Discover Plants

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Mechanisms and applications of biochar in environmental remediation, energy, and catalysis

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Abstract

Biochar is a carbonaceous material produced from the thermochemical treatment of biomass in the absence or with a limited supply of oxygen. Despite the use of carbonized biomass to improve agricultural soils over centuries, the application and interest in biochar have grown dramatically owing to its diverse applications in the environment, energy, industry, etc. This review focuses on key technologies of biochar production, comparing their advantages, disadvantages, and their effect on biochar properties. Emphasis has been placed on the physical-chemical properties of biochar (pore structure, surface chemistry, element composition, specific surface area, etc.) as well as the production parameters that control them. Approaches for modifying and activating biochar to improve performance in targeted applications are also discussed. The review further examines the growing role of biochar in pollutant removal, renewable energy systems, and catalytic transformations. In addition, recent advances in nanobiochar are highlighted, emphasizing how reducing particle dimensions to the nanoscale alters surface reactivity, adsorption behavior, and functional performance. Nanomaterials, generally defined as materials with dimensions below 100 nm, possess exceptionally high surface-to-volume ratios that can result in unique physicochemical properties not observed in their bulk counterparts. Finally, current challenges, emerging opportunities, and future pathways for the development and application of biochar-based materials are critically evaluated.

1 Introduction

Biochar is a carbonaceous substance formed through the pyrolysis of biomass (lack of oxygen) or its anaerobic combustion. Biochar usage in improving soil fertility has a long history, dating back thousands of years, when farmers used char in the soil, and was revived recently because of its potential in solving many problems due to its structure and properties [1]. It gained popularity in recent years in solving many problems because of its unique structure and properties [2]. Different properties of biochar depend on the source of feedstock and processes in its production. Pyrolysis temperature is one of the

variables affecting the properties of biochar significantly. Several studies have proved that surface area and porosity increase with an increase in pyrolysis temperature [3–5].

Syngas and bio-oil are produced as other products of pyrolysis together with biochar; they have great potential as substitutes for conventional fossil fuels, and the utilization of these by-products could increase the energy neutrality of biochar-producing systems [6–10]. Biochemically, the components of biochar can be divided into two kinds, organic and inorganic. For organic matter, the major elements are C, H, and O, and part of N and S also exist; more than 80–90% of the total amount of biochar composition is carbon, which makes the structure stable and ensures its function in carbon sequestration. H and O elements are primarily in the form of surface functional groups, including hydroxyl (-OH) and carboxyl (-COOH); it is mainly because of these groups that the reactivity of biochar and reactions with contaminants can occur. Inorganic matter is minerals and metals, including Fe, Mn, Zn, Ca, Mg, P, Si, etc.; the species depends on the feedstock nature [11].

Apart from the composition, the aforementioned production parameters affect a wide variety of physical and mechanical properties of biochars. These properties include, among others: porosity, specific surface area, particle size, water holding capacity, mechanical stability and grindability, zeta potential and hardness, strength and Young's modulus of elasticity. The above-mentioned properties are tunable and are the reason for the wide application range of biochars in numerous fields. Biochar has been mostly used as a soil additive [12–16] to increase soil productivity, sequester carbon, and mitigate climate change, but it also serves as a highly efficient adsorbent in air purification, water treatment, and the adsorption of heavy metals and organic contaminants [12, 13]. It has been used as a heterogeneous catalyst in biodiesel synthesis [15, 16], and the use as an additive in feed supplements is also under consideration, where it stimulates growth of desirable bacteria and improves feed assimilation. Recent engineering approaches applied to biochar have enabled production of nanobiochar, a nanosize derivative where surface area, reactivity, and functional complexity have been significantly enhanced. Nanobiochar can be either top-down produced (e.g., by ball milling or ultrasonication) or bottom-up produced (e.g., via thermal chemical exfoliation, microwave pyrolysis, hydrothermal carbonization) or by combined methods. Enrichment with function via physical/chemical activation and doping with heteroatoms could extend the applicability of this material for advanced applications such as photocatalysis, supercapacitors, and energy storage [17, 18]. (Fig. 1)

Biochar and nanobiochar represent promising technologies, but scientific and technical barriers that are essential to overcome prior to safe and broad implementation of biochar and nanobiochar exist. Factors such as impacts on plant, animal, and human health, and potential for mobilizing and transporting contaminants in aquatic ecosystems require greater scientific understanding. Higher yield per production cycle and assessment of whether optimizing production processes or large-scale production of these products could influence their properties and performance need to be addressed. Long-term experimental studies that examine the chemical stability, structural integrity, and fate, as well as overall life cycle analysis of biochar-based products, are critical. Within the scope of this review, there is a current overview of research related to biochar and nanobiochar, on production processes, physicochemical properties and modification approaches, an overview of existing applications, a summary of what currently restricts

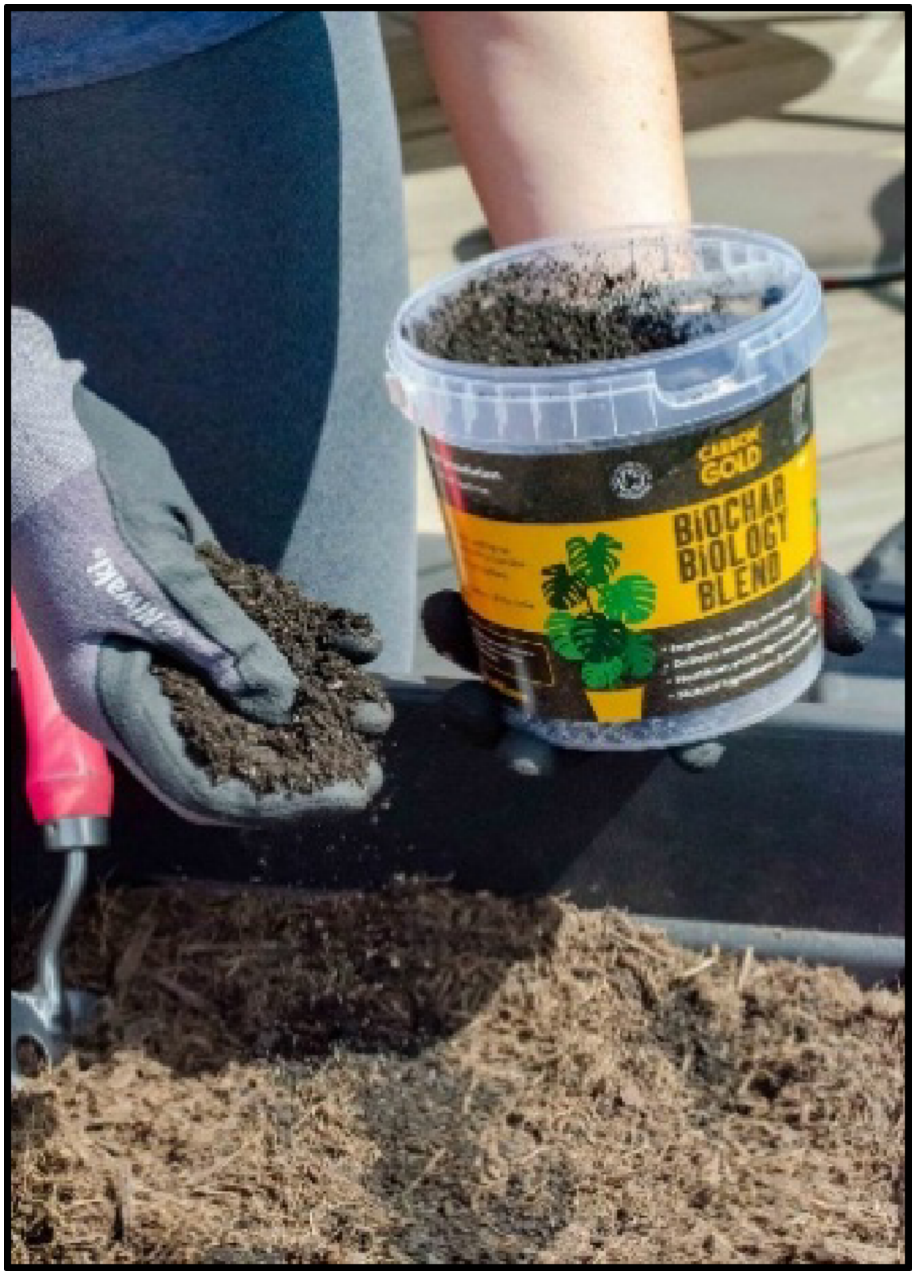


Fig. 1 Biochar formation

the usage, and emerging prospects for a better utilization of biochar-based products (Fig. 2).

