and palm oil sludge shows that increasing the latter from 0 to 100 wt%, there was a distinct decrease in bio-oil yield, approximately by 27%, whereas there was a significant increase in biochar yield, nearly by 1.5 times[110]. This shift is primarily attributed to the presence of inorganic materials, specifically alkali and alkaline earth metals, present in the biomass blend. These materials exhibit catalytic properties that can potentially enhance the production of organic acids during the pyrolysis process[111]. Adjusting raw material ratios can thus optimize co-pyrolysis to achieve desired biochar and bio-oil yields.

Microwave pyrolysis, or microwave-assisted pyrolysis, heats biomass using the electric field of microwaves, causing the electric dipoles in the biomass to flip and generate heat. This process occurs at 300–600 °C, pressures of 1–2 MPa, and a residence time of about 30 min[112], converting biomass into biochar with 70%–80% fixed carbon and a yield of 40%–50%[13]. The process involves four stages: (1) initial heating from dielectric recovery of water molecules; (2) stabilization of temperature based on feedstock properties; (3) rapid temperature rise and biomass reduction; and (4) reaching thermal equilibrium[75]. Unlike established pyrolysis, which uses electric resistance heating, microwave pyrolysis achieves rapid and efficient volumetric heating without the need for external drying. However, it faces challenges like uneven temperature distribution due to the lack

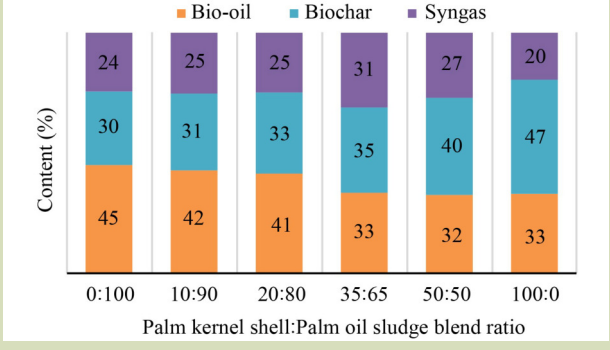

Fig. 7 Effect of the blending ratio palm kernel shell and palm oil sludge on product yield (data from Vasu et al.[110]).

of agitation and difficulties in scaling up due to efficient microwave energy transfer[77].

HTC is a thermochemical process for pretreatment high-moisture biomass using compressed water at temperatures of 220–240 °C, under considerable pressure, usually between 2 and 10 MPa[97] within a reactor for several hours. This process, also known as wet torrefaction, converts organic components into hydrochar, a carbon-rich solid, along with minor fractions of aqueous and gaseous phases like CO_2, CO, CH_4 and H_2[100]. HTC primarily involves decarboxylation, dehydration and polymerization, reducing the O:C ratio and increasing energy density. The yield of hydrochar (35$ to 65% of dry feedstock) and its properties are influenced by temperature, residence time, water: biomass ratio, and the pH of the biomass-water-solution system[113]. Generally, higher temperatures speed up biomass conversion but decrease hydrochar yield as more organic matter is converted into gaseous products such as methane, carbon dioxide and hydrogen[114]. For example, increasing the temperature from 150 to 350 °C reduce hydrochar yield by 49% and increase bio-oil by 10%[115]. Residence time also impacts the process, research has shown that extending the residence time in HTC led to a minor reduction in higher heating values (16 ± 0.3 $MJ \cdot kg^{-1}$) but improved several slagging and fouling indices of the hydrochar[116].

In established pyrolysis, biomass is transformed into biochar, bio-oil, and synthesis gas using an external energy source due to its endothermic nature. This becomes challenging at larger scales because the energy needed (proportional to volume) often exceeds the energy supplied through heat transfer (proportional to surface area)[21], leading to inefficiencies and variations in product quality[85]. Autothermal pyrolysis, or oxidative pyrolysis, addresses this by balancing endothermic and exothermic reactions. It either recycles heat generated from the biomass itself or introduces controlled amount of oxygen to facilitate combustion, producing the necessary heat for the process. As an illustration, Mesa-Pérez et al.[103] achieved 470 °C in a pilot-scale fluidized bed reactor using an equivalence ratio of 7:5 without external energy supply[103], whereas Polin et al.[21] demonstrated a threefold increase in pyrolysis intensity using an equivalence ratio of 1:10.

4 Key factors for biochar yield and properties

Determining the key factors for biochar yield and properties is crucial for optimizing biochar production efficiency. Figure 8 presents these key factors: feedstock selection, reaction conditions and modification techniques.

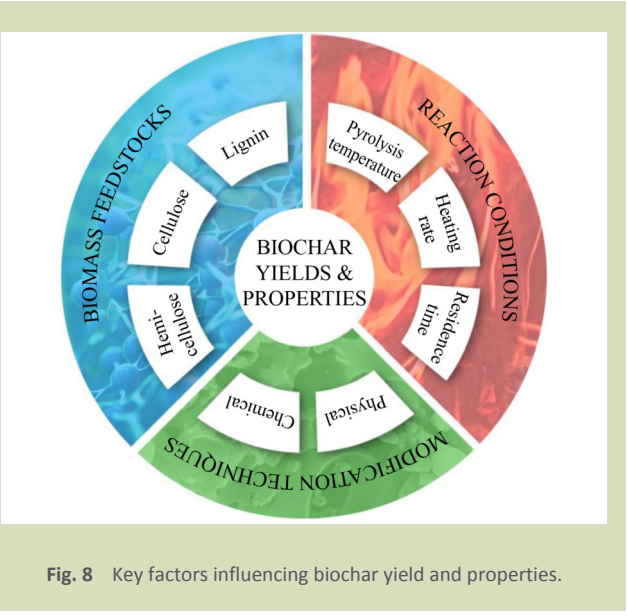

Fig. 8 Key factors influencing biochar yield and properties.

4.1 Biomass feedstock

Biochar properties are heavily influenced by the type of biomass utilized in its production, affecting its chemical composition, structure and characteristics[46]. Different biomass sources contain different levels of organic compounds, including lignin, cellulose, hemicellulose and other constituents. During pyrolysis, these compounds decompose and transform differently, resulting in biochars with unique chemical compositions. For example, feedstocks in high cellulose and hemicellulose, such as sugarcane bagasse, generally produce biochar with a lower fixed carbon content and aromaticity but higher levels of oxygen-containing functional groups (–COOH, –OH and –CHO)[7]. Oxygen-containing functional groups in biochar act as key binding sites for contaminants, increasing its adsorption properties[8,9]. Lignin-rich biomass feedstocks, such as palm shell, produce biochar with a more porous structure, higher surface area, aromaticity, stability and fixed carbon content[10]. Biochar with higher fixed carbon contents and aromaticity tends to be more recalcitrant, making it more effective for carbon sequestration in soils, improving soil quality and supporting plant growth[117]. Figure 9 provides an overview of how lignin content in biomass influences biochar properties.

Lignin produces more biochar upon heating than hemicellulose or cellulose. This explains why wood biochar, such as that from mesquite wood, often yields more biochar compared to grasses such as *Miscanthus*. Mesquite wood has a lignin content of about 640 $g \cdot kg^{-1}$, whereas *Miscanthus*

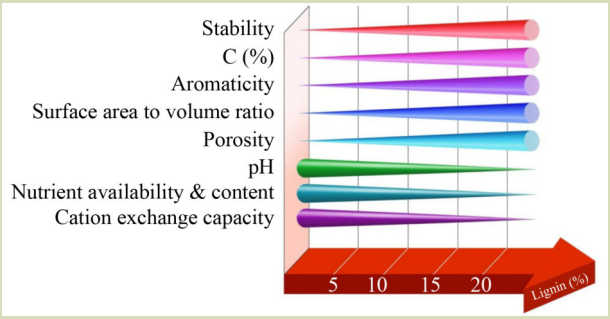

Fig. 9 Effect of lignin content in feedstock on biochar properties (data from published sources[7–10,117,118]).

contains between 100 g·kg^{-1} to 300 g·kg^{-1} of lignin[118]. Therefore, the higher lignin content in wood biomass results in greater production during pyrolysis, leading to higher biochar yields. The properties of biochar are greatly affected by the characteristics of the original plant tissue[119]. Lignocellulosic biomass, which is the precursor of biochar, typically has low water content, minimal debris, low porosity, high density and high calorific value[120]. Consequently, biochar from lignocellulosic biomass retains structural features from its source material, such as the xylem structure[121]. Structural factors like particle size, density and porosity influence the physical and mechanical properties of biochar, including its surface area, pore volume and mechanical strength[122]. Dense, compact woody biomass generally produces biochar with higher density and lower porosity, whereas more porous agricultural residues result in biochar with increased surface area and water-holding capacity. For example, wood biochar has densities of 0.47–0.6 g·cm^{-3}, compared to 0.25–0.3 g·cm^{-3} for grass biochar[118]. Moisture content, ash content, and volatile matter also impact biochar properties. High moisture may require extra drying to avoid steam-induced reactions[123], high ash content can increase mineral content and pH[1], and high volatile matter can lead to more gas production and lower biochar yield[124].

Figure 10 highlights the substantial variations in biochar properties resulting from the use of different feedstocks under identical pyrolysis temperatures (e.g., 500 °C), confirming that the selection of biomass feedstock greatly affects biochar characteristics.

4.2 Pyrolysis conditions

Pyrolysis conditions, including temperature, heating rate and residence time, directly affect biochar properties by influencing biomass decomposition, which impacts yield, chemical composition and physical characteristics of biochar. Table 2 provides a detailed summary of how various operational parameters influence the properties of biochar.