2 Biochar production

The history of the application and production of biochar is very old. There is archaeological evidence showing that biochar was applied to soils over 2000 years ago [19]. It was produced on purpose by ancient people to improve soil fertility and agricultural productivity.19 The amendment of soil with biochar helped to increase nutrient availability of soils, improved moisture storage capacity, and enriched the soils' capacity for nutrient holding, which resulted in an improvement of crop yield [20]. Besides its agricultural

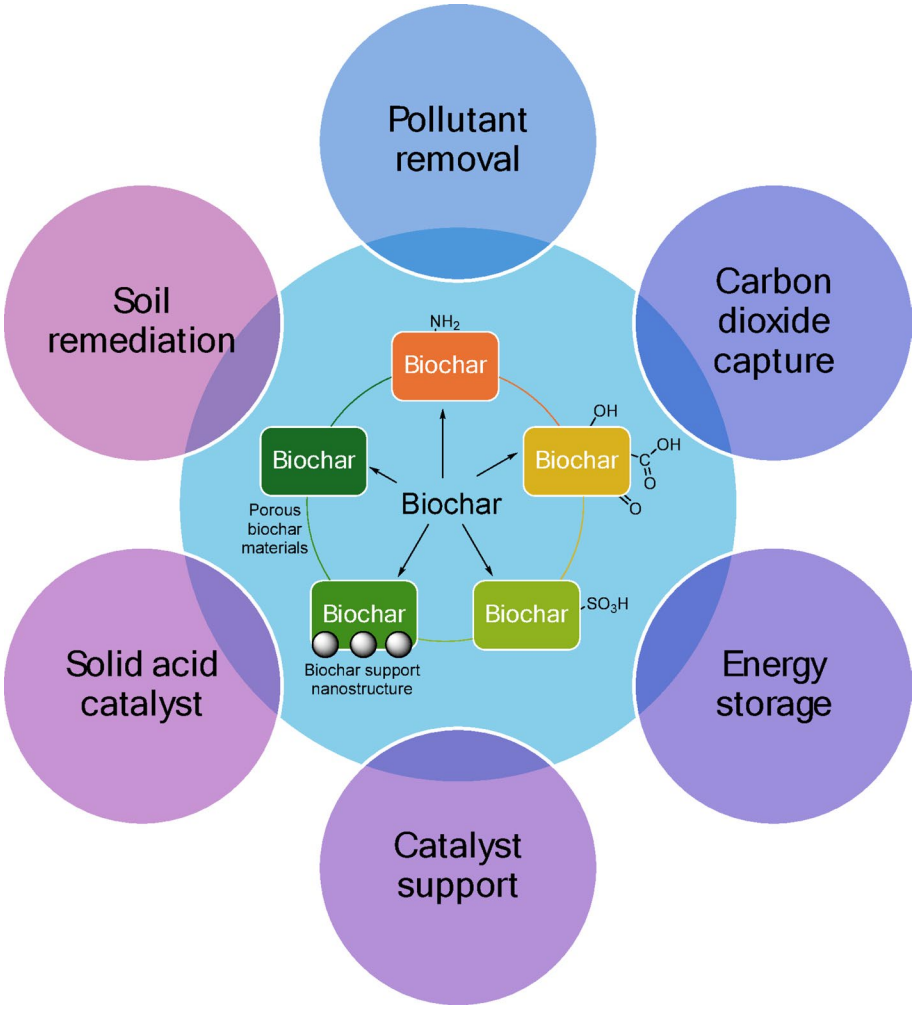
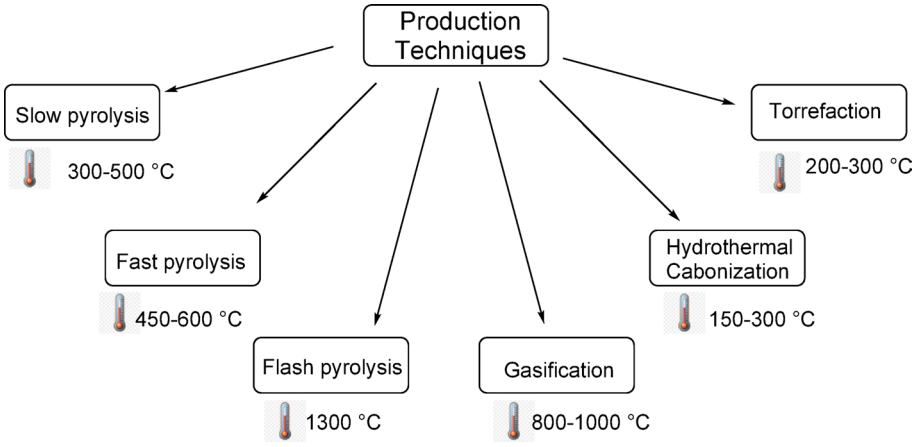


Fig. 2 Biochar for the Synthesis of Various Functional Materials and Their Potential Applications

use, the carbonization process can create side-products that have many uses. It was used for mummification, to make paints and pigments, as binders for building materials, and for arms [19, 21, 22]. In terms of traditional production of biochar, the method was dependent on location, the type of biomass, and the type of kilns. In Spain, underground kilns were used to produce nutrient-rich biochar for agriculture using plant biomass [23]. Indonesia and Sweden used different kinds of kilns, respectively, vertical kilns and a platform-type kiln, adapted to other types of feedstocks and production purposes [24–26]. In common, all types of traditional kilns were built mostly out of clay, and the yield was 20–30% of the initial feedstock [21]. These facts clearly show the awareness about biochar applications and versatility. Scheme 1 summarizes different types of traditional production of biochar.

Due to the growing need to improve the efficiency of biochar production and solve the environmental issues it causes, such as deforestation and air pollution, alternative types of kilns and kiln materials have been designed and fabricated [21, 27]. Metal kilns have been found to be popular for a number of reasons, namely greater durability, efficiency in heat transfer, and greater emission control compared to that achieved in traditional



Scheme 1 Scheme of biochar production methods

kilns made from clay [28]. As a result of their success, metal kilns are still used in many countries for both cooking and small-scale biochar production [19].

Retort kilns were introduced as another technological improvement; these types of kilns recirculate and combust the volatile matter produced during pyrolysis [29]. The heat from the combustion of volatile matter can be recirculated to complete the carbonization of biomass, increasing energy efficiency, reducing emissions, and improving biochar yield [30]. Due to the demand for biochar from various sectors such as agriculture, environment, and industry, a range of new production technologies have been developed. The production technology chosen largely depends on the desired biochar characteristics and the biomass type available; thus, production conditions play a significant role in defining both yield and physicochemical properties of biochar and so their application.

2.1 Pyrolysis

Pyrolysis is one of the oldest and most commonly used methods for biochar production in both traditional and modern contexts. The pyrolysis process relies on the thermal decomposition of organic feedstock in the absence or in a limited presence of oxygen at temperatures typically ranging between 300 and 900 °C [31, 32]. Three distinct products arise from this process, namely: solid biochar, liquid bio-oil, and gaseous syngas. The gases generated consist of carbon monoxide (CO), carbon dioxide (CO), hydrogen (H), and lighter hydrocarbons. There is a complex interdependence of yields of the three products with regard to operating conditions, though usually it is found that higher temperatures result in greater gas yield, and consequently a lower biochar yield [33–36].

Many operational variables like reaction temperature, heating rate, and residence time play a significant role in the pyrolysis process. By varying operational variables, various types of pyrolysis processes can be operated (Table 1). Catalytic pyrolysis is unlike conventional pyrolysis as the catalysts are used to produce pyrolysis products at a lower temperature, which saves energy consumption [58]. Also, catalysts can produce products with good selectivity and quality, which also depend on various properties such as surface area, pore size, pore volume, and acidity [59]. The thermal pyrolysis process can be a slow or fast type. In slow pyrolysis, a low temperature (150–400 °C) and heating rate are adopted, which allows volatile products to stay inside the reactor for a sufficiently

Table 1 Physical properties of biochar

Property	Influencing Factors	Key Observations	References
Surface Area	Pyrolysis temperature, volatile content, feedstock composition, two-step pyrolysis, particle size (nano vs. macro), ball milling	Increases with temperature due to gas evolution; excessive > 900 °C causes pore collapse. Two-step pyrolysis enhances surface area. Cellulose-rich feedstocks produce a larger surface area. Nanobiochar is often higher than macrobiochar; milling may reduce it.	[37–42]
Water-Holding Capacity	Porosity, pore-size distribution, pyrolysis temperature, residual functional groups	Highly porous biochars retain more water. Low-temp biochars may absorb less due to tar blockage and hydrophobic residues. High-temp biochars have developed pore networks for better water retention.	[43–45]
Density	Pyrolysis temperature, biomass density, particle size/shape, heating rate, atmosphere	Decreases due to mass loss. Linear correlation between biomass and biochar density (coefficient ~ 0.82 under N_2 at 15 °C h^{-1} up to 900 °C).	[46]
Mechanical Stability	Internal porosity, carbonization rate, and feedstock composition	Slow carbonization reduces cracks, improving strength. Higher porosity decreases stability. Cellulose- and hemicellulose-rich biochars are more fragile, aiding nanobiochar production.	[20, 46, 47]
Zeta Potential	Surface functional groups, particle size, feedstock origin, solution pH	Nanobiochars have more negative potentials than macrobiochars → better dispersion. Woody/agricultural residues are more negative than sludge/manure. pH affects surface charge; significant changes < 4.5 or > 9.5.	[48–50]
Chemical Composition	H/C & O/C ratios, pyrolysis temperature, particle size, feedstock, trace elements	H/C indicates aromaticity; lower H/C → more condensed aromatics. O/C indicates polarity & oxygen functionality; decreases at higher temperatures. Nanobiochar may alter H/C & O/C depending on feedstock. Trace elements: P, Ca, Mg, Na, K, Mn, Fe, Si, Al (Si, K, Ca most abundant).	[39, 49–51]
pH	Pyrolysis temperature, residence time, particle size, feedstock, metal ions	Raw biomass is acidic to mildly basic. Pyrolysis increases alkalinity; the largest increase is in the first 10 min. Nanobiochar may lower pH by 0.6–0.9 units, feedstock-dependent. Metal ions (Mn, Fe) stabilize pH.	[37, 49–57]

long duration and react secondary [60, 61]. The specific surface area (SSA) of biochar produced from slow pyrolysis is usually high, and the SSA is increased as the temperature increases up to about 600 °C [62]. In the case of slow pyrolysis, temperature had a greater effect on biochar properties compared with residence time (Fig. 3).