Pyrolysis temperature

In addition to the feedstock, pyrolysis temperature significantly affects the physicochemical properties of biochar. Increasing temperature increases the fixed carbon content, ash,

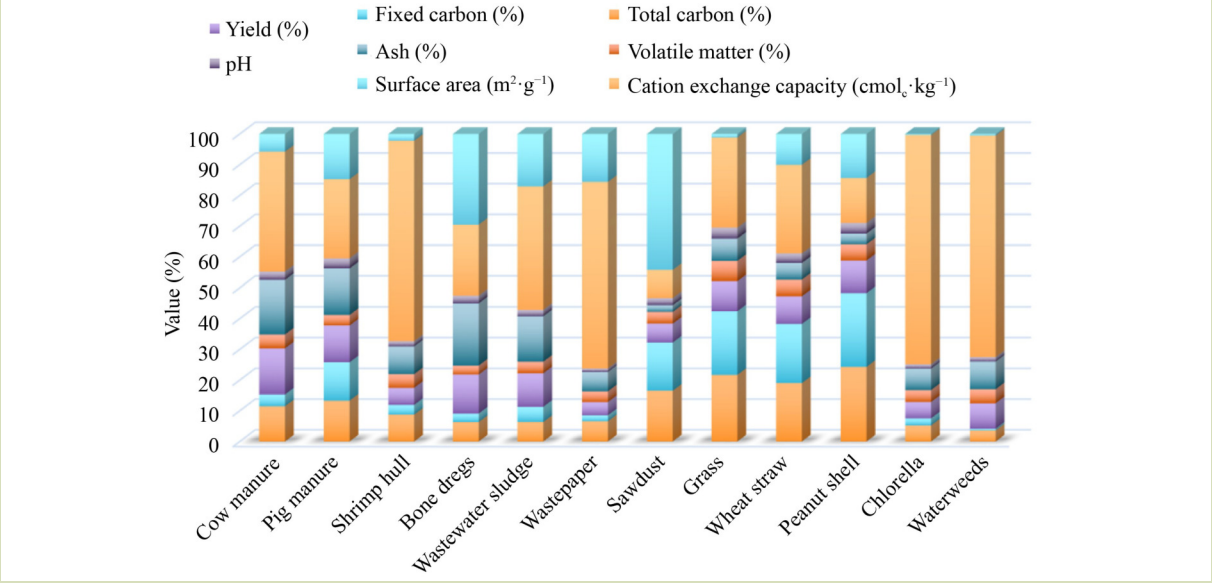

Fig. 10 Physical and chemical characteristics of biochar from different feedstocks produced at 500 °C (data from Zhao et al.[125])

Table 2 Impact of operational parameters on biochar properties

Parameter	Biochar property	Observation	Reference
Pyrolysis temperature	Fixed carbon	Higher temperatures increase volatile decomposition, resulting in higher fixed carbon content in biochar	[126,127]
	Ash	Higher temperatures increase ash content by volatilizing minerals	[128,129]
	Aromaticity	Higher temperatures enhance aromaticity in biochar by forming more aromatic carbon structures	[10,130]
	Zeta potential	Higher temperatures usually increase zeta potential due to changes in surface chemistry and structure	[131,132]
	Hydrophobicity	Biochar becomes more hydrophobic with higher temperatures, but extreme temperatures may lower hydrophobicity	[122,133,134]
	Yield	Higher temperatures reduce biochar yield by increasing organic matter decomposition and volatilization	[129,135]
	Hydrogen and oxygen	Higher temperatures reduce hydrogen and oxygen content in biochar by breaking C–H and C–O bonds	[136,137]
	Polarity	Higher temperatures lower biochar polarity by removing polar groups and increasing aromatic structures	[138,139]
	Surface area	Surface area increase with temperature but can decline due to excessive degradation and ash accumulation	[30,129,140]
Residence time	pH and ash	Longer residence times increase the pH and ash content of biochar	[141,142]
	C, N, and H	Longer residence times lower the carbon, nitrogen, and hydrogen contents of biochar	[143,144]
	Surface area and pore volume	Increase up to a point, then decrease with extended residence time	[143,145]
	Iodine adsorption (slow pyrolysis)	Increasing residence time decreases iodine adsorption	[146–148]
	Iodine adsorption (fast pyrolysis)	Increasing residence time increases iodine adsorption	[146]
Heating rate	Surface area	Higher heating rates produce biochar with a larger surface area	[135,149]
		Increase up to a point, then decrease with higher heating rate	[5]
Heating rate and residence time	Vapor and yield	Higher heating rates and shorter residence times increase vapor production, decreasing biochar yield	[141,150]
Residence times, temperature and heating rate	Yield	Longer residence times at lower temperatures and heating rates maximize biochar yield	[135,151]

aromaticity, surface area and zeta potential, while decreasing yield, hydrogen, oxygen and polarity (Fig. 11).

Increasing temperature during pyrolysis impacts biochar characteristics in several ways. Higher temperature enhanced fixed carbon content due to thermal decomposition of biomass in the absence of oxygen. As temperature rises, biomass releases volatile components like water, gases and organic compounds, leaving behind more fixed carbon in the biochar[126]. Higher temperatures enhance decomposition by breaking more chemical bonds, which increase the proportion of fixed carbon in the solid residue[127]. Besides, higher temperature during pyrolysis increases the ash content of biochar by converting volatile minerals in the feedstock into ash residues. High temperatures break chemical bonds minerals, leading to their volatilization and incorporation into the biochar[128]. Additionally, aromaticity, which indicates the presence of aromatic carbon structures, generally increases with temperature during pyrolysis. Higher temperatures also promote the breakdown of complex organic compounds in biomass into simpler aromatic structures, resulting in a greater proportion of aromatic carbon structures in the biochar[10]. Also, as temperature rises, the zeta potential of biochar particles typically increases, reflecting changes in their electrical charge[131]. Higher temperatures alter surface chemistry by triggering reactions that modify functional groups and chemical species, impacting the distribution and density of charged sites. These changes, along with structural rearrangements and increased thermal energy, affect zeta potential and surface properties[132]. Increasing pyrolysis temperature enhances hydrophobicity of biochar by removing polar groups[133], forming less polar aromatic carbon structures and reducing surface oxygen[122]. However, extremely high temperatures can cause excessive degradation and carbonization, potentially decreasing hydrophobicity[134]. Mineral residues or ash can also negatively affect

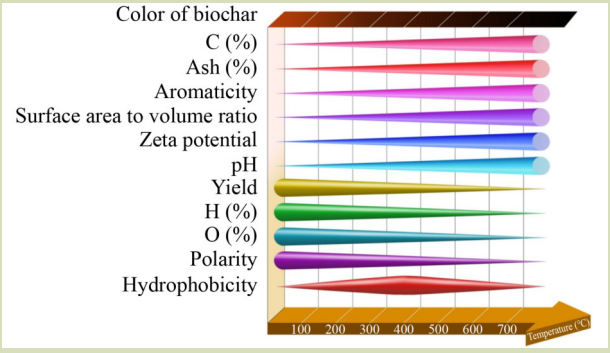

Fig. 11 Effect of temperature on the properties of biochar (data from published sources[126–129]).

hydrophobicity. Increasing pyrolysis temperature generally decreases biochar yield[135]. Higher temperatures enhance the decomposition of organic compounds into volatile components, enhancing their volatilization and leading to greater losses in the gas phase. This reduces the carbon content retained in the solid biochar. Also, during pyrolysis, higher temperatures increase thermal energy, promoting the breakdown of organic compounds and cleavage of C–H and C–O bonds[136]. This process releases volatile gases, leading to a decrease in hydrogen and oxygen in the solid biochar residue. Consequently, biochar produced at higher temperatures typically has lower hydrogen and oxygen content compared to biochar produced at lower temperatures[137]. Finally, as pyrolysis temperature increases, biochar surface area typically grows due to volatile removal, carbon re-structuring and pore formation[129]. However, excessive thermal degradation and carbonization can collapse pores and reduce surface area[30], whereas ash residue can block pores[140]. Therefore, although higher temperatures initially boost biochar surface area, this effect may plateau and decline with further increases due to detrimental effects on pore structure and carbonization.

The impact of biomass feedstock and pyrolysis temperature on biochar characteristics can be seen in Fig. 12. Higher pyrolysis temperatures led to a decrease in volatile content and an increase in ash content. Biochars derived from rice residues had higher ash content because of their greater mineral content, which supports plant growth, whereas biochars from woody materials contained more fixed carbon.

Residence time

Residence time is the total duration that components spend in the reactor, closely related to carrier gas flow rate[153]. In pyrolysis, it includes both solid and gas phase residence time, with the latter typically being more significant[154]. Depending on the pyrolysis method, residence time can last either seconds (fast pyrolysis) or hours (slow pyrolysis), impacting biomass carbonization and influencing biochar yield and properties. Generally, higher heating rate and shorter the residence time increase vapor production. Conversely, higher carbonization temperature and longer residence time produce more vapor and lower biochar yields. To maximize biochar yield, a longer residence time at slower temperature and slower heating rate is preferred[141].

Prolonged residence time increases the pH and ash content of biochar but decreases its H, C and N contents[143]. Surface area

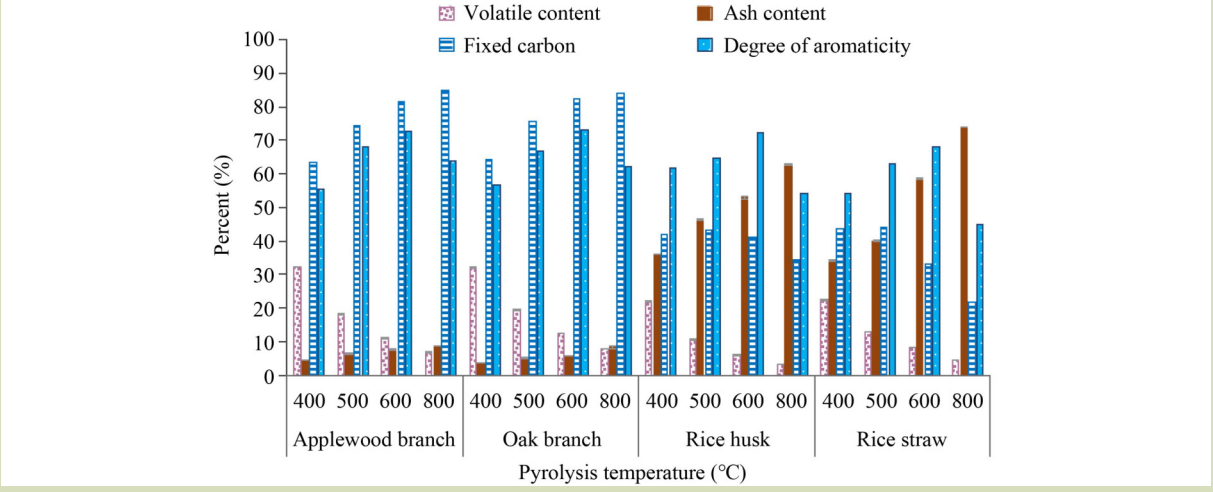

Fig. 12 Physical and chemical properties of biochar from various feedstocks (data from Jindo & Sonoki[152]).

and pore volume rise with residence times up to 90 min but decline beyond 150 min[143]. For residence times under 2 h, surface area and pore volume improve, whereas longer durations have the opposite effect[145]. Additionally, residence time impacts iodine adsorption differently, it decreases with longer residence times in slow pyrolysis, but increases in fast pyrolysis[146].

Heating rate

Residence time in the pyrolysis reactor affects biomass decomposition and biochar yield. Longer residence times generally ensure more complete conversion but may increase energy consumption and costs, whereas shorter residence times can result in incomplete pyrolysis and lower yields. For example, Parthasarathy et al.[155] found that higher heating rates significantly increased biochar yield from camel manure, with yields of 5.25 (22.5%), 7.00 (28.3%) and 8.64 mg (31.5%) at heating rates of 10, 20 and 50 °C·min^{-1}, respectively. The impact of heating rate on biochar properties, particularly surface area, has been reported to vary (Fig. 13). Some studies indicate that higher heating rates increase the surface area of biochar. For example, biochar derived from walnut shells exhibited a gradual and consistent rise in specific surface area across different heating rates from 10 to 40 °C·min^{-1}, ranging from 19.3 to 127 m^2·g^{-1} [149]. Zhao et al.[135] also observed a surface area increase from 296 to 384 m^2·g^{-1} with heating rate rising from 1 to 20 °C·min^{-1}, suggesting that faster heating promotes more extensive thermal decomposition and surface characteristics in the biochar.

Some studies indicate that there is an optimal heating rate for maximizing biochar surface area, with surface area initially increasing before decreasing beyond a certain threshold. For example, surface area rose from 210 to 245 m^2·g^{-1} as heating rate increased from 10 to 30 °C·min^{-1} [163] but dropped to 385 m^2·g^{-1} at 50 °C·min^{-1}[163]. Excessively high heating rates can negatively affect surface area by melting particles, smoothing surface, blockage of pore channels[167] or causing micropore collapse[30].

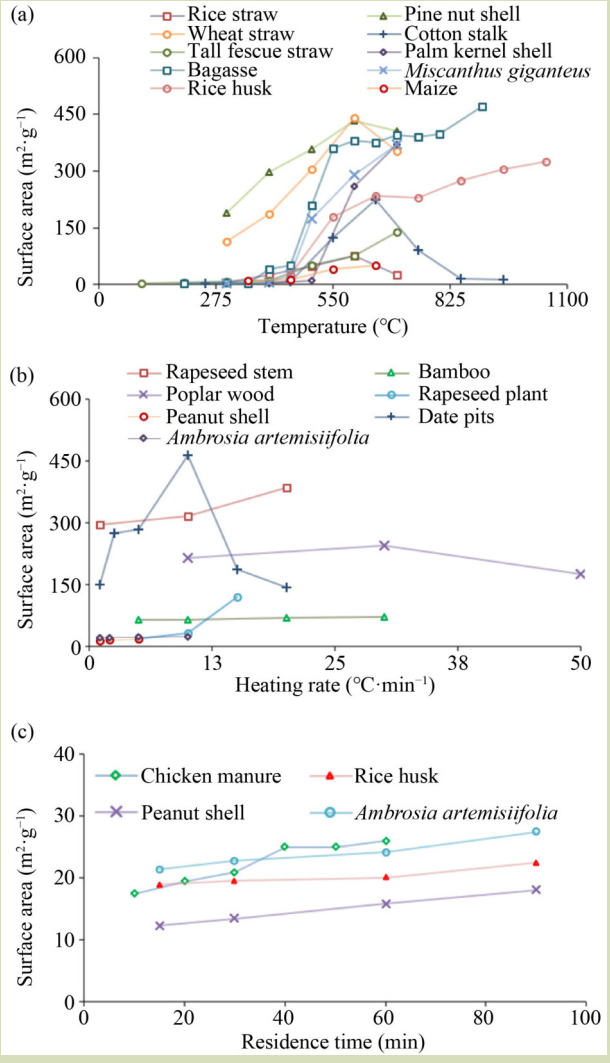

Fig. 13 (a) Relationship between biochar surface area and temperature (data from published sources[135,156–161]); (b) heating rate (data from published sources[135,156,161–165]); and (c) residences time (data from published sources [135,156,161,162,166]).

5 Biochar modification techniques

Biochar from biomass pyrolysis is often characterized by its low specific surface area, constrained porosity, and limited surface functional groups[168], which can restrict its applications, especially if surface area is below 200 m^2·g^{-1} [126]. To overcome these limitations, biochar is modified using agents like alkalis, acids, metal oxides and oxidizing, which improve surface properties create new structures[133]. These modifications are generally of two main types: chemical and physical (Fig. 14).

Chemical modification

Chemical modification techniques for biochar involve various treatments aimed at altering its chemical composition and surface properties. Key methods, as illustrated in the Fig. 14, are briefly as follows.

- Oxidizing treatment: oxidizing agents such as hydrogen

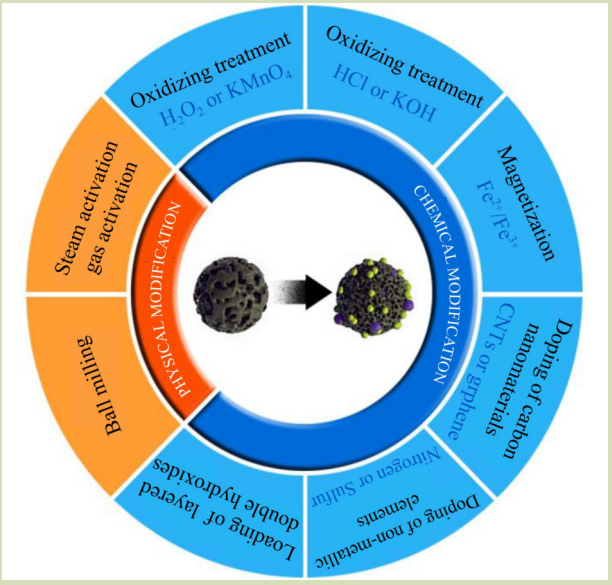

Fig. 14 Schematic diagrams depicting methods for chemical and physical modification of biochar.

peroxide or potassium permanganate can be used to introduce oxygen-containing functional groups onto the biochar surface. This enhances the ability of biochar to complex with heavy metals, increasing its reactivity and adsorption capacity of biochar for these metals[169].

• Acid/base soaking: acid modification introduces acidic functional groups, such as amine and carboxyl groups, to biochar, increasing its metal removal capacity through surface complexation and cation exchange[170]. In contrast, alkaline modification increases the presence of oxygen-containing functional groups, such as ether, carbonyl, carboxyl and hydroxyl groups, while also enhancing the specific surface area of biochar[171]. This process improves the ability of biochar to remove various environmental contaminants.

• Magnetization: incorporating magnetic nanoparticles to biochar, typically through methods like coprecipitation or impregnation, enables magnetic separation, enhancing the recovery and reusability of biochar in water treatment. This modification facilitates easy separation of biochar from water using magnetic fields, thereby simplifying the treatment process and allowing for the efficient recovery of biochar for repeated use, thus improving the sustainability of water treatment[172].

• Doping of carbon nanomaterials: depositing carbon nanotubes onto biochar enhances pollutant removal efficiency and promotes sustainable use in environmental remediation. Carbon nanotubes are effective due to their excellent physicochemical characteristics, including high surface area, exceptional thermal conductivity, superior electron mobility, and high mechanical strength[173]. However, their high cost and engineering challenges limit their use. To overcome these limitations, biochar can serve as a mesoporous and microporous carrier for carbon nanotubes, facilitating the development of novel, recyclable, and effective sorbents for wastewater and polluted soil treatment. Combining them with biochar, which acts as a porous carrier, creates a cost-effective and recyclable composite that enhances sorption capabilities for wastewater and soil treatment[170].

• Non-metallic elements: introducing non-metallic elements such as nitrogen, phosphorus or sulfur to biochar via chemical treatments or precursor materials can modify its electronic characteristics, therefore increasing its functionality, reactivity and adsorption capacity.

• Layered double hydroxides: Layered double hydroxides known for their easy synthesis, uniform layered structure, surface hydroxyl groups and compatibility with various molecules, and promising for composite applications[174,175]. Their alkaline properties and positively charged surfaces enables electrostatic interactions with anionic pollutants, a feature absent in biochar[176]. Nonetheless, their dense layered structure may limit pollutant adsorption when used alone[177]. Therefore, integrating LDHs into biochar synergistically enhances their adsorptive capacity for a wide range of contaminants in water, leveraging the unique characteristics of both materials. This combining the strengths of both materials and improving water remediation efficiency and versatility[178].

In general, these chemical modification techniques are designed to enhance the chemical properties of biochar, particularly surface area. Additionally, they impact the chemical characteristics of biochar, such as surface functional groups, elemental distribution, zeta potential, electron transfer capacity and cation exchange capacity[170,179]. Such modifications are essential for enhancing the performance and adaptability of biochar across various applications. The preparation of porous biochar through chemical activation can be achieved via one- or two-step methods. The one-step method involves directly pyrolyzing a mixture of biomass and activator at elevated temperatures (700–900 °C)[163], eliminating the need for separate pyrolysis and activation stages. Conversely, in the two-step approach, biochar is first produced from biomass pyrolysis at lower temperatures (400–600 °C). Activators are then introduced to the biochar,

which is further heated to higher temperatures (700–900 °C) to create the desired porous structure[159]. For example, using KOH activation followed by pyrolysis can dramatically increase the surface area of biochar, achieving up to 3000 $m^2 \cdot g^{-1}$[180,181]. A recent study found that bamboo biochar pyrolyzed at 600 °C had a specific surface area of only 24.9 $m^2 \cdot g^{-1}$. However, with KOH activation, the surface area improved to 457 $m^2 \cdot g^{-1}$ at a KOH/bamboo ratio of 1:8 (with ~2 g bamboo mass), and further increased to 913 $m^2 \cdot g^{-1}$ at a ratio of 1:1. This enhancement is due to KOH etching carbon fragments and reacting with the oxygen species in biomass to form large quantities of pores and release gaseous products[163,182].

A thorough evaluation of activation processes and heating rates on biochar properties was reported[149]. The study highlighted the significant influence of activation process and heating rates on biochar yield and surface area. KOH-activated biochar showed higher yields compared to steam-activated biochar and neutral walnut shell biochar, demonstrating the efficacy of KOH activation in enhancing production, see Fig. 15(a). Additionally, the surface area of KOH-activated biochar varied notably with heating rates, with a 26% varied observed between 10 and 20 °C·min^{-1}. Significant increases in surface area were recorded at higher heating rates, reaching about 89% and 104% at 30 and 40 °C·min^{-1}, respectively, highlighting the impact of both activation process and heating rates on biochar surface area, see Fig. 15(b).

Physical modification

Physical modification methods have proven effective in enhancing the functionality of biochar. These techniques improve the performance of biochar by adjusting its hydrophobicity, polarity, and surface functional groups. Enhancing hydrophobicity can enhance the affinity of biochar for specific contaminants or improve its compatibility with aqueous environments. Similarly, modifying polarity and surface functional groups can impact the adsorption capacity and reactivity of biochar toward specific pollutants or target molecules[183].