By contrast, high-temperature fast pyrolysis is normally operated with 450–600 °C at a high heating rate [63]. The rate of breakdown of biomass under these conditions will greatly increase, thus resulting in decreased yield of biochar and increased yield of volatile matter [64]. With prolonged residence time, more volatile matter is released, thus resulting in even lower solid yield [65]. Traditionally, the reactors used for pyrolysis are kilns, retorts, and converters. The kilns are mainly used to carbonize woody biomass into charcoal, and the liquid and gaseous products are recovered in retorts and converters. Slow pyrolysis was commonly carried out in kilns and retorts, while fast pyrolysis must be carried out in a more complex reactor, such as converters [66, 67]. Although

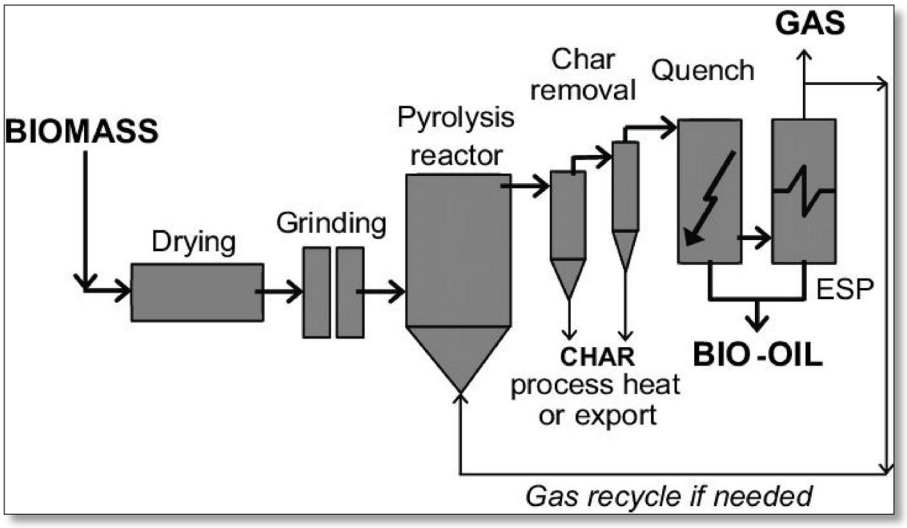


Fig. 3 Biochar production methods by pyrolysis

kilns have low efficiency and cause environmental pollution [68], they have been widely used as economical charcoal producers in developing countries [69, 70]. (Fig. 4)

Retort kilns were originally an enclosed system that enhanced process efficiency by re-burning gaseous and liquid by-products in an efficient way to generate the process heat [71, 72]. However, the performance of the retort kilns demands a constant and rich feedstock material. Converters could process small feedstock particles, enhancing gas permeation efficiency. It allowed continuous fast pyrolysis at higher reaction rates [71]. Current designs of fast pyrolysis reactors could be summarized in rotating cone reactor, ablative reactor, conical spouted bed reactor, bubbling fluidized bed reactor, and circulating fluidized bed reactor [73, 74]. These reactors were designed to produce more bio-oil by providing quick heating rates, a consistent temperature distribution, and a very short vapor residence time [75, 76].

Flash pyrolysis is an intensified form of fast pyrolysis that operates at heat transfer rates > 1000 °C s-1 and temperature ~ 1300 °C [77]. At these severe conditions, the amount of biochar formed is reduced to ~ 17 wt%, but the production of bio-oil can be increased to 65–70 wt% [78]. Fine milled biomass and very short contact times, and specially adapted reactors (e.g., fluidized-bed reactors, twin-screw mixers) are needed for flash pyrolysis. The continuous breakdown of the particles and the high particle-to-particle contact achieved in a twin-screw reactor enables effective heat transfer [79]. However, flash pyrolysis is not economically viable for large-scale industry [19].

2.2 Gasification

Gasification is a thermochemical process in which biomass is partially oxidized, under the influence of a gasification agent (air, CO 2, oxygen, or its mixture), to produce gaseous products [80]. The process conditions, such as temperature and air-to-oxygen ratio, play an important role in changing gas composition as well as characteristics of biochar [81, 82]. Since it focuses on gas products rather than solid products, biochar yield of gasification is typically between 5 and 10%, which is even lower compared to fast and flash pyrolysis [83].

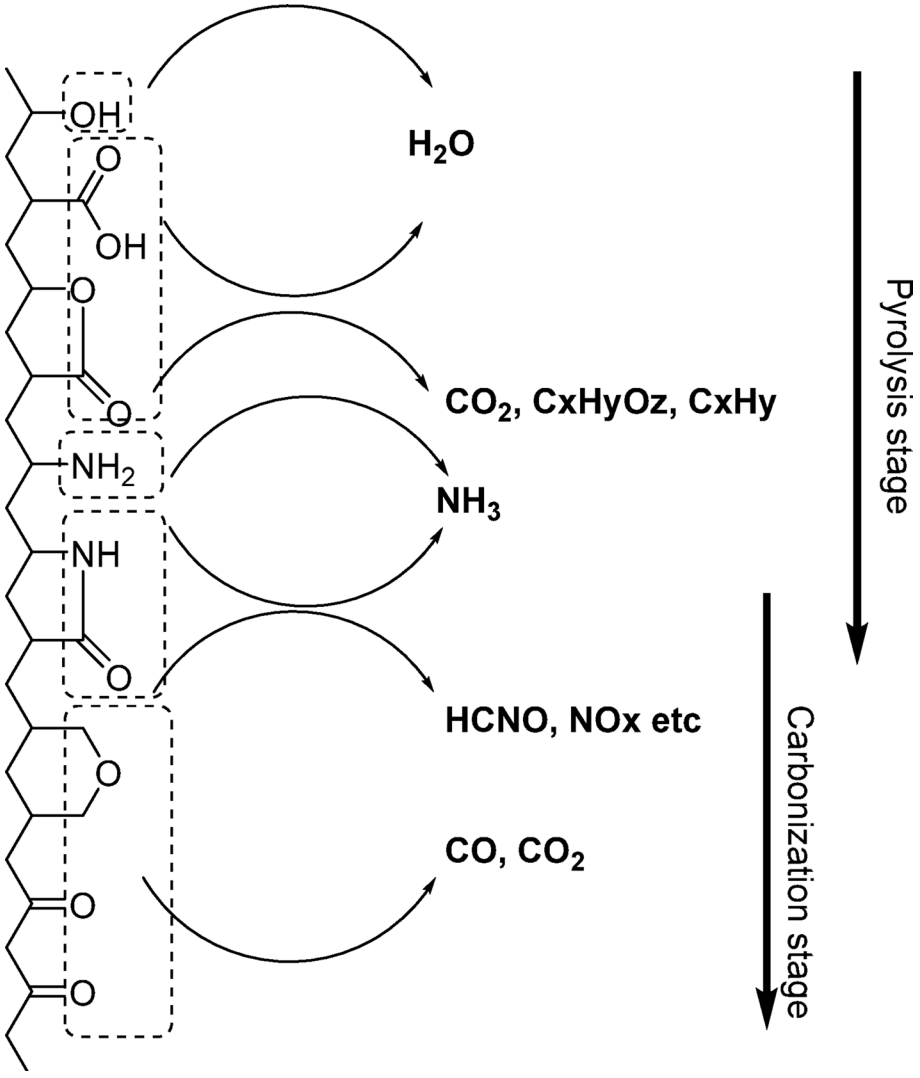
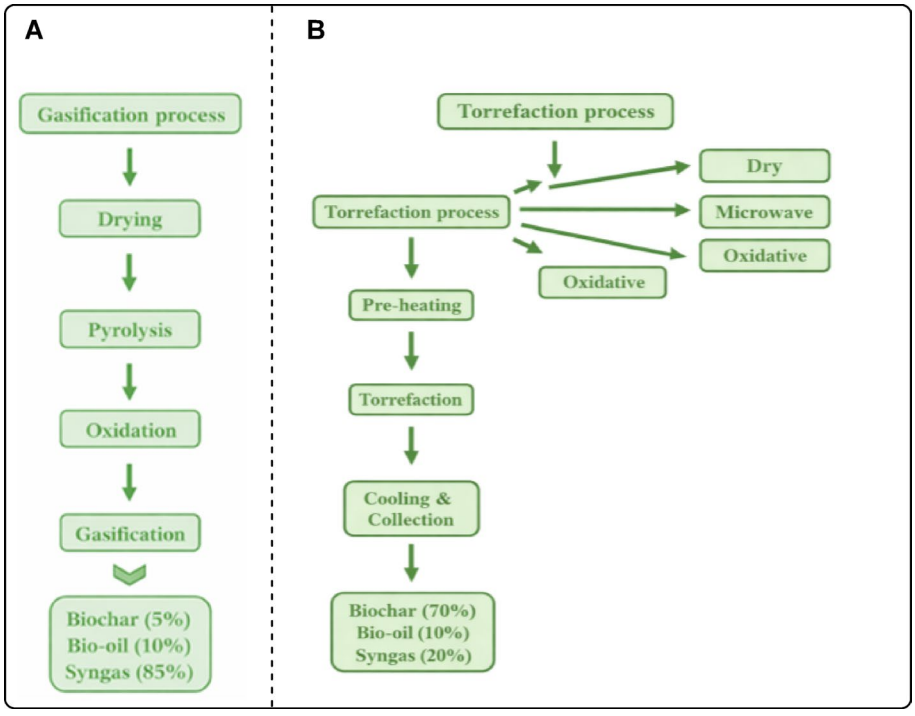


Fig. 4 Decomposition of Biomass with the increase in Pyrolysis Temperature

This process proceeds through four overlapping stages: drying, pyrolysis, oxidation, and gasification. Drying removes moisture from biomass, consuming energy that cannot be recovered. Biomass moisture content below 20% is generally considered suitable for efficient gasification [84]. Pyrolysis usually happens at temperatures around 150–400 °C, followed by oxidation reactions that produce CO_2 [85]. During gasification, char is further converted into gaseous products. (Scheme 2A)

Gasification reactors are classified based on the interaction between biomass and gasifying agents:

1. **Fixed-bed reactors**, commonly used for small-scale power generation due to their high efficiency [86].
2. **Moving-bed reactors**, in which biomass flows continuously through the reactor [87].
3. **Fluidized bed reactors**, in which the biomass particles are entrained in a fluid [88].
4. **Entrained flow reactors**, characterized by very high gas velocities and rapid reaction kinetics [89].



Scheme 2 A) Gasification Steps B)Torrefaction Steps

2.3 Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical process to convert biomass into a coal-like carbon-rich solid through sequential dehydration and decarboxylation reactions [90]. HTC possesses many benefits, in particular the possibility of treating wet biomass such as agricultural waste, municipal solid waste (MSW), sewage sludge, etc. Without requiring an energy-consuming drying step before treatment [91, 92]. HTC is performed at relatively moderate temperatures between 150 and 300 °C, which consequently demands less energy compared to conventional thermochemical conversion technologies [93]. Besides producing hydrochar, other liquid and gas fractions can also be recovered and used as additional energy sources, making the whole process more sustainable [93].