Physical activation methods, while effective in improving biochar properties, have some drawbacks. One notable limitation is the extended activation time, typically around 4 h, due to the gradual changes in the structure and surface characteristics of biochar. Additionally, these methods generally require more energy than chemical activation, with energy requirements ranging from 10.6 to 58.0 kcal[184], due to prolonged heating or mechanical agitation. Despite these challenges, physical activation remains a valuable approach for enhancing biochar functionality, though its time and energy requirements need to be considered[170]. Physical modification techniques commonly using oxidizing agents like gas and steam. Gas treatment exposes biochar to gases such as carbon dioxide or air, altering its surface chemistry and structure. Steam treatment involved high-temperature steam to enhance the porosity and surface area of biochar. During pyrolysis, steam treatment facilitates partial devolatilization and the formation of crystalline carbon, removing trapped byproducts of incomplete combustion and thereby increasing in surface area[136]. CO_2 purging during pyrolysis can increase the surface area of biochar by forming additional micropores through CO_2

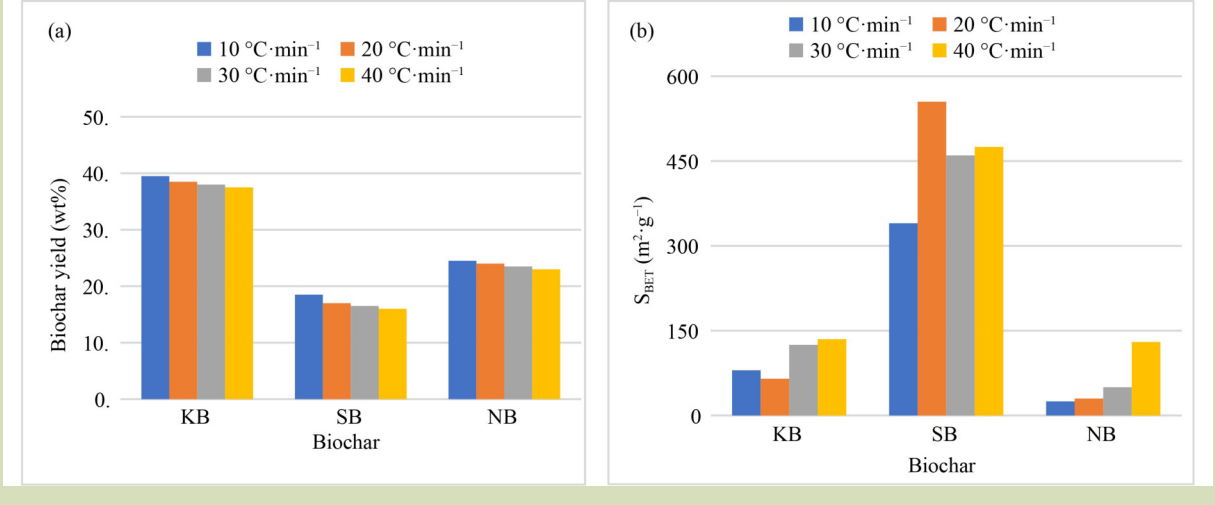

Fig. 15 Comparative heating rate effects on the yield and surface area of KOH-activated (KB), steam-activated (SB) and neutral biochar (NB) (data from Shagali et al.[149]).

activation. CO_2 reacts with the surface carbon structure of the biochar, releasing CO and creating new pores[185]. For example, the surface area of biochar derived from orange peel waste increased from 95.6 to 159 $m^2 \cdot g^{-1}$ for CO_2 activation and up to 305 $m^2 \cdot g^{-1}$ for steam activation[186]. Similarly, research indicates that biochar produced from biomass feedstocks like barley straw, through CO_2 activation, has microporosity with a high surface area (e.g., 789 $m^2 \cdot g^{-1}$), whereas steam activation results in pore enlargement and increased mesoporosity (e.g., 552 $m^2 \cdot g^{-1}$)[187]. Also, combining microwave heating with steam or CO_2 offers advantages such as lower temperature requirements, reduced flow rate and shorter processing times compared to established methods[188].

In addition to steam and air activation, ball milling offers a cost-effective and ecofriendly technique for modifying biochar. This mechanical method uses grinding balls to break down biochar particles, which increases their surface area and enhances their reactivity. Ball milling improves key characteristics such as pore structure, specific surface area and the development of various surface functional groups compared to unmodified biochar[189]. Xiang et al.[190] studied the impact of ball milling on biochar, focusing on surface characteristics and adsorption capabilities, especially in capturing volatile organic compounds. Similarly, Yuan et al.[191] examined the impact of wet and dry ball milling on sawdust-derived biochar, observing a significant increase in specific surface area to 360 $m^2 \cdot g^{-1}$, compared to 154 $m^2 \cdot g^{-1}$ for unmodified biochar, marking a notable enhancement by up to 200 times. This improved surface area boosts the effectiveness of biochar as an adsorbent. Also, incorporating Al/Mg layered double hydroxide into the biochar through ball milling created a composite material with enhanced adsorption properties, notably achieving a Cd^{2+} ions uptake capacity of 119 $mg \cdot g^{-1}$[192].

6 Conclusions

In conclusion, this review has aimed to provide an extensive overview of recent advancements in optimizing biochar production from lignocellulosic biomass through pyrolysis. It has examined various pyrolysis techniques, including both established and new methods, revealing crucial insights into the factors that affect biochar yield and properties. The study emphasizes the importance of understanding the intricate relationship between feedstock composition, pyrolysis conditions and modification methods in determining biochar characteristics and yields. Through careful selection of feedstock, optimization of pyrolysis parameters and using appropriate modification techniques to tailor biochar properties for specific application.

In biochar production, achieving objectives like enhancing properties, ensuring cost-effectiveness, minimizing environmental impact, and maximizing coproduct generation necessitates a comprehensive approach that includes careful feedstock selection, optimized pyrolysis conditions, and effective modification methods. The selection of feedstock is critical for achieving the desired final characteristics and performance of biochar. Choosing renewable and readily available feedstocks reduces dependence on finite resources and repurposes waste materials, thereby mitigating environmental impacts. Key pyrolysis conditions, such as temperature, heating rate and residence time, are vital for maximizing biochar yield and quality while reducing energy consumption and environmental impact. Employing renewable energy sources, efficient heat recovery systems and effective management of byproducts and emissions further enhances sustainability. Also, modification techniques are essential for improving biochar properties to meet specific applications, overcoming the limitations of standard biochar, and enhancing its effectiveness. Sustainable modification approaches can minimize waste, reduce environmental impacts and promote resource efficiency throughout the production process.

Based on the findings presented in this review, several recommendations can be made to further optimize biochar production efficiency and effectiveness:

- Integration of new pyrolysis techniques: promote the use of new pyrolysis techniques, including microwave-assisted pyrolysis, co-pyrolysis, and autothermal pyrolysis, for their benefits in efficiency, scalability, and reduced environmental impact.

- Optimization of feedstock selection: prioritize the selection of feedstocks with optimal lignocellulosic compositions to maximize biochar yield and tailor its properties to specific application requirements.

- Optimization of pyrolysis conditions: adjust pyrolysis parameters, including temperature, heating rate and residence time, to balance biochar yield, properties and process efficiency.

- Exploration of modification methods: investigate both physical and chemical modification to further enhance biochar properties and functionality for targeted applications.

• Integration of sustainable practices: implement sustainable practices, such as renewable energy sources and optimizing feedstock sourcing, to minimize environmental impact and improve the overall sustainability of biochar production.

Implementing these recommendations enables researchers and practitioners to advance biochar production, and fully realize its potential for the sustainable utilization of lignocellulosic biomass resources.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2024597 contains supplementary material (Tables S1).

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Compliance with ethics guidelines

Nguyen Xuan Loc and Do Thi My Phuong declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Lehmann J, Joseph S. Biochar for Environmental Management: an Introduction. In: Lehmann J, Joseph S, eds. Biochar for Environmental Management. 2nd ed. London: *Routledge*, 2015, 1–14
2. Weber K, Quicker P. Properties of biochar. *Fuel*, 2018, **217**: 240–261
3. Li B, Zhao L J, Xie X, Lin D, Xu H B, Wang S, Xu Z X, Wang J F, Huang Y, Zhang S, Hu X, Liu D J. Volatile-char interactions during biomass pyrolysis: effect of char preparation temperature. *Energy*, 2021, **215**(Part B): 119189
4. Dhyani V, Bhaskar T. A comprehensive review on the pyrolysis of lignocellulosic biomass. *Renewable Energy*, 2018, **129**(Part B): 695–716
5. Chen D Y, Cen K H, Zhuang X Z, Gan Z Y, Zhou J B, Zhang Y M, Zhang H. Insight into biomass pyrolysis mechanism based on cellulose, hemicellulose, and lignin: evolution of volatiles and kinetics, elucidation of reaction pathways, and characterization of gas, biochar and bio-oil. *Combustion and Flame*, 2022, **242**: 112142
6. Lai W Y, Lai C M, Ke G R, Chung R S, Chen C T, Cheng C H, Pai C W, Chen S Y, Chen C C. The effects of woodchip biochar application on crop yield, carbon sequestration and greenhouse gas emissions from soils planted with rice or leaf beet. *Journal of the Taiwan Institute of Chemical Engineers*, 2013, **44**(6): 1039–1044
7. Hassan M, Liu Y J, Naidu R, Parikh S J, Du J H, Qi F J, Willett I R. Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: a meta-analysis. *Science of the Total Environment*, 2020, **744**: 140714
8. Gao Y X, Gao W R, Zhu H N, Chen H R, Yan S S, Zhao M, Sun H Q, Zhang J J, Zhang S. A review on N-doped biochar for oxidative degradation of organic contaminants in wastewater by persulfate activation. *International Journal of Environmental Research and Public Health*, 2022, **19**(22): 14805
9. Xie N, Wang H M, You C F. Role of oxygen functional groups in Pb^{2+} adsorption from aqueous solution on carbonaceous surface: a density functional theory study. *Journal of Hazardous Materials*, 2021, **405**: 124221
10. Leng L J, Huang H J. An overview of the effect of pyrolysis process parameters on biochar stability. *Bioresource Technology*, 2018, **270**: 627–642
11. Chaturvedi S, Singh S V, Dhyani V C, Govindaraju K, Vinu R, Mandal S. Characterization, bioenergy value, and thermal stability of biochars derived from diverse agriculture and forestry lignocellulosic wastes. *Biomass Conversion and Biorefinery*, 2021, **13**(2): 879–892
12. Yek P N Y, Wan Mahari W A, Kong S H, Foong S Y, Peng W, Ting H, Liew R K, Xia C, Sonne C, Tabatabaei M, Almomani F, Aghbashlo M, Lam S S. Pilot-scale co-processing of lignocellulosic biomass, algae, shellfish waste via thermochemical approach: recent progress and future directions. *Bioresource Technology*, 2022, **347**: 126687
13. Panwar N L, Pawar A, Salvi B L. Comprehensive review on production and utilization of biochar. *SN Applied Sciences*, 2019, **1**(2): 1–19
14. Suriapparao D V, Tejasvi R. A review on role of process parameters on pyrolysis of biomass and plastics: present scope and future opportunities in conventional and microwave-assisted pyrolysis technologies. *Process Safety and Environmental Protection*, 2022, **162**: 435–462

15. Gohar H, Khoja A H, Ansari A A, Naqvi S R, Liaquat R, Hassan M, Hasni K, Qazi U Y, Ali I. Investigating the characterisation, kinetic mechanism, and thermodynamic behaviour of coal-biomass blends in co-pyrolysis process. *Process Safety and Environmental Protection*, 2022, **163**: 645–658
16. Kostas E T, Beneroso D, Robinson J P. The application of microwave heating in bioenergy: a review on the microwave pre-treatment and upgrading technologies for biomass. *Renewable & Sustainable Energy Reviews*, 2017, **77**: 12–27
17. Remya N, Lin J G. Current status of microwave application in wastewater treatment—A review. *Chemical Engineering Journal*, 2011, **166**(3): 797–813
18. Parvez A M, Wu T, Afzal M T, Mareta S, He T B, Zhai M. Conventional and microwave-assisted pyrolysis of gumwood: a comparison study using thermodynamic evaluation and hydrogen production. *Fuel Processing Technology*, 2019, **184**: 1–11
19. Yang J T, Zhang Z M, Wang J Y, Zhao X L, Zhao Y, Qian J Q, Wang T F. Pyrolysis and hydrothermal carbonization of biowaste: a comparative review on the conversion pathways and potential applications of char product. *Sustainable Chemistry and Pharmacy*, 2023, **33**: 101106
20. Liu X, Burra K R G, Wang Z W, Li J H, Che D F, Gupta A K. Towards enhanced understanding of synergistic effects in co-pyrolysis of pinewood and polycarbonate. *Applied Energy*, 2021, **289**: 116662
21. Polin J P, Carr H D, Whitmer L E, Smith R G, Brown R C. Conventional and autothermal pyrolysis of corn stover: overcoming the processing challenges of high-ash agricultural residues. *Journal of Analytical and Applied Pyrolysis*, 2019, **143**: 104679
22. Li C X, Wu K N, Wu J Y. A bibliometric analysis of research on haze during 2000–2016. *Environmental Science and Pollution Research International*, 2017, **24**(32): 24733–24742
23. Wang Y Y, Chen L, Zhu Y R, Fang W, Tan Y D, He Z Q, Liao H Q. Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: a scientometric review. *Environmental Sciences Europe*, 2024, **36**(1): 25
24. Vassilev S V, Baxter D, Andersen L K, Vassileva C G. An overview of the chemical composition of biomass. *Fuel*, 2010, **89**(5): 913–933
25. Li D C, Jiang H. The thermochemical conversion of non-lignocellulosic biomass to form biochar: a review on characterizations and mechanism elucidation. *Bioresource Technology*, 2017, **246**: 57–68
26. Jayakumar M, Hamda A S, Abo L D, Daba B J, Prabhu S V, Rangaraju M, Jabesa A, Periyasamy S, Suresh S, Baskar G. Comprehensive review on lignocellulosic biomass derived biochar production, characterization, utilization and applications. *Chemosphere*, 2023, **345**: 140515
27. Kataki R, Bordoloi N J, Saikia R, Sut D, Narzari R, Gogoi L, Bhuyan N. Waste valorization to fuel and chemicals through pyrolysis: technology, feedstock, products, and economic analysis. In: Singhania R, Agarwal R, Kumar R, Sukumaran R, eds. Waste to Wealth. Energy, Environment, and Sustainability. Berlin: *Springer*, 2018, 477–514
28. Yang S T. Bioprocessing—From biotechnology to biorefinery. In: Yang S T, ed. Bioprocessing for Value-added Products from Renewable Resources: New Technologies and Applications. Amsterdam: *Elsevier*, 2007, 1–24
29. Shi X J, Wang X, Tang B, Dai Z, Chen K F, Zhou J H. Impact of lignin extraction methods on microstructure and mechanical properties of lignin-based carbon fibers. *Journal of Applied Polymer Science*, 2018, **135**(10): 45580
30. Leng L J, Xiong Q, Yang L H, Li H, Zhou Y Y, Zhang W J, Jiang S J, Li H L, Huang H J. An overview on engineering the surface area and porosity of biochar. *Science of the Total Environment*, 2021, **763**: 144204
31. Abdel Hamid A M, Solbiati J O, Cann I K. Insights into lignin degradation and its potential industrial applications. In: Sariaslani S, Gadd G M, eds. Advances in Applied Microbiology. San Diego: *Academic Press*, 2013, **82**: 1–28
32. Abdolali A, Guo W S, Ngo H H, Chen S S, Nguyen N C, Tung K L. Typical lignocellulosic wastes and by-products for biosorption process in water and wastewater treatment: a critical review. *Bioresource Technology*, 2014, **160**: 57–66
33. Osman A I, Farghali M, Ihara I, Elgarahy A M, Ayyad A, Mehta N, Ng K H, Abd El Monaem E M, Eltaweil A S, Hosny M, Hamed S M, Fawzy S, Yap P S, Rooney D W. Materials, fuels, upgrading, economy, and life cycle assessment of the pyrolysis of algal and lignocellulosic biomass: a review. *Environmental Chemistry Letters*, 2023, **21**(3): 1419–1476
34. Ghavidel A, Scheglov A, Karius V, Mai C, Tarmian A, Vioel W, Vasilache V, Sandu I. In-depth studies on the modifying effects of natural ageing on the chemical structure of European spruce (*Picea abies*) and silver fir (*Abies alba*) woods. *Journal of Wood Science*, 2020, **66**(1): 77
35. Pang C H, Gaddipatti S, Tucker G, Lester E, Wu T. Relationship between thermal behaviour of lignocellulosic components and properties of biomass. *Bioresource Technology*, 2014, **172**: 312–320
36. Collard F X, Blin J. A review on pyrolysis of biomass constituents: mechanisms and composition of the products obtained from the conversion of cellulose, hemicelluloses and lignin. *Renewable & Sustainable Energy Reviews*, 2014, **38**: 594–608
37. Solar J, De Marco I, Caballero B M, Lopez-Urionabarrenechea A, Rodriguez N, Agirre I, Adrados A. Influence of temperature and residence time in the pyrolysis of woody biomass waste in a continuous screw reactor. *Biomass and Bioenergy*, 2016, **95**: 416–423
38. Farrokh N T, Suopajärvi H, Mattila O, Umeki K, Phounglamcheik A, Romar H, Sulasalmi P, Fabritius T. Slow

pyrolysis of by-product lignin from wood-based ethanol production—A detailed analysis of the produced chars. *Energy*, 2018, **164**: 112–123

39. Tumuluru J S, Sokhansanj S, Hess J R, Wright C T, Boardman R D. A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, 2011, **7**(5): 384–491
40. Lu X Y, Gu X L. A review on lignin pyrolysis: pyrolytic behavior, mechanism, and relevant upgrading for improving process efficiency. *Biotechnology for Biofuels and Bioproducts*, 2022, **15**(1): 106
41. Amalina F, Abd Razak A S, Krishnan S, Sulaiman H, Zularisam A, Nasrullah M. Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications. *Cleaner Materials*, 2022, **6**: 100137
42. Nzediegwu C, Naeth M A, Chang S X. Biochar production from lignocellulosic and nonlignocellulosic biomass using conventional and microwave heating. In: Tsang D C, Ok Y S, eds. Biochar in Agriculture for Achieving Sustainable Development Goals. San Diego: *Academic Press*, 2022, 85–95
43. Zaker A, Chen Z, Wang X L, Zhang Q. Microwave-assisted pyrolysis of sewage sludge: a review. *Fuel Processing Technology*, 2019, **187**: 84–104
44. Adelawon B O, Latinwo G K, Eboibi B E, Agbede O O, Agarry S E. Comparison of the slow, fast, and flash pyrolysis of recycled maize-cob biomass waste, box-benhken process optimization and characterization studies for the thermal fast pyrolysis production of bio-energy. *Chemical Engineering Communications*, 2022, **209**(9): 1246–1276
45. Shukla N, Sahoo D, Remya N. Biochar from microwave pyrolysis of rice husk for tertiary wastewater treatment and soil nourishment. *Journal of Cleaner Production*, 2019, **235**: 1073–1079
46. Yameen M Z, Naqvi S R, Juchelková D, Khan M N A. Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability. *Biochar*, 2024, **6**(1): 1–80
47. Qambrani N A, Rahman M M, Won S, Shim S, Ra C S. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: a review. *Renewable & Sustainable Energy Reviews*, 2017, **79**: 255–273
48. Uddin M N, Techato K, Taweekun J, Rahman M M, Rasul M G, Mahlia T M I, Ashrafur S M. An overview of recent developments in biomass pyrolysis technologies. *Energies*, 2018, **11**(11): 3115
49. Mukherjee A, Patra B R, Podder J, Dalai A K. Synthesis of biochar from lignocellulosic biomass for diverse industrial applications and energy harvesting: effects of pyrolysis conditions on the physicochemical properties of biochar. *Frontiers in Materials*, 2022, **9**: 870184
50. Bruun E W, Ambus P, Egsgaard H, Hauggaard-Nielsen H. Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology & Biochemistry*, 2012, **46**: 73–79
51. Ronsse F. Biochar production. In: Bruckman V J, Varol E A, Uzun B B, Liu J, eds. Biochar: A Regional Supply Chain Approach in View of Climate Change Mitigation. Cambridge: *Cambridge University Press*, 2016, 199–226
52. Greco G, Di Stasi C, Rego F, González B, Manyà J J. Effects of slow-pyrolysis conditions on the products yields and properties and on exergy efficiency: a comprehensive assessment for wheat straw. *Applied Energy*, 2020, **279**: 115842
53. Naqvi S R, Ali I, Nasir S, Taqvi S A A, Atabani A E, Chen W H. Assessment of agro-industrial residues for bioenergy potential by investigating thermo-kinetic behavior in a slow pyrolysis process. *Fuel*, 2020, **278**: 118259
54. Heidari A, Khaki E, Younesi H, Lu H R. Evaluation of fast and slow pyrolysis methods for bio-oil and activated carbon production from eucalyptus wastes using a life cycle assessment approach. *Journal of Cleaner Production*, 2019, **241**: 118394
55. Brown T R, Wright M M, Brown R C. Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. *Biofuels, Bioproducts & Biorefining*, 2011, **5**(1): 54–68
56. San Miguel G, Makibar J, Fernandez-Akarregi A R. New advances in the fast pyrolysis of biomass. *Journal of Biobased Materials and Bioenergy*, 2012, **6**(2): 193–203
57. Kaur R, Singh S P. Commercial or pilot-scale pyrolysis units for conversion of biomass to bio-oils: state of the art. In: Nandabalan Y K, Garg V K, Labhsetwar N K, Singh A, eds. Zero Waste Biorefinery. Energy, Environment, and Sustainability. Singapore: *Springer*, 2022, 489–514
58. Zinchik S, Klinger J L, Westover T L, Donepudi Y, Hernandez S, Naber J D, Bar-Ziv E. Evaluation of fast pyrolysis feedstock conversion with a mixing paddle reactor. *Fuel Processing Technology*, 2018, **171**: 124–132
59. Mašek O. Biochar in thermal and thermochemical biorefineries—Production of biochar as a coproduct. In: Luque R, Clark J, eds. Handbook of Biofuels Production: Processes and Technologies. 2nd ed. Cambridge: *Woodhead Publishing*, 2016, 655–671
60. Mohan D, Pittman C U Jr, Steele P H. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & Fuels*, 2006, **20**(3): 848–889
61. Mohanty P, Nanda S, Pant K K, Naik S N, Kozinski J A, Dalai A K. Evaluation of the physiochemical development of biochars obtained from pyrolysis of wheat straw, timothy grass and pinewood: effects of heating rate. *Journal of Analytical and Applied Pyrolysis*, 2013, **104**: 485–493
62. Kumar V K, Panwar N L. Pyrolysis technologies for biochar