HTC systems are generally categorized into batch and continuous reactor configurations, with batch reactors being more widely employed because of their simpler operation and easier pressure management [92]. The most basic HTC reactor consists of a sealed cylindrical metal vessel heated within a furnace, where the biomass is contained in a perforated holder that permits the release and circulation of volatile compounds generated during the reaction [94]. More advanced systems include autoclave reactors, which offer improved control over operating pressure and reaction conditions [95]. Among the available designs, stirred HTC reactors are considered the most sophisticated, as they incorporate magnetic agitation and precise monitoring of temperature and pressure through integrated thermocouples, ensuring enhanced process control and product consistency [96].

2.4 Torrefaction

Torrefaction is a type of moderate thermochemical treatment which has frequently been applied as a biomass pretreatment. Torrefaction takes place under relatively mild temperature and low heating rate in an inert or oxygen-limited atmosphere [97, 98]. Varying the atmosphere, humidity, and method of heating has led to several types of torrefaction, such as dry, wet, oxidative, steam, and microwave torrefaction. Dry torrefaction (DT) is the earliest type of the torrefaction process, which mainly produces solid biochar (70 wt% of original biomass) along with relatively small amounts of bio-oil and non-condensable gases [99]. The properties of DT biochar are good calorific value, hydrophobicity, and grindability [97, 100]. The process usually takes place at temperature ranges of 200 ~ 300 °C at atmospheric pressure under an inert atmosphere [101]. In contrast, dry torrefaction requires dry feedstock to be input into the reactor, which will require more energy during pretreatment and make the reactor complex and expensive [102, 103]. (Scheme 2B)

Wet torrefaction (WT), also known as hydrothermal torrefaction, addresses this limitation by processing wet biomass in boiling compressed H_2O at 180–260 °C [104–107]. Hydrochar constitutes the main product (~ 88 wt%), accompanied by gaseous by-products from decarboxylation reactions [103, 108]. WT reactors include batch systems for laboratory-scale studies [109] and continuous reactors for industrial applications. Oxidative torrefaction introduces controlled amounts of oxygen or partially oxidative gases, combining thermal decomposition with oxidation [110]. Although economically advantageous, this method often reduces solid and energy yields. However, improved performance has been reported for woody biomass, including increased calorific value and solid conversion [111, 112].

Microwave torrefaction (MT) uses electromagnetic radiation to achieve selective, volumetric heating, improving energy efficiency and reducing processing time [113, 114]. Microwave heating activates polar molecules, facilitates removal of bound H_2O, and enhances the lignin and hemicellulose decomposition through localized hot spots [113]. Unlike conventional heating, MT transfers heat from the interior outward [115], resulting in more uniform heating and reduced energy losses [116–118].

2.5 Nanobiochar production

Nanobiochar (NB) is biochar particles with a diameter less than 100 nm [119]. Nanobiochar is usually prepared using either bottom-up or top-down routes. Bottom-up approaches, like chemical precipitation and microwave pyrolysis, prepare nanobiochar through molecular or atomic self-assembly, while top-down routes, which are mostly adopted for preparing nanobiochar, involve physical breakdown of macro-biochar into nanoparticles via arc discharge, laser ablation, and mechanical milling [120]. Of these techniques, the mechanical approaches, especially ball milling, are attractive for their relatively lower energy consumption and ease of operation [121]. In ball milling, biochar is subjected to multiple impacts against metallic balls, which cleaves chemical bonds and enables charge transfer to yield nanoparticles. The size of the nanoparticles could be tuned via modification of milling time, milling speed, and ball-to-particle ratio [122–124].

The properties of nanobiochar are also greatly dependent upon the type of feedstock used, with the majority of applications utilizing agricultural waste, wood, and forest

residue [125]. High content of hemicellulose present in agricultural waste is beneficial for ease of grinding [126, 127]. Properties of nanobiochar can also be tailored by performing certain modification stages before and/or after its production by using acidic solutions [128, 129], iron compounds [130], magnetite [131, 132], hematite [130] or by adding a polymer like styrene-butadiene rubber [133]. Modified characteristics can either be intensified or novel properties are induced by the modification process based on the modification of chemical species and surface groups. Ball milling is currently the most predominantly used method in order to produce modified nanobiochar, and each stage can be performed at different points in the production process [134].

3 Types of biomass and their influence on biochar properties

The nature of the feedstock is crucial in dictating the physicochemical characteristics, in particular the surface area and porosity of biochar. This is due to the differing amounts and types of mineral and organic fractions that different types of biomass comprise. Feedstock types fall into four categories: (1) woody biomass (e.g., tree residues, sawdust), (2) herbaceous/agricultural biomass (e.g., straw, husk, shells, seeds), (3) waste biomass (e.g., Manure, sewage sludge), and (4) algal biomass (e.g., Microalgae and macroalgae). The inherent minerals within the biomass can affect the pores that form during pyrolysis. The presence of some metals may have pore-activating effects [135], but an overwhelming abundance of mineral material may result in a high ash content, which can clog micropores and lower the surface area. Lignocellulosic biochars thus typically have larger surface areas than biochars produced from manure or waste, the former containing larger amounts of minerals and ash-forming materials [135]. Regarding ash content, manure- and waste-derived biomasses generally have the highest content, followed by algal biomass, herbaceous and agricultural residues, and woody biomass last [136, 137].

It has also been shown that certain metallic elements play an activating role. Zhang et al. (2017) [138] indicated that biochar produced from lotus stems and leaves has a high specific surface area owing to high contents of alkali metals, especially potassium(K). Alkali metals and alkaline-earth metals could serve as auto-activating agents during pyrolysis and enhance pore development [139]. In another study, the porosity of biochar prepared from red mud and lignin was increased by increasing the content of iron(Fe) in the feedstock, which implies that a number of metallic species are likely to be active agents responsible for the pore formation.

Besides the chemical structure of biomass material, the original morphology of the biomass is also considered as an influencing factor for pore characteristics [140]. Compared with sewage sludge biochar, lignin-derived biochar (a hollow and tubular structure) will tend to contain more micropores. Further to the above-mentioned morphology features, particle size also affected the characteristics of surface area and pore volumes. Liu et al. (2018) [141] showed that small particle sizes resulted in increased surface area and micropore volume. But Mui et al. (2010) [142] observed that surface area decreased when particle size reduced to a certain point. Small particles allow more homogeneous heating and carbonization and can increase the formation of pores, but it might lead to more homogeneous ash content, which blocks access to pores. So it's difficult to define a universal relation between biomass features and biochar surface properties due to the complicated influence of feedstock characteristics and treatment conditions.

4 Properties of biochar

A variety of properties are found within biochar that are heavily dependent on the feedstock used for its creation and also the conditions that this material was exposed to. The nature of the source material and also the parameters under which it was pyrolyzed result in differing characteristics, including particle size, physical structure, and function. Nano biochar shares much of the functionality with macro biochar but also possesses differing physical and chemical properties, which are outlined below.

4.1 Physical properties

4.1.1 Surface area

Surface area of biochar is important and greatly affected by the evolution of volatile compounds during pyrolysis. A high amount of volatile compounds facilitates the formation of pores and leads to a higher surface area. As a result, at high temperature, the surface area of biochar usually increases with the temperature, as indicated by gas evolution [37]. Whereas the surface area would be reduced at excessively high temperature (> 900 C) due to shrinkage of the matrix and collapse of the pores [38]. At a low pyrolysis temperature (< 500 C), less carbonization resulted in lower surface area. With the increasing temperature up to around 500 C, there was an increasing amount of volatile evolution and a porous carbon matrix formed. The surface area increased with the increasing temperature up to a maximum and then, above ~ 800 C, a decrease in total pore volume and pore closure caused by pore sintering and graphitization can be detected [39].

It has also been demonstrated that using two-step pyrolysis methods (secondary higher temperature treatment of initial carbonization) yields even greater surface area increases [38]. Feedstock composition is also key; it has been demonstrated that cellulose-rich biomasses produce a higher surface area biochar than hemicellulose or lignin-rich feedstock at equal temperatures, as the smaller thermal stability of cellulose will result in increased volatile release at higher temperature [41]. Nanobiochar does show increased surface area compared to macrobiochar, but not in all cases [39]; it can even result in a decrease due to pore closure and collapse upon milling [40]. For example, rice straw nanobiochar, synthesized at 400 C, showed reduced surface area compared to its macrobiochar counterpart, while at 700 C it showed a substantial increase in surface area [41]. Ball milling primarily affects the external surface rather than the internal pore structure. Lyu et al. (2019) [42] reported only marginal increases in micropore and nanopore surface areas following milling, suggesting that size reduction mainly promotes particle fragmentation and dispersion rather than altering pre-existing internal porosity.

4.1.2 Water retention characteristics

Water retention is dependent on intra-pore structure, i.e., Pore volume and pore size distribution (rather than just particle size) of the biochar, not simply particle size [43]. Large volumes of water can be contained in highly porous networks while simultaneously increasing aeration of the soil. Pyrolysis temperature had the greatest effect on water-retention compared with other production parameters [44]. Low-temperature pyrolyzed biochars have high proportions of oxygenated functional groups, allowing them to interact with water via hydrogen bonding. However, these materials frequently exhibit lower water-storage capacity because residual tars may obstruct pore channels

and limit accessible surface area [45]. Furthermore, the presence of unconverted aliphatic compounds can impart hydrophobic characteristics. In contrast, high-temperature pyrolysis promotes the formation of extensive pore networks and larger surface areas. Although the concentration of polar functional groups decreases, the enhanced pore structure improves the physical retention of water, often resulting in superior moisture-holding performance [44].