production in waste management: a review. *Clean Energy*, 2024, **8**(4): 61–78

63. Naik S N, Goud V V, Rout P K, Dalai A K. Production of first and second generation biofuels: a comprehensive review. *Renewable & Sustainable Energy Reviews*, 2010, **14**(2): 578–597
64. Aguado R, Olazar M, Gaisán B, Prieto R, Bilbao J. Kinetic study of polyolefin pyrolysis in a conical spouted bed reactor. *Industrial & Engineering Chemistry Research*, 2002, **41**(18): 4559–4566
65. Frantzi D, Zabaniotou A. Waste-based intermediate bioenergy carriers: syngas production via coupling slow pyrolysis with gasification under a circular economy model. *Energies*, 2021, **14**(21): 7366
66. Ighalo J O, Iwuchukwu F U, Eyankware O E, Iwuozor K O, Olotu K, Bright O C, Igwegbe C A. Flash pyrolysis of biomass: a review of recent advances. *Clean Technologies and Environmental Policy*, 2022, **24**(8): 2349–2363
67. Ore O T, Adebiyi F M. A review on current trends and prospects in the pyrolysis of heavy oils. *Journal of Petroleum Exploration and Production Technology*, 2021, **11**(3): 1521–1530
68. Singh S, Pant K K, Krishania M. Current perspective for bio-oil production from agricultural residues in commercialization aspect: a review. *Journal of Analytical and Applied Pyrolysis*, 2023, **175**(130-171): 106160
69. Gholizadeh M, Li C, Zhang S, Wang Y, Niu S L, Li Y J, Hu X. Progress of the development of reactors for pyrolysis of municipal waste. *Sustainable Energy & Fuels*, 2020, **4**(12): 5885–5915
70. Muthu Kumar K, Varunkumar S. Ultra-rich carbonization through flash devolatilization for synthesis of biochar from biomass. *Biomass Conversion and Biorefinery*, 2024, **14**(11): 12001–12012
71. Ayyadurai S, Arunachalam K D. Experimental investigations on sugarcane bagasse pyrolytic oil production from flash pyrolysis using a rotary screw reactor. *Biofuels, Bioproducts & Biorefining*, 2022, **16**(2): 576–586
72. Asomaning J, Haupt S, Chae M, Bressler D C. Recent developments in microwave-assisted thermal conversion of biomass for fuels and chemicals. *Renewable & Sustainable Energy Reviews*, 2018, **92**(C): 642–657
73. Lam S S, Chase H A. A review on waste to energy processes using microwave pyrolysis. *Energies*, 2012, **5**(10): 4209–4232
74. Wang Y, Wang C R, Huang X Y, Zhang Q, Wang T, Guo X T. Guideline for modeling solid-liquid adsorption: kinetics, isotherm, fixed bed, and thermodynamics. *Chemosphere*, 2024, **349**: 140736
75. Santhoshkumar A, Anand R. Microwave-assisted fast pyrolysis of hazardous waste engine oil into green fuels. In: Azad K, ed. Advances in eco-fuels for a sustainable environment. Cambridge: *Woodhead Publishing*, 2019, 119–155
76. Huang Y F, Chiueh P T, Shih C H, Lo S L, Sun L P, Zhong Y, Qiu C S. Microwave pyrolysis of rice straw to produce biochar as an adsorbent for CO_2 capture. *Energy*, 2015, **84**: 75–82
77. Bi Z, He B B. Biochar from microalgae. In: Jacob-Lopes E, Zepka L Q, Severo I A, Maroneze M M, eds. 3rd Generation Biofuels: Disruptive Technologies to Enable Commercial Production. Cambridge: *Woodhead Publishing*, 2022, 613–637
78. Lin J H, Liu S W, Han Z J, Ma R, Cui C W, Sun S C. Scaled-up microwave pyrolysis of sludge for hydrogen-rich biogas and life cycle assessment: parameters synergistic optimization, carbon footprint analysis and technology upgrade. *Chemical Engineering Journal*, 2023, **452**: 139551
79. Zhou N, Dai L L, Lv Y N, Li H, Deng W Y, Guo F Q, Chen P, Lei H W, Ruan R. Catalytic pyrolysis of plastic wastes in a continuous microwave assisted pyrolysis system for fuel production. *Chemical Engineering Journal*, 2021, **418**(6387): 129412
80. Robinson J, Binner E, Vallejo D B, Perez N D, Al Mughairi K, Ryan J, Shepherd B, Adam M, Budarin V, Fan J, Gronnow M, Peneranda-Foix F. Unravelling the mechanisms of microwave pyrolysis of biomass. *Chemical Engineering Journal*, 2022, **430**: 132975
81. Siddique I J, Salema A A, Antunes E, Vinu R. Technical challenges in scaling up the microwave technology for biomass processing. *Renewable & Sustainable Energy Reviews*, 2022, **153**: 111767
82. Lam S S, Liew R K, Jusoh A, Chong C T, Ani F N, Chase H A. Progress in waste oil to sustainable energy, with emphasis on pyrolysis techniques. *Renewable & Sustainable Energy Reviews*, 2016, **53**: 741–753
83. Bermúdez J M, Beneroso D, Rey Raap N, Arenillas A, Menéndez J A. Energy consumption estimation in the scaling-up of microwave heating processes. *Chemical Engineering and Processing*, 2015, **95**: 1–8
84. Önal E, Uzun B B, Pütün A E. Bio-oil production via co-pyrolysis of almond shell as biomass and high density polyethylene. *Energy Conversion and Management*, 2014, **78**: 704–710
85. Vuppaladadiyam A K, Liu H, Zhao M, Soomro A F, Memon M Z, Dupont V. Thermogravimetric and kinetic analysis to discern synergy during the co-pyrolysis of microalgae and swine manure digestate. *Biotechnology for Biofuels*, 2019, **12**(1): 1–18
86. Engamba Esso S B, Xiong Z, Chaiwat W, Kamara M F, Longfei X, Xu J, Ebako J, Jiang L, Su S, Hu S, Wang Y, Xiang J. Review on synergistic effects during co-pyrolysis of biomass and plastic waste: significance of operating conditions and interaction mechanism. *Biomass and Bioenergy*, 2022, **159**: 106415
87. Ahmed M H M, Batalha N, Mahmudul H M D, Perkins G, Konarova M. A review on advanced catalytic co-pyrolysis of

biomass and hydrogen-rich feedstock: insights into synergistic effect, catalyst development and reaction mechanism. *Bioresource Technology*, 2020, **310**: 123457

88. Abnisa F, Wan Daud W M A, Sahu J N. Optimization and characterization studies on bio-oil production from palm shell by pyrolysis using response surface methodology. *Biomass and Bioenergy*, 2011, **35**(8): 3604–3616
89. Garforth A A, Ali S, Hernández-Martínez J, Akah A. Feedstock recycling of polymer wastes. *Current Opinion in Solid State and Materials Science*, 2004, **8**(6): 419–425
90. Uzoejinwa B B, He X, Wang S, El-Fatah Abomohra A, Hu Y, Wang Q. Co-pyrolysis of biomass and waste plastics as a thermochemical conversion technology for high-grade biofuel production: recent progress and future directions elsewhere worldwide. *Energy Conversion and Management*, 2018, **163**: 468–492
91. Crombie K N, Mašek O. Investigating the potential for a self-sustaining slow pyrolysis system under varying operating conditions. *Bioresource Technology*, 2014, **162**: 148–156
92. Yoder J, Galinato S, Granatstein D, Garcia-Pérez M. Economic tradeoff between biochar and bio-oil production via pyrolysis. *Biomass and Bioenergy*, 2011, **35**(5): 1851–1862
93. Al-Rumaihi A, Shahbaz M, Mckay G, Mackey H, Al-Ansari T. A review of pyrolysis technologies and feedstock: a blending approach for plastic and biomass towards optimum biochar yield. *Renewable & Sustainable Energy Reviews*, 2022, **167**: 112715
94. Mašek O, Brownsort P, Cross A, Sohi S. Influence of production conditions on the yield and environmental stability of biochar. *Fuel*, 2013, **103**: 151–155
95. Liew J X, Loy A C M, Chin B L F, Alnouss A, Shahbaz M, Al-Ansari T, Govindan R, Chai Y H. Synergistic effects of catalytic co-pyrolysis of corn cob and HDPE waste mixtures using weight average global process model. *Renewable Energy*, 2021, **170**(4): 948–963
96. Titirici M M, Thomas A, Yu S H, Müller J O, Antonietti M. A direct synthesis of mesoporous carbons with bicontinuous pore morphology from crude plant material by hydrothermal carbonization. *Chemistry of Materials*, 2007, **19**(17): 4205–4212
97. Gabhane J W, Bhange V P, Patil P D, Bankar S T, Kumar S. Recent trends in biochar production methods and its application as a soil health conditioner: a review. *SN Applied Sciences*, 2020, **2**(7): 1–21
98. Funke A, Ziegler F. Hydrothermal carbonization of biomass: a summary and discussion of chemical mechanisms for process engineering. *Biofuels, Bioproducts & Biorefining*, 2010, **4**(2): 160–177
99. Kirtania K. Thermochemical conversion processes for waste biorefinery. In: Bhaskar T, Pandey A, Mohan S V, Lee D J, Khanal S K, eds. Waste Biorefinery: Potential and Perspectives. Amsterdam: *Elsevier*, 2018, 129–156
100. Yan W, Hastings J T, Acharjee T C, Coronella C J, Vásquez V R. Mass and energy balances of wet torrefaction of lignocellulosic biomass. *Energy & Fuels*, 2010, **24**(9): 4738–4742
101. Ducey T F, Jeong C, Ro K S. Renewable energy, cleaner environments, and sustainable agriculture from pyrolysis and hydrothermal carbonization of residuals. In: Tsang D C, Ok Y S, eds. Biochar in Agriculture for Achieving Sustainable Development Goals. San Diego: *Academic Press*, 2022, 401–409
102. Abdeldayem O M, Dupont C, Ferras D, Ndiaye L G, Kennedy M. Reconsidering lab procedures for hydrothermal carbonization of biomass: the impact of pre-drying and stirring. *Journal of Analytical and Applied Pyrolysis*, 2024, **179**: 106459
103. Mesa Pérez J M, Rocha J D, Barbosa Cortez L A, Penedo Medina M, Luengo C A, Cascarosa E. Fast oxidative pyrolysis of sugar cane straw in a fluidized bed reactor. *Applied Thermal Engineering*, 2013, **56**(S1–S2): 167–175
104. Luo G Q, Wang W M, Zhao Y, Tao X, Xie W, Wang K G. Autothermal pyrolysis of lignocellulosic biomass: experimental, kinetic, and thermodynamic studies. *Journal of Analytical and Applied Pyrolysis*, 2023, **171**: 105972
105. Jiang S J, Hu X, Wu L P, Zhang L, Wang S, Li T T, Xia D H, Li C Z. Oxidative pyrolysis of mallee wood biomass, cellulose and lignin. *Fuel*, 2018, **217**: 382–388
106. Amutio M, Lopez G, Aguado R, Bilbao J, Olazar M. Biomass oxidative flash pyrolysis: autothermal operation, yields and product properties. *Energy & Fuels*, 2012, **26**(2): 1353–1362
107. Zhao S H, Zhang Y L, Su Y. Experimental investigation of rice straw oxidative pyrolysis process in a hot-rod reactor. *Journal of Analytical and Applied Pyrolysis*, 2019, **142**: 104646
108. Wu L M, Zhou C H, Tong D S, Yu W H. Catalytic thermochemical processes for biomass conversion to biofuels and chemicals. In: Gupta V G, Tuohy M, Kubicek C P, Saddler J, Xu F, eds. Bioenergy Research: Advances and Applications. Amsterdam: *Elsevier*, 2014, 243–254
109. Usino D O, Ylitervo P, Moreno A, Sipponen M H, Richards T. Primary interactions of biomass components during fast pyrolysis. *Journal of Analytical and Applied Pyrolysis*, 2021, **159**: 105297
110. Vasu H, Wong C F, Vijiaretnam N R, Chong Y Y, Thangalazhy-Gopakumar S, Gan S, Lee L Y, Ng H K. Insight into co-pyrolysis of palm kernel shell (PKS) with palm oil sludge (POS): effect on bio-oil yield and properties. *Waste and Biomass Valorization*, 2020, **11**(11): 5877–5889
111. Edmunds C W, Reyes Molina E A, André N, Hamilton C, Park S, Fasina O, Adhikari S, Kelley S S, Tumuluru J S, Rials T G, Labbé N. Blended feedstocks for thermochemical conversion: biomass characterization and bio-oil production from switchgrass-pine residues blends. *Frontiers in Energy Research*, 2018, **6**: 79

112. Wang W L, Wang M, Huang J, Li X P, Cai L P, Shi S Q, Cui Y, Chen L, Ni Y H. High efficiency pyrolysis of used cigarette filters for ester-rich bio-oil through microwave-assisted heating. *Journal of Cleaner Production*, 2020, **257**: 120596
113. Lima E C, Naushad M, Dos Reis G S, Dotto G L, Pavan F A, Guleria A, Seliem M K, Sher F. Production of carbon-based adsorbents from lignocellulosic biomass. In: Anastopoulos I, Lima E C, Meili L, Giannakoudakis D A, eds. Biomass-derived Materials for Environmental Applications. Amsterdam: *Elsevier*, 2022, 169–192
114. Nakason K, Panyapinyopol B, Kanokkantapong V, Viriya Empikul N, Kraithong W, Pavasant P. Hydrothermal carbonization of unwanted biomass materials: effect of process temperature and retention time on hydrochar and liquid fraction. *Journal of the Energy Institute*, 2018, **91**(5): 786–796
115. Mahmood R, Parshetti G K, Balasubramanian R. Energy, exergy and techno-economic analyses of hydrothermal oxidation of food waste to produce hydro-char and bio-oil. *Energy*, 2016, **102**: 187–198
116. Cao Z B, Hülsemann B, Wüst D, Oechsner H, Lautenbach A, Kruse A. Effect of residence time during hydrothermal carbonization of biogas digestate on the combustion characteristics of hydrochar and the biogas production of process water. *Bioresource Technology*, 2021, **333**(3): 125110
117. Windeatt J H, Ross A B, Williams P T, Forster P M, Nahil M A, Singh S. Characteristics of biochars from crop residues: potential for carbon sequestration and soil amendment. *Journal of Environmental Management*, 2014, **146**: 189–197
118. Brewer C E, Chuang V J, Masiello C A, Gonnermann H M, Gao X D, Dugan B E, Driver L E, Panzacchi P, Zygourakis K, Davies C A. New approaches to measuring biochar density and porosity. *Biomass and Bioenergy*, 2014, **66**: 176–185
119. Deluca T H, Gundale M J, Mackenzie M D, Jones D L. Biochar effects on soil nutrient transformations. In: Lehmann J, Joseph S, eds. Biochar for Environmental Management. 2nd ed. London: *Routledge*, 2015, 419–452
120. Jafri N, Wong W Y, Doshi V, Yoon L W, Cheah K H. A review on production and characterization of biochars for application in direct carbon fuel cells. *Process Safety and Environmental Protection*, 2018, **118**: 152–166
121. Ippolito J A, Cui L Q, Kammann C, Wrage-Mönnig N, Estavillo J M, Fuertes-Mendizabal T, Cayuela M L, Sigua G, Novak J, Spokas K, Borchard N. Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, 2020, **2**(4): 421–438
122. Tan X F, Zhu S S, Wang R P, Chen Y D, Show P L, Zhang F F, Ho S H. Role of biochar surface characteristics in the adsorption of aromatic compounds: pore structure and functional groups. *Chinese Chemical Letters*, 2021, **32**(10): 2939–2946
123. Tripathi M, Sahu J N, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: a review. *Renewable & Sustainable Energy Reviews*, 2016, **55**: 467–481
124. Shaaban A, Se S M, Dimin M F, Juoi J M, Husin M H M, Mitan N M M. Influence of heating temperature and holding time on biochars derived from rubber wood sawdust via slow pyrolysis. *Journal of Analytical and Applied Pyrolysis*, 2014, **107**: 31–39
125. Zhao L, Cao X D, Mašek O, Zimmerman A R. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials*, 2013, **256**: 1–9
126. Sakhiya A K, Anand A, Kaushal P. Production, activation, and applications of biochar in recent times. *Biochar*, 2020, **2**(3): 253–285
127. Nhuchhen D R, Afzal M, Dreise T, Salema A A. Characteristics of biochar and bio-oil produced from wood pellets pyrolysis using a bench scale fixed bed, microwave reactor. *Biomass and Bioenergy*, 2018, **119**: 293–303
128. Wang L W, Ok Y S, Tsang D C W, Alessi D S, Rinklebe J, Wang H L, Mašek O, Hou R J, O'connor D, Hou D Y, Fiona N. New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. *Soil Use and Management*, 2020, **36**(3): 358–386
129. Tomczyk A, Sokołowska Z, Boguta P. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Biotechnology*, 2020, **19**(1): 191–215
130. Wiedemeier D B, Abiven S, Hockaday W C, Keiluweit M, Kleber M, Masiello C A, Mcbeath A V, Nico P S, Pyle L A, Schneider M P, Smernik R J, Wiesenberg G L B, Schmidt M W I. Aromaticity and degree of aromatic condensation of char. *Organic Geochemistry*, 2015, **78**: 135–143
131. Guo C B, Zou J J, Yang J L, Wang K H, Song S Y. Surface characterization of maize-straw-derived biochar and their sorption mechanism for Pb^{2+} and methylene blue. *PLoS One*, 2020, **15**(8): e0238105
132. Qin T T, Wang Z W, Xie X Y, Xie C R, Zhu J M, Li Y. A novel biochar derived from cauliflower (*Brassica oleracea* L.) roots could remove norfloxacin and chlortetracycline efficiently. *Water Science and Technology*, 2017, **76**(11–12): 3307–3318
133. Tan Z X, Yuan S G, Hong M F, Zhang L M, Huang Q Y. Mechanism of negative surface charge formation on biochar and its effect on the fixation of soil Cd. *Journal of Hazardous Materials*, 2020, **384**: 121370
134. Chen W F, Wei R, Ni J Z, Yang L M, Qian W, Yang Y S. Sorption of chlorinated hydrocarbons to biochars in aqueous environment: effects of the amorphous carbon structure of biochars and the molecular properties of adsorbates. *Chemosphere*, 2018, **210**: 753–761

135. Zhao B, O'connor D, Zhang J L, Peng T Y, Shen Z T, Tsang D C W, Hou D. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. *Journal of Cleaner Production*, 2018, **174**: 977–987
136. Zhang W D, Sun S Z, Zhu H H, Zhang L Y, Zhao Y J, Wang P X. The evolution characteristics of bituminous coal in the process of pyrolysis at elevated pressure. *Fuel*, 2021, **302**: 120832
137. Pariyar P, Kumari K, Jain M K, Jadhao P S. Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Science of the Total Environment*, 2020, **713**(11): 136433
138. Peiris C, Nayanathara O, Navarathna C M, Jayawardhana Y, Nawalage S, Burk G, Karunanayake A G, Madduri S B, Vithanage M, Kaumal M N, Mlsna T E, Hassan E B, Abeysundara S, Ferez F, Gunatilake S R. The influence of three acid modifications on the physicochemical characteristics of tea-waste biochar pyrolyzed at different temperatures: a comparative study. *RSC Advances*, 2019, **9**(31): 17612–17622
139. Fan M, Li C, Shao Y, Zhang S, Gholizadeh M, Hu X. Pyrolysis of cellulose: correlation of hydrophilicity with evolution of functionality of biochar. *Science of the Total Environment*, 2022, **825**: 153959
140. Wang X Y, Zhai M, Guo H K, Panahi A, Dong P, Levendis Y A. High-temperature pyrolysis of biomass pellets: the effect of ash melting on the structure of the char residue. *Fuel*, 2021, **285**: 119084
141. Hoang A T, Ong H C, Fattah I R, Chong C T, Cheng C K, Sakthivel R, Ok Y S. Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. *Fuel Processing Technology*, 2021, **223**(7): 106997
142. Wang B, Lehmann J, Hanley K, Hestrin R, Enders A. Ammonium retention by oxidized biochars produced at different pyrolysis temperatures and residence times. *RSC Advances*, 2016, **6**(48): 41907–41913
143. Wang Z P, Liu K, Xie L K, Zhu H N, Ji S B, Shu X Q. Effects of residence time on characteristics of biochars prepared via co-pyrolysis of sewage sludge and cotton stalks. *Journal of Analytical and Applied Pyrolysis*, 2019, **142**: 104659
144. Yaashikaa P R, Kumar P S, Varjani S, Saravanan A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnology Reports*, 2020, **28**: e00570
145. Kumar A, Kumar J, Bhaskar T. High surface area biochar from Sargassum tenerrimum as potential catalyst support for selective phenol hydrogenation. *Environmental Research*, 2020, **186**: 109533
146. Liang C F, Gascó G, Fu S L, Méndez A, Paz-Ferreiro J. Biochar from pruning residues as a soil amendment: effects of pyrolysis temperature and particle size. *Soil & Tillage Research*, 2016, **164**: 3–10
147. Sun J N, He F H, Pan Y H, Zhang Z H. Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. *Acta Agriculturæ Scandinavica. Section B, Soil and Plant Science*, 2017, **67**(1): 12–22
148. Janu R, Mrlik V, Ribitsch D, Hofman J, Sedláček P, Bielská L, Soja G. Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resources Conversion*, 2021, **4**(5): 36–46
149. Shagali A A, Hu S, Wang Y K, Li H J, Wang Y, Su S, Xiang J. Comparative study on one-step pyrolysis activation of walnut shells to biochar at different heating rates. *Energy Reports*, 2021, **7**: 388–396
150. Li W W, Amin F R, Fu Y S, Zhang H, He Y F, Huang Y, Liu G Q, Chen C. Effects of temperature, heating rate, residence time, reaction atmosphere, and pressure on biochar properties. *Journal of Biobased Materials and Bioenergy*, 2019, **13**(1): 1–10
151. Nath B, Chen G N, Bowtell L, Nguyen-Huy T. Pyrolysis of wheat straw pellets in a pilot-scale reactor: effect of temperature and residence time. *Energy Science & Engineering*, 2024, **12**(8): 3524–3539
152. Jindo K, Sonoki T. Comparative assessment of biochar stability using multiple indicators. *Agronomy*, 2019, **9**(5): 254
153. Parmar S, Daki S, Shrivastav A. Application of biochar for soil remediation. Kapoor R T, Treichel H, Shah M P, eds. Biochar and its application in bioremediation. Berlin: *Springer*, 2021: 455–471
154. Wang X B, Bai S J, Jin Q M, Li S S, Li Y K, Li Y, Tan H Z. Soot formation during biomass pyrolysis: effects of temperature, water-leaching, and gas-phase residence time. *Journal of Analytical and Applied Pyrolysis*, 2018, **134**: 484–494
155. Parthasarathy P, Al-Ansari T, Mackey H R, Mckay G. Effect of heating rate on the pyrolysis of camel manure. *Biomass Conversion and Biorefinery*, 2023, **13**(7): 6023–6035
156. Abbas Q, Liu G J, Yousaf B, Ali M U, Ullah H, Munir M A M, Liu R J. Contrasting effects of operating conditions and biomass particle size on bulk characteristics and surface chemistry of rice husk derived-biochars. *Journal of Analytical and Applied Pyrolysis*, 2018, **134**: 281–292
157. Tang J C, Lv H H, Gong Y Y, Huang Y. Preparation and characterization of a novel graphene/biochar composite for aqueous phenanthrene and mercury removal. *Bioresource Technology*, 2015, **196**: 355–363
158. Ma Z Q, Yang Y Y, Ma Q Q, Zhou H Z, Luo X P, Liu X H, Wang S R. Evolution of the chemical composition, functional group, pore structure and crystallographic structure of bio-char from palm kernel shell pyrolysis under different temperatures. *Journal of Analytical and Applied Pyrolysis*, 2017, **127**: 350–359