4.1.3 Density

During the thermal conversion of biomass, some volatile elements are released, and the overall mass decreases, which in turn causes the density of the material to decrease. The strong relationship between feedstock and biochar densities was previously confirmed by researchers [46]. The final density is subject to parameters such as feedstock shape, particle size, heating rate, reaction temperature and pressure, as well as the atmospheric environment. In particular, under an atmosphere of nitrogen and a slow heating rate up to 900 C, the density coefficient is about 0.82 [46].

4.1.4 Mechanical properties

The structural durability of biochar is controlled by both production conditions and the degree of pore development within the carbon matrix. Slower carbonization processes generally reduce crack formation and produce materials with greater mechanical integrity [46, 47]. However, extensive pore formation often compromises structural strength because highly porous materials are more susceptible to fragmentation [47]. Feedstocks rich in cellulose and hemicellulose tend to generate biochars with lower mechanical resistance. While this may limit some engineering applications, it is advantageous for nanobiochar production because weaker structures can be milled more efficiently into nanoscale particles [20].

4.1.5 Surface charge and zeta potential

Zeta potential is often applied as an indicator of surface charge and suspension stability for biochar particles. Nearly all biochar nanoparticles exhibit negative surface charges due to the dissociation of hydroxyl-containing functional groups. Absolute zeta potential of nano-biochar tends to be higher in magnitude relative to conventional biochars, thus resulting in enhanced colloidal stability and reduced aggregation [48]. Enhanced stability is especially significant when considering particle motion and pollutant transport in the aqueous phase [49]. The magnitude of the zeta potential depends on the nature of the feedstock. Biochar made from woody biomass and agricultural residues usually exhibits greater negative surface charge than that made from sewage sludge and manure. This can mainly be explained by the fact that woody materials and agricultural residues contain more lignin-derived phenolics and carboxylic groups than sewage sludge and manure [49, 50]. The solution pH has a significant impact on the charge of the surface as well. In acidic conditions, the protonation of functional groups can reduce the magnitude of negative charge, lowering the colloidal stability. A dramatic alteration is typically seen below 4.5 and above 9.5, where there is acid/base behavior of carboxyl and phenolic groups on the biochar surface [49].

4.2 Chemical characteristics

4.2.1 Elemental composition

The elemental analysis results for biochar are often discussed using H/C and O/C ratios. These are indicative of structure and can provide information about specific properties of biochar. The H/C ratio is generally an indicator of aromaticity. Lower H/C values typically indicate more aromatic condensation and carbonization. The O/C ratio represents the surface polarity and is related to the number of oxygenated groups present on the biochar surface, which affects polar contaminant interactions. Materials with H/C ratios > 1 still possess a high amount of aliphatic nature from original cellulosic, hemicellulosic, and lignin structures. These elemental ratios are tunable by altering conditions, and so an application may benefit from a biochar that has been designed to have a particular structure. The O/C ratio generally decreases with pyrolysis temperature, as oxygenated groups are continually removed [39]. However, particle size can also play a role in the elemental analysis results. Several studies have demonstrated that the elemental analysis of biochar conversion to nano-biochar may increase or decrease both the H/C and O/C ratio depending on the feedstock and milling process applied [49]. Beyond the major constituents carbon, hydrogen, and oxygen, biochars contain a variety of inorganic elements, typically in trace concentrations. Commonly detected minerals include aluminum, silicon, iron, manganese, potassium, sodium, magnesium, calcium, and phosphorus [51]. Silicon, potassium, and calcium are often the dominant species, although their abundance is highly dependent on the original biomass source. Current investigations comparing macro- and nanoscale biochars have not established a consistent trend in mineral composition following particle-size reduction [51].

4.3 pH characteristics

The biochar pH has the property of influencing its suitability for environmental and agricultural applications. Excessively acidic or alkaline materials may alter soil chemistry and affect nutrient availability. Most untreated biomass feedstocks exhibit neutral to mildly acidic characteristics [52]. During pyrolysis, acidic organic groups are progressively removed, causing the resulting biochar to become increasingly alkaline as processing temperature rises [37]. Residence time also contributes to pH development, with the largest changes typically occurring during the initial stages of thermal treatment [53]. In general, biochars produced through conventional pyrolysis possess higher pH values than hydrochars obtained from hydrothermal carbonization, where organic acid formation is favored [37]. Mechanical downsizing to produce nanobiochar frequently results in a slight decrease in pH. This effect is commonly led to the generation of additional O_2-containing acidic functional groups during milling [50, 54]. Reported decreases generally range from approximately 0.6 to 0.9 pH units [55]. Nevertheless, the response is not universal. Depending on feedstock composition and processing conditions, some studies have observed little change or even an increase in pH following particle-size reduction [49, 51, 57]. Mineral materials present (e.g., Iron and manganese) might even have additional effects on the pH behavior, as they provide positively charged surface sites which buffer pH variations [56]. Based on current evidence, it seems clear that the effect of nanosizing on biochar pH is very system-dependent.

4.4 Influence of biochar properties on environmental behavior

Reducing biochar to the nanoscale introduces unique physicochemical characteristics that can substantially alter its environmental performance. One of the most important consequences of nanosizing is the dramatic increase in surface area relative to particle volume. This enlarged surface provides greater reactive sites, encouraging increased interaction with contaminants, nutrients, and biological systems. As a result, nanobiochar often demonstrates enhanced adsorption, faster reaction rates, and improved catalytic activity compared with conventional biochar materials. Changes in particle size can also modify the electronic and surface properties of biochar. At the nanoscale, variations in surface energy, redox behavior, and electronic structure may influence chemical reactivity and interactions with surrounding environments. These changes can enhance the ability of nanobiochar to participate in oxidation–reduction processes, pollutant transformation, and contaminant immobilization.

The fate of nanobiochar in the environment depends on factors such as small size, surface charge, and surface functional groups. Nanoparticles can move more readily through soil pores and aquatic environments than larger particles, increasing their mobility and potential bioavailability. Their transport behavior is strongly affected by aggregation tendencies, colloidal stability, and interactions with natural organic matter. Surface characteristics also influence transformation processes such as oxidation, dissolution, and photochemical reactions that occur after environmental release [49, 51, 57]. The high reactivity of nanobiochar can provide significant benefits for environmental remediation by improving contaminant removal and accelerating degradation processes. This same property can also result in environmental problems. Enhanced surface activity can promote the formation of ROS species, which can result in microorganisms, plants, and aquatic life experiencing oxidative stress [49, 51, 57]. Consequently, evaluating the environmental implications of nanobiochar requires consideration of its entire life cycle, including production, application, transformation, and eventual disposal. Optimization of particle size, morphology, and surface functionality is essential to maximize environmental benefits while minimizing potential ecological and health risks.

5 Activation methods

As synthesized biochars obtained directly through thermochemical treatment usually has low adsorption and catalytic capacity due to partially blocking of pore networks by remaining tars, ash and other carbons, various activation methods (such as steam activation, CO 2 activation, chemical activation and so on) are developed to alter the pore structure, increase specific surface area and add active surface groups, which facilitates the accessibility of the active sites and the interaction between biochar and targets. Activation strategies generally aim to increase chemisorption capacity by creating chemically active surface functionalities capable of forming stronger interactions with pollutants and other adsorbates. Depending on the desired application, activation can be accomplished through thermal treatment, chemical modification, biological approaches, or surface functionalization methods (Table 2) [163–165].

5.1 Physical activation

Physical activation or thermal activation is the process where biochar is treated with oxidizing gases such as steam, CO2, and air at high temperatures. Physical activation helps

Table 2 Summary of biochar activation methods and their effects on surface area and pore characteristics

Activation Strategy	Processing Conditions	BET Surface Area ($m^2 g^{-1}$)	Pore Volume ($mL g^{-1}$)	Main Outcome	Ref.
Aluminum chloride-assisted activation	$AlCl_3$ impregnation for 6 h, dried at 80 °C for 48 h	212.58–418.14	0.056–0.077	Promoted pore development and improved incorporation of metal species	[143]
Phosphoric acid treatment	5% H_3PO_4, 70–80 °C, 2 h	199–557	0.026–0.22	Increased porosity and expanded surface area	[144]
Alkali sulfide or potassium hydroxide activation	Mixing with Na_2S or KOH solution	32.85–59.23	–	Generated additional surface sites and moderate porosity enhancement	[145]
Steam-assisted physical activation	Steam treatment at 900 °C for 1 h	702–2079	0.53–1.212	Produced extensive micro- and mesoporous networks	[146]
Zinc chloride activation	$ZnCl_2$ impregnation followed by carbonization at 800 °C	583–1067	0.001–0.511	Favored formation of a predominantly microporous structure	[147]
High-temperature pyrolysis under inert atmosphere	900 °C under N_2 for 4 h	204–1080	0.118–0.95	Improved pore characteristics and adsorption capability	[148]
Sodium hydroxide activation	NaOH treatment 2 h at 800 °C	583–1470	0.01–0.705	Enhanced porosity and contaminant uptake performance	[149]
Carbon dioxide activation	CO_2 exposure 11 h at 750 °C	429–621	–	Developed a more homogeneous pore structure	[150]
Microwave-assisted activation	Heating at 900 °C for 75 min	702–2079	–	Increased micropore content and catalytic potential	[151]
Sulfuric acid modification	H_2SO_4 treatment at 180–380 °C	5.3–29.6	0.18–0.30	Introduced acidic surface groups and improved pollutant removal	[152]
Sodium sulfide-assisted activation	Na_2S treatment with drying and mixing at room temperature	32.85–59.23	–	Increased availability of adsorption-active sites	[153]
Steam activation of lignocellulosic residues	Lignin and pruning waste treated at 850 °C	204–1080	–	Enhanced catalytic behavior through increased porosity	[154]
Mixed-gas activation	CO_2/N_2 treatment at 750–920 °C for 0.5 h	435–687	0.18–0.30	Improved pore distribution and structural uniformity	[155]
Moderate-temperature thermal activation	Heating at 500 °C under N_2 for 4 h	13–16	–	Improved surface characteristics for adsorption applications	[65]
Dilute phosphoric acid activation	Low-concentration H_3PO_4 treatment at 70–80 °C	199–557	0.026–0.22	Increased acidic functionalities beneficial for pollutant capture	[156]
Tungsten precursor impregnation	Ammonium tungstate treatment followed by 1000 °C calcination	> 1500	–	Generated thermally stable tungsten carbide phases	[157]
Iron nitrate modification	$Fe(NO_3)_3$ impregnation and thermal treatment at 800 °C	496–716	0.08–0.27	Improved catalytic activity through well-dispersed Fe species	[158]
Oxidative thermal activation	Air treatment	450–800	0.2–0.5	Enhanced pore accessibility for gas adsorption	[159]
Plasma-assisted surface activation	Plasma exposure for 20 min	600–1000	–	Introduced reactive functional groups onto the carbon surface	[160]
Potassium hydroxide activation	KOH treatment at 700 °C	1200–1800	–	Produced highly porous carbons suitable for energy-storage devices	[161]
Combined chemical–physical activation	Sequential H_3PO_4 and CO_2 treatment	800–1400	0.3–0.6	Increased active-site density and overall porosity	[162]

in removing carbon deposits and opening the pore channels. It leads to an increase in pore availability and surface area [166]. Although the process is traditionally described as "physical" activation, the underlying mechanism involves chemical reactions between carbon and activating gases. For example, steam becomes highly reactive at temperatures above approximately 750 °C and participates directly in carbon gasification reactions rather than merely removing volatile residues [167].

Physical activation success is commonly quantified by burn-off percentage (weight lost during treatment). Moderate burn-off percentage levels favor pore development and enhance adsorption efficiency; too much carbon loss leads to the structural breakdown of the pore framework and causes structural collapse. Therefore, activation parameters need to be properly controlled in the case of both developing porosity and maintaining the structure. Steam activation is a broadly adopted physical activation method and could be conducted directly after pyrolysis. Under temperatures typically ranging from 200 to 800 °C with a heating rate of 5–10 °C min and a treatment time of 30–60 min, a highly porous structure containing micropores and mesopores may be generated, leading to good adsorption and catalytic performance [16, 112, 168]. The activation process generally involves three major steps [80]:

a) Water molecules interact with the carbon surface, forming oxygen-containing surface complexes and carbon monoxide.
b) These intermediate surface species subsequently participate in gasification reactions, generating carbon dioxide and creating additional pore space.
c) In parallel with this process, the water-gas shift reactions are also taking place, leading to a more advanced structural modification and development of porosity of the carbon matrix.

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The generation of CO_2 and H_2 is critical for surface activation, as these species further react with the carbon matrix through:

$$C + CO_2 \rightleftharpoons 2CO$$

$$C + 2H_2 \rightleftharpoons CH_4$$

The CO activation also follows the same principles and operates within the 200–900 °C range. Both steam and CO are helpful in the formation and growth of pores, and both of them resulted in little or no differences in adsorption capacity and micropore volume of the activated samples [23, 86]. At the same time, the steam-activated biochar is reported to be more reactive with a greater number of oxygen-containing functional groups [21]. However, the reaction kinetics of the CO activation are found to be slow, which allows better control of oxidation, and a more homogeneous pore structure with higher surface area is attained [27, 139]. At temperatures higher than about 700 C, CO is very reactive through the reverse Boudouard reaction:

$$C + CO_2 \rightleftharpoons 2CO$$

While this reaction is essential for pore development, it also reduces overall biochar yield by converting solid carbon into gaseous products. Consequently, optimizing activation conditions requires balancing surface development against excessive carbon loss.

5.2 Chemical activation

Chemical activation is an extensively employed method to enhance the physicochemical properties of biochar. In this technique, the biochar is treated with chemicals that are active and can induce changes in the surface chemistry and pore structures of biochar, through methods such as oxidation, sulfonation, amination, and metal loading. Various activating agents can be applied, including acids, alkalis, and oxidizing agents, depending on the target applications. The selection of the activating agents is especially critical in the adsorption process, where the target functional groups are necessary to achieve desired interactions with the specific contaminant species. High concentrations of the reagents or harsh temperatures may damage the carbon framework structure and affect its performance.

5.2.1 Alkali activation

Among chemical activation methods, alkali treatment using potassium carbonate (K_2CO_3) and potassium hydroxide (KOH) has received considerable attention due to its effectiveness in generating highly porous carbon materials [169]. The activation temperature plays a critical role in determining the resulting pore structure and surface characteristics.

Studies have shown that both K_2CO_3 and KOH increase the surface area of biochar as activation temperature rises; however, their effects on pore development differ significantly. Activation with K_2CO_3 generally produces biochars with greater surface areas and more extensive pore networks, particularly at elevated temperatures. This treatment promotes the formation of both micropores and mesopores, resulting in a well-developed hierarchical pore structure.

In contrast, KOH activation primarily increases the overall surface area but may alter the distribution of pore sizes. Although pore formation is enhanced, a reduction in microporous volume has been reported in some cases. Consequently, the selection between K_2CO_3 and KOH should be guided by the desired pore architecture and the specific application of the activated biochar.

5.2.2 Metal-assisted activation

Incorporation of metal species is an effective approach for increasing the catalytic and adsorption properties of biochar. Metal-functionalized biochars can be prepared either by introducing metal precursors before carbonization or by modifying the biochar after its formation. During one-step synthesis, metal salts are combined directly with the biomass feedstock prior to thermal treatment. Under these conditions, volatile compounds and carbonaceous intermediates generated during pyrolysis can act as reducing agents, while the metal species facilitate carbon transformation and pore development [170, 171]. Alternatively, a two-step procedure involves the impregnation of preformed biochar with metal-containing solutions. This method enables metal ions or nanoparticles to be anchored onto the carbon surface, providing additional active sites and improving material functionality. An instance of this preparation is the synthesis of iron oxide-modified nanobiochar from rice husks [172]. In this process, ball-milled biomass was combined with iron sulfate and urea before pyrolysis under reducing conditions at 600 °C. The resulting Fe_3O_4-containing nanobiochar exhibited superior adsorption performance

for arsenic removal compared with the unmodified material, demonstrating the benefits of metal incorporation for environmental remediation applications (Fig. 5).

5.2.3 Oxidative activation

The oxidative activation method is widely used to install oxygen-containing functional groups on the biochar surface in order to enhance adsorption performance. Among the oxidizing agents used, hydrogen peroxide (HO) is preferred for its low cost, high availability, and eco-friendly character. Indeed, in case of decomposition, HO leads to only water and oxygen as byproducts and avoids any secondary pollution [173]. The treatment with hydrogen peroxide leads to a functionalization of the biochar surface with oxygen-containing groups (hydroxyl, carbonyl, and carboxyl groups), increasing polarity and thus leading to better adsorption of diverse contaminants. This oxidation agent does not introduce other heteroatoms than the initial carbon backbone, contrary to other oxidation processes [173].

5.2.4 Activation using alkali hydroxides (KOH and NaOH)

Hydroxides of both potassium and sodium are some of the most commonly utilized chemical activating agents for generating ultra-porous biochar [80, 174]. In the thermal activation process, the alkali hydroxides react with the carbon matrix via several redox and gasification reactions, creating new pore structure and significantly enhancing the surface area. The mechanism of activation includes reactions between hydroxides and carbon producing metallic species, gaseous products, and intermediaries that etch the carbon structure. Such interactions are responsible for forming additional micro- and mesopores, thus enhancing access to the intra-surface active sites. Therefore, both KOH- and NaOH-activated biochar are used in large volumes for processes where large surface area materials are required, such as adsorption of pollutants, catalysis, energy storage, etc. [80, 174].

$$2C + 6NaOH \rightleftharpoons 2Na_2CO_3 + 3H_2 + 2Na$$

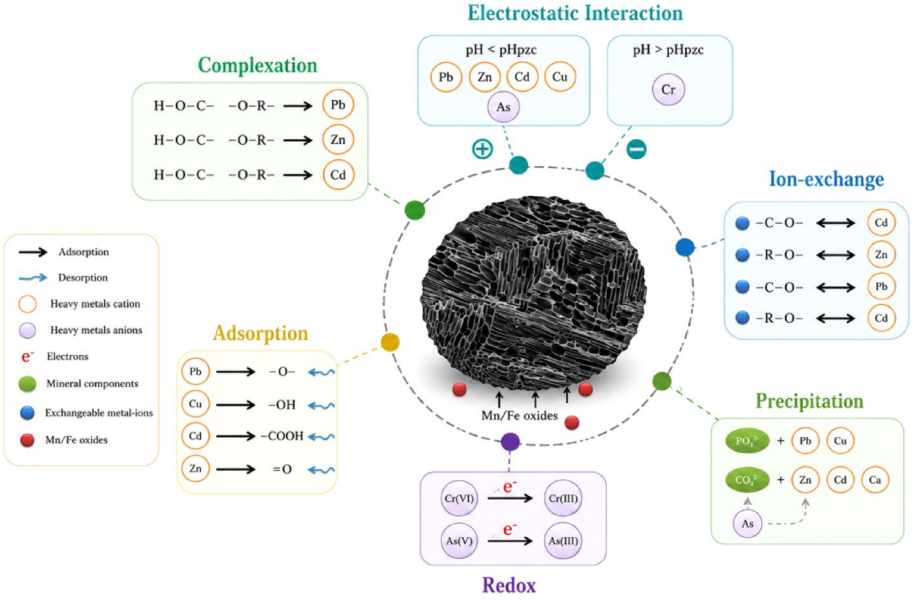


Fig. 5 Biochar interaction mechanisms proposed for organic contaminant removal

Table 3 Biomass-derived biochars: production conditions, properties, and adsorption performance