159. Chen D Y, Chen X J, Sun J, Zheng Z C, Fu K X. Pyrolysis polygeneration of pine nut shell: quality of pyrolysis products and study on the preparation of activated carbon from biochar. *Bioresource Technology*, 2016, **216**: 629–636
160. Keiluweit M, Nico P S, Johnson M G, Kleber M. Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science & Technology*, 2010, **44**(4): 1247–1253
161. Liu R J, Liu G J, Yousaf B, Abbas Q. Operating conditions-induced changes in product yield and characteristics during thermal-conversion of peanut shell to biochar in relation to economic analysis. *Journal of Cleaner Production*, 2018, **193**: 479–490
162. Yousaf B, Liu G J, Abbas Q, Ali M U, Wang R W, Ahmed R, Wang C M, Al-Wabel M I, Usman A R. Operational control on environmental safety of potentially toxic elements during thermal conversion of metal-accumulator invasive ragweed to biochar. *Journal of Cleaner Production*, 2018, **195**: 458–469
163. Chen D Y, Li Y J, Cen K K, Luo M, Li H Y, Lu B. Pyrolysis polygeneration of poplar wood: effect of heating rate and pyrolysis temperature. *Bioresource Technology*, 2016, **218**: 780–788
164. Bouchelta C, Medjram M S, Zoubida M, Chekkat F A, Ramdane N, Bellat J P. Effects of pyrolysis conditions on the porous structure development of date pits activated carbon. *Journal of Analytical and Applied Pyrolysis*, 2012, **94**: 215–222
165. Karaosmanoğlu F, Işığıgür-Ergüdenler A, Sever A. Biochar from the straw-stalk of rapeseed plant. *Energy & Fuels*, 2000, **14**(2): 336–339
166. Nguyen B T, Lehmann J, Hockaday W C, Joseph S, Masiello C A. Temperature sensitivity of black carbon decomposition and oxidation. *Environmental Science & Technology*, 2010, **44**(9): 3324–3331
167. Angın D. Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresource Technology*, 2013, **128**: 593–597
168. Liu W J, Jiang H, Yu H Q. Development of biochar-based functional materials: toward a sustainable platform carbon material. *Chemical Reviews*, 2015, **115**(22): 12251–12285
169. Fan Z X, Zhang Q, Li M, Niu D Y, Sang W J, Verpoort F. Investigating the sorption behavior of cadmium from aqueous solution by potassium permanganate-modified biochar: quantify mechanism and evaluate the modification method. *Environmental Science and Pollution Research International*, 2018, **25**(9): 8330–8339
170. Murtaza G, Ahmed Z, Valipour M, Ali I, Usman M, Iqbal R, Zulfiqar U, Rizwan M, Mahmood S, Ullah A, Arslan M, Rehman M H U, Ditta A, Tariq A. Recent trends and economic significance of modified/functionalized biochars for remediation of environmental pollutants. *Scientific Reports*, 2024, **14**(1): 217
171. Ihsanullah I, Khan M T, Zubair M, Bilal M, Sajid M. Removal of pharmaceuticals from water using sewage sludge-derived biochar: a review. *Chemosphere*, 2022, **289**: 133196
172. Zhu S S, Huang X C, Wang D W, Wang L, Ma F. Enhanced hexavalent chromium removal performance and stabilization by magnetic iron nanoparticles assisted biochar in aqueous solution: mechanisms and application potential. *Chemosphere*, 2018, **207**: 50–59
173. Han H W, Rafiq M K, Zhou T Y, Xu R, Mašek O, Li X K. A critical review of clay-based composites with enhanced adsorption performance for metal and organic pollutants. *Journal of Hazardous Materials*, 2019, **369**: 780–796
174. Daud M, Hai A, Banat F, Wazir M B, Habib M, Bharath G, Al-Harthi M A. A review on the recent advances, challenges and future aspect of layered double hydroxides (LDH)—Containing hybrids as promising adsorbents for dyes removal. *Journal of Molecular Liquids*, 2019, **288**: 110989
175. He X, Qiu X H, Hu C Y, Liu Y W. Treatment of heavy metal ions in wastewater using layered double hydroxides: a review. *Journal of Dispersion Science and Technology*, 2018, **39**(6): 792–801
176. Huang D L, Liu C H, Zhang C, Deng R, Wang R Z, Xue W J, Luo H, Zeng G, Zhang Q, Guo X Y. Cr(VI) removal from aqueous solution using biochar modified with Mg/Al-layered double hydroxide intercalated with ethylenediaminetetra-acetic acid. *Bioresource Technology*, 2019, **276**: 127–132
177. Jia Q, Gao J Q, Qiu C, Dong L, Jiang Y H, Liu X H, Hong M, Yang S H. Ultrasound-seeded vapor-phase-transport growth of boundary-rich layered double hydroxide nanosheet arrays for highly efficient water splitting. *Chemical Engineering Journal*, 2022, **433**(6128): 134552
178. Vithanage M, Ashiq A, Ramanayaka S, Bhatnagar A. Implications of layered double hydroxides assembled biochar composite in adsorptive removal of contaminants: current status and future perspectives. *Science of the Total Environment*, 2020, **737**: 139718
179. Enaime G, Baçaoui A, Yaacoubi A, Lübken M. Biochar for wastewater treatment—Conversion technologies and applications. *Applied Sciences*, 2020, **10**(10): 3492
180. Deng J, Li M M, Wang Y. Biomass-derived carbon: synthesis and applications in energy storage and conversion. *Green Chemistry*, 2016, **18**(18): 4824–4854
181. Li S P, Song X Y, Wang X J, Xu C G, Cao M Y, Xiao Z H, Qi C L, Wu M Z, Yang Z P, Fu L R, Ma X L, Gao J S. One-step construction of hierarchically porous carbon nanorods with extraordinary capacitive behavior. *Carbon*, 2020, **160**: 176–187
182. Wang J C, Kaskel S. KOH activation of carbon-based materials for energy storage. *Journal of Materials Chemistry*, 2012, **45**(22): 23710–23725
183. Mo Z L, Shi Q L, Zeng H H, Lu Z, Bi J H, Zhang H, Rinklebe J, Lima E C, Rashid A, Shahab A. Efficient removal of Cd(II) from aqueous environment by potassium permanganate-

modified eucalyptus biochar. *Biomass Conversion and Biorefinery*, 2024, **14**(1): 77–89

184. Kasera N, Kolar P, Hall S G. Nitrogen-doped biochars as adsorbents for mitigation of heavy metals and organics from water: a review. *Biochar*, 2022, **4**(1): 17
185. Alvarez J, Lopez G, Amutio M, Bilbao J, Olazar M. Physical activation of rice husk pyrolysis char for the production of high surface area activated carbons. *Industrial & Engineering Chemistry Research*, 2015, **54**(29): 7241–7250
186. Yek P N Y, Peng W, Wong C C, Liew R K, Ho Y L, Wan Mahari W A, Azwar E, Yuan T Q, Tabatabaei M, Aghbashlo M, Sonne C, Lam S S. Engineered biochar via microwave CO_2 and steam pyrolysis to treat carcinogenic Congo red dye. *Journal of Hazardous Materials*, 2020, **395**: 122636
187. Pallarés J, González-Cencerrado A, Arauzo I. Production and characterization of activated carbon from barley straw by physical activation with carbon dioxide and steam. *Biomass and Bioenergy*, 2018, **115**: 64–73
188. Duan X H, Srinivasakannan C, Peng J H, Zhang L B, Zhang Z Y. Comparison of activated carbon prepared from Jatropha hull by conventional heating and microwave heating. *Biomass and Bioenergy*, 2011, **35**(9): 3920–3926
189. Gao Y Y, Qin Y B, Zhang M, Xu L H, Yang Z C, Xu Z L, Wang Y, Men M. Revealing the role of oxygen-containing functional groups on graphene oxide for the highly efficient adsorption of thorium ions. *Journal of Hazardous Materials*, 2022, **436**: 129148
190. Xiang W, Zhang X Y, Chen K Q, Fang J, He F, Hu X, Tsang D C W, Ok Y S, Gao B. Enhanced adsorption performance and governing mechanisms of ball-milled biochar for the removal of volatile organic compounds (VOCs). *Chemical Engineering Journal*, 2020, **385**: 123842
191. Yuan Y, Zhang N, Hu X. Effects of wet and dry ball milling on the physicochemical properties of sawdust derived-biochar. *Instrumentation Science & Technology*, 2020, **48**(3): 287–300
192. Cui S H, Zhang R, Peng Y T, Gao X, Li Z, Fan B B, Guan C Y, Beiyuan J Z, Zhou Y Y, Liu J, Chen Q, Sheng J, Guo L. New insights into ball milling effects on MgAl-LDHs exfoliation on biochar support: a case study for cadmium adsorption. *Journal of Hazardous Materials*, 2021, **416**: 126258