Feedstock Source	Preparation Method	Pollutant Removed	Key Characteristics and Removal Efficiency
Spirulina microalgae	Pyrolyzed in an inert atmosphere at 750 °C for 2 h	Tetracycline	Produced a carbon material with low oxygen functionality and limited surface area (2.63 $m^2 g^{-1}$). Despite this, adsorption capacity reached 147.9 mg g^{-1}, with approximately 61% desorption efficiency.
Wheat straw	Pyrolysis at 500 °C followed by $KMnO_4$/KOH activation	Tetracycline	Activation produced a very porous material that had a surface area greater than 1500 m^2,g and a pore volume of 0.85 cm^3/g. This material showed good tetracycline uptake (584.19 mg/g) and good resilience against interfering dissolved ions.
Sunflower seed husk	Carbonization at 700 °C combined with $KMnO_4$, KOH, and $ZnCl_2$ activation	Tetracycline	Displayed a well-developed pore structure (1578.3 $m^2 g^{-1}$) and large pore volume (1.138 $cm^3 g^{-1}$). The maximum adsorption capacity reached 673 mg g^{-1} while maintaining high performance in the presence of common cations.
Chlorella microalgae	Wet and microwave-assisted torrefaction at 160–170 °C	Methylene blue	Generated biochar with modest porosity and a low specific surface area. Nevertheless, dye removal efficiency exceeded 85%, with adsorption capacities up to 113 mg g^{-1} across a broad pH range.
Penicillin fermentation residues	Nitrogen-assisted torrefaction followed by KOH impregnation	Methylene blue	Produced a highly porous carbon material with a surface area approaching 1810 $m^2 g^{-1}$ and a pore volume of 1.02 $cm^3 g^{-1}$. Maximum methylene blue uptake was reported as 620 mg g^{-1}.
Bamboo biomass	Pyrolysis at 700 °C with $KHCO_3$ and urea treatment	Methylene blue	Resulted in a nitrogen-modified porous carbon possessing a surface area of 1693 $m^2 g^{-1}$ and substantial pore volume. Adsorption capacity toward methylene blue reached 499 mg g^{-1}.
Orange peel	Slow pyrolysis at 400 °C followed by KOH activation	Chromium species [Cr(III)/Cr(VI)]	The activated biochar exhibited a high surface area (998 $m^2 g^{-1}$) and significant pore development. Cr(VI) adsorption capacity was reported at 285.5 mg g^{-1} under acidic conditions.
Rice husk/ polyethylene waste blend	Co-pyrolysis at 390 °C under nitrogen	Cr(III)	Produced a material with very limited surface area (< 5 $m^2 g^{-1}$). Consequently, chromium adsorption capacity was comparatively low at 9.23 mg g^{-1}.
Potamogeton crispus algae	Pyrolysis at 300 °C for 2 h	Cr(VI)	Generated biochar with minimal porosity and low surface area. The material relied primarily on surface functional groups rather than pore structure for chromium removal.

$$2C + 6\mathrm{KOH} \rightleftharpoons \ 2\mathrm{K_2CO_3} \ + 3\mathrm{H_2} + \ 2\mathrm{K}$$

The aforementioned reactions create a large increase in the surface area and pore volume. Biochar made from brewer's draff activated by 2 M KOH resulted in an increase in total pore volume from 0.01 mL/g to 8.74 mL/g and an increase in surface area from 9.8 m^2/g to 11.6 m g [175]. NaOH has consistently proved less effective than KOH for creating surface area and porosity [176].

5.2.5 $ZnCl_2$ activation

The reason for the high activity of Zinc chloride is due to its dehydrating properties and inhibition effect for tar formation, high diffusion rate into biomass even at low temperature, because ZnCl has a wide range of temperatures in the liquid state. This helps for good impregnation [177, 178]. The biochar derived from rice husk, when activated by ZnCl in a ratio of 3:1 to obtain a specific surface area, was found to be 645 m/g, while only 28 m/g of non-activated biochar possessed. Similarly, for safflower seed press cake

and corn stalk biochar, an increased activation temperature and impregnation ratio increased the surface area, pore size, and adsorption capacity [179, 180].

5.3 Thiol functionalization

A common method for introducing thiol functional groups is 3-mercaptopropyltrimethoxysilane (3-MPTS), which reacts with the hydroxyl groups of the surface to obtain stable thiol-modified surfaces while methanol is generated. The common method for the preparation is impregnation and ball milling. The adsorption capacities of thiol-functionalized biochar prepared by ball milling for Hg (320.1 mg/g) and CHHg (104.9 mg/g) were significantly higher than the modified biochar before ball milling [181].

5.4 Nitrogen doping

One of the most common strategies applied to modify surface chemistry and improve catalytic properties of biochar is nitrogen doping. This can be done either by employing nitrogen-containing precursors such as ammonium hydroxide, ammonium nitrate, urea, and ammonia, or by employing a synthesis in a nitrogen-containing atmosphere. The introduction of nitrogen atoms to the carbon framework leads to the creation of more active sites and affects the electronic properties and adsorbents/reactants adsorption. The effectiveness of nitrogen doping in increasing catalytic activity has been proven by a number of research works. For example, Xing et al. [182] have synthesized N-enriched carbon nanoparticles from graphite powder and a nitrogen-containing atmosphere that possess excellent activity for the oxygen reduction reaction. Pyrolysis temperature plays a significant role in the doping efficiency, as overly high temperatures remove oxygenated surface groups, which are preferential adsorption sites for nitrogen-doped precursors, and lead to lower doping efficiency [183].

Compared with higher-temperature-produced biochars, biochars produced at moderate temperatures tend to show better nitrogen incorporation efficiency. For instance, biochars produced at 450 C after nitrogen modification were found to have a larger surface area than that initially produced at 600 C [183]. Oxygen-containing functional groups can react readily with ammonia and similar nitrogen sources to form more stable nitrogen functional groups within the carbon network. However, it should be noted that the resulting nitrogen functionalities, including pyridinic, pyrrolic, or graphitic nitrogen, are highly dependent on the synthesis parameters and treatment conditions [182–184]. Recently, research also pointed out that modifying mechanical processing parameters like ball milling can help to optimize the dispersion and preferential formation of nitrogen-containing groups [183, 184].

6 Biochar applications

The high surface area, modifiable pore network, and multitude of surface chemistries the biochar possesses contribute to the diversity in potential applications that exist. The ability to tailor the biochar for specific interactions with pollutants, nutrients, gases, and biological systems has given the material broad appeal for applications as varied as adsorption, catalysis, energy, and environmental management. As production techniques improve and biochar modifications continue to emerge, the material's potential use continues to grow to now include applications for agriculture, wastewater treatment, biomedical, animal production, and advanced materials. Biochar has many potential

applications in various fields. In agriculture, biochar is used as a soil conditioner to enhance carbon retention of nutrients. In biomedicine, targeted biochars are studied as drug carriers and adsorbent platforms. In the animal industry, biochar application as a feed additive to diminish methane emissions is being researched. In the construction sector, biochar addition has been made to improve the mechanical performance, insulate, and extend durability. It is projected that biochar will be further used in various fields, contributing to more sustainable technologies and increased circularity of resources.

6.1 Environmental remediation

The uses of biochar are manifold; however, the area in which it has been one of the most studied is that of remediation. The large specific surface area, porous structure, and a plethora of reactive surface groups present in biochar allow it to adsorb or fix many contaminants from water, soil, and air. In aquatic systems, the effectiveness of biochar in the remediation of organic pollutants and toxic metals has been extensively studied. Agricultural and forestry-derived biochars are highly effective in the removal of drugs and other organic contaminants (like dyes) and show removal efficiencies of above 90% under optimal conditions [185–187]. Adsorption of species such as tetracycline and methylene blue occurs via a mechanism involving pore filling, electrostatic interaction, hydrogen bonding, and pi-pi interaction. Removal of heavy metals from contaminated environments represents another area that is highly researched. Lead, cadmium, copper, and zinc, among others, can be removed or immobilized using biochar. Their removal depends largely on the feedstock composition, the amount of minerals contained in the feedstock, and the surface chemistry of the char. The performance in the remediation of heavy metals can be significantly improved in biochars produced from biosolids or other mineral-rich feedstocks since these chars contain an increased amount of inorganic materials, responsible for mechanisms of ion exchange and precipitation [188].

There are several mechanisms of contaminant removal, including electrostatic attraction, forming complexes with surface oxygen-containing functional groups, ion-exchange reactions, precipitation with carbonates and phosphates, and so forth [189, 190]. These adsorption mechanisms are highly influenced by the preparation process conditions of biochar. Generally, an increase in pyrolysis temperature causes the formation of a porous structure and increases surface area, leading to the improvement of adsorption efficiency toward organic and inorganic pollutants [68, 191–193]. Solution factors such as pH have great effects on contaminant speciation and surface functional group ionization status; thus, divalent metal capture capacity by biochar is improved with increasing pH due to enhancement of electrostatic interaction and surface complexation [188].

Biochar has attracted more interest as a material for air pollution control. Various biochars were employed to capture volatile organic compounds (VOCs), S-containing gases, and NO2 from the gas phase [194]. Activation treatment can significantly improve the gas adsorption efficiency by improving porous accessibility and surface reactivity, which includes steam activation or alkali activation. In addition, doping metal oxides such as iron- and aluminum-based materials can increase the capture efficiency of CO2 by increasing active adsorption sites [194]. Recent developments in advanced production methods, including microwave-assisted pyrolysis and engineered surface

modification, have further improved the gas adsorption properties of biochar [195–198]. These approaches can increase both physical and chemical adsorption processes, resulting in significantly enhanced pollutant removal efficiency.

In soil remediation, biochar contributes not only to contaminant immobilization but also to improvements in soil quality. Iron-modified and magnetic biochars have demonstrated excellent performance in the removal of toxic metals while offering the added advantage of magnetic recovery and reuse [199, 200]. In addition, biochar amendments can increase cation-exchange capacity, improve nutrient retention, and reduce bioavailability and mobility of heavy metals, thereby lowering environmental risks and improving agricultural productivity [196]. Overall, the versatility of biochar in soil restoration, air treatment, and water purification highlights its value as a sustainable remediation material [201–205]. High removal efficiencies, broad contaminant applicability, and adaptability through surface modification continue to drive interest in biochar-based technologies for environmental protection and resource recovery [11, 194, 197] (Table 3).

7 Environmental implications of biochar production and use

Biochar has considerable potential in sustainable technologies because of its usefulness in remediation, energy storage, and catalysis. However, its overall environmental value depends not only on its final application but also on how it is produced, modified, transported, and disposed of. Therefore, the benefits of biochar must be evaluated across its full life cycle. Biochar can effectively remove heavy metals and organic contaminants and minimize their discharge to aquatic systems during wastewater treatment [43, 174]. Such removal of pollutants is strongly related to its porous structure, large surface area, and surface functional groups [175]. However, volatile organic matter, particulates, etc. Can be released during the process of biochar preparation if the pyrolysis conditions are not optimal [176, 177]. Therefore, the type of feedstock and the temperature of pyrolysis determine whether the biochar has a net positive environmental effect [176]. Biochar is also being explored as a renewable material for batteries and supercapacitors. Its use can reduce dependence on conventional activated carbons and support circular use of biomass resources [178, 179]. However, activation or chemical modification steps used to improve electrochemical performance may require additional energy and chemicals. As a result, optimization of activation methods is necessary to improve performance without increasing environmental burdens [175, 176].

In catalysis, biochar can function either as a catalyst or as a support material for active catalytic species. Its use may reduce reliance on conventional metal-based catalysts, which can be expensive, toxic, or difficult to dispose of [180, 181]. Biochar surface chemistry can also be adjusted to promote catalytic activity in reactions such as biodiesel production and pollutant degradation [43, 180]. However, emissions such as PAHs and VOCs during production must be carefully monitored to ensure that catalytic applications remain environmentally sustainable [176, 177]. Overall, biochar can contribute to greener remediation, energy, and catalytic technologies. However, its sustainability depends on responsible production, controlled emissions, appropriate feedstock selection, and detailed environmental assessment. Future studies should place greater emphasis on life-cycle analysis, emission monitoring, and long-term environmental behavior to confirm the true sustainability of biochar-based systems.

8 Scalability and practical implementation of biochar technologies

Although biochar has shown strong promise at the laboratory scale, large-scale production remains challenging. Industrial implementation requires consistent product quality, reliable reactor operation, sufficient biomass supply, and economic feasibility. All these are critical issues for such applications as soil amendment, carbon sequestration, water treatment, or energy storage [182]. One major problem is ensuring the homogeneity of biochar properties when scaling up biochar production: properties such as surface area, adsorption capacity, porosity, pH, or chemical stability depend on several parameters related to the pyrolysis, such as the temperature and residence time during the heating phase or the heating rate and the feedstock properties [183, 206–208]. Laboratory systems allow close control of these variables, but industrial reactors often experience temperature gradients and operational fluctuations. These variations can lead to inconsistent biochar quality, reducing performance reliability and market acceptance.

8.1 Pyrolysis control, energy use, and co-product recovery

Slow pyrolysis is commonly used for large-scale biochar production because it favors high fixed-carbon retention. However, controlling temperature and residence time becomes more difficult as reactor size increases. Industrial systems must therefore be designed to process large biomass volumes while maintaining stable thermal conditions [182, 209–212]. Another essential aspect in a commercial-scale operation is energy efficiency. The pyrolysis process gives rise to several co-products, including bio-oil and syngas, which can be utilized in the biochar plant as a source of energy, heat, or electricity. By means of their recovery, the dependency on external energy sources can be reduced and thus operating costs decreased, and a higher overall sustainability of the process increased [182]. A highly integrated system may have biochar plants that move towards partial or total energy self-sufficiency due to the exploitation of co-products.

8.2 Feedstock availability and optimization

The choice of biomass feedstock is central to successful scale-up. While many materials can be tested in laboratory studies, industrial production depends on feedstocks that are affordable, locally available, and obtainable in large quantities. Agricultural residues, forestry wastes, and other lignocellulosic materials are especially attractive because they are abundant, carbon-rich, and generally low in toxicity [183]. However, biomass variability remains a major limitation. Differences in moisture content, ash content, mineral composition, and organic structure can affect pyrolysis efficiency and final biochar properties [182, 183, 213–218]. Pretreatment steps such as drying, grinding, or sorting may improve consistency but can also increase processing costs. Therefore, feedstock optimization must balance product quality with economic practicality.

8.3 Economic feasibility and policy support

The commercial success of biochar depends on both production cost and market demand. Agricultural use, water treatment, carbon sequestration, and replacement of activated carbon are among the most promising markets. However, high capital costs, operational expenses, and competition with established materials can limit adoption. Policy support can play an important role in improving economic feasibility. Carbon credits and/or climate incentives, as well as subsidies for carbon removal technologies,

may contribute to offset production costs and motivate investment in biochar production plants [182]. In addition, integrating biochar production into biorefinery systems can improve profitability by generating multiple products, including biochar, syngas, bio-oil, and heat [184].

8.4 Commercial biochar producers and certification standards

Biochar production has moved beyond academic research, with several companies now operating at commercial scale. These companies often use certification systems to demonstrate product quality, environmental safety, and carbon-removal credibility. Certification is particularly important for participation in carbon markets and for building confidence among customers, regulators, and investors.

8.4.1 NetZero

NetZero operates in France and Brazil and produces biochar mainly from agricultural residues. The company follows the Puro Standard developed by Puro Earth, which focuses on durable carbon removal. This certification entails independent verification, life cycle assessment, and full carbon storage and emission calculation concerning the use and production of biochar [185, 186]. The use of a certification will increase transparency and the credibility of biochar as a carbon credit.

8.4.2 Biochar works

Biochar Works, based in the United States, uses certification approaches such as the VM0044 methodology for biochar-related greenhouse gas mitigation projects. This framework evaluates long-term carbon storage, environmental safeguards, and climate benefits, particularly for soil applications [187]. These requirements help ensure that certified biochar projects contribute meaningfully to emissions reduction.

8.4.3 Carbon gold

Carbon Gold, based in the UK, adheres to schemes such as the International Biochar Initiative standard and European Biochar Certificate. The schemes stipulate quality and safety requirements for the production and application of biochar, particularly in agricultural applications. The IBI requirements outline composition, stability, and acceptable contaminant levels of biochar, while the EBC addresses emissions tracking, product quality, and European regulations [187, 188] (Table 4).

9 Environment and toxicity

The inherent toxicity and environmental risk of biochar, particularly nanobiochar, have grown to be significant research topics given its emerging application into various environmental and agricultural systems [219]. Though generally regarded as environmentally sound, biochar in nano size is associated with a higher surface reactivity and mobility than biochar, which may contribute to increased interactions with living organisms and ecosystems. Research suggests that nanobiochar may lead to a decrease in soil microbial communities, influence plant growth patterns, and may also pose a risk to aquatic organisms due to increased dispersion and bioavailability [220–224]. Furthermore, materials like biochar may absorb co-contaminants such as heavy metals and organic pollutants and distribute these pollutants within soil and water systems instead of immobilizing

Table 4 Summary of biochar studies indicating lignocellulosic feedstocks, key biochar properties evaluated for different applications, analytical techniques employed, and multi-criteria decision-making (MCDM) tools applied

End-Use Category	Biomass Sources Investigated	Main Evaluation Parameters	Characterization Methods Employed	Decision-Making Approach
Energy and Fuel Production	Grape pomace	Biochar recovery, carbon enrichment, calorific value, and combustion behavior	Proximate and elemental analyses, calorimetry, TG/DTG measurements	Pareto-based compromise optimization
Energy and Fuel Production	Grape pomace, cherry and peach pits, rapeseed, sunflower husks, softwood residues	Moisture content, ash fraction, heating value, and thermal degradation characteristics	Proximate analysis, calorific testing, thermogravimetric analysis	Pareto dominance and compromise programming
Energy and Fuel Production	Fruit-derived seed wastes	Carbon enrichment, energy enhancement, and energy–mass performance indices	Elemental composition and calorific analyses	Multi-criteria optimization using Pareto methods
Energy and Fuel Production	Spent coffee grounds and brewery by-products	Atomic H/C and O/Cratios, energy yield, and upgrading fuel efficiency	Elemental and calorimetric analyses	Compromise programming framework
Energy and Fuel Production	Tree-pruning biomass	Fixed carbon content, ash concentration, elemental ratios, and heating value	Proximate, ultimate, and calorific analyses	Pareto-based ranking strategy
Catalytic Material Development	Grape pomace, fruit stones, oilseed residues, and softwood	Mineral composition (K, Ca, P), carbon concentration, and surface area	EDS, BET surface analysis, and elemental characterization	Compromise programming with Pareto evaluation
Agricultural Soil Improvement	Fruit seed biomass	Nutrient content, elemental ratios, and carbon enhancement metrics	EDS and ultimate analysis	Pareto dominance assessment
Agricultural Soil Improvement	Grape pomace	Carbon content, nutrient availability (N, P, Mg, K), and elemental ratios	Elemental and EDS analyses	Multi-objective optimization approach
Carbon Sequestration, Soil Conditioning, and Energy Storage	Grape pomace, cherry stones, peach stones, rapeseed, sunflower husks, and softwood	Mineral content, carbon concentration, porosity, bulk density, electrical conductivity, and pH	BET analysis, EDS, elemental analysis, conductivity, and pH measurements	Pareto compromise decision model
Water Purification and Pollutant Removal	Algal biomass, wheat straw, sunflower husks, penicillin residues, bamboo, orange peel, rice husk, and paper sludge	Surface chemistry, O/C ratio, pore characteristics, graphitic order (ID/IG), and adsorption/desorption behavior	Physicochemical characterization, Raman spectroscopy, elemental analysis, and surface analytical techniques	Not reported

the contaminants. Long-term impacts concern the persistence and accumulation of these particles within the environment, and also the generation of reactive oxygen species from the biochar materials [225–227]. Although at present data are contradictory because of differences in feedstock, methods of preparation, and experimental conditions, standardized toxicity tests, environmental monitoring, and lifecycle assessments are of necessity for responsible application of biochar and nanobiochar on a large scale [228–232].

10 Conclusion

Although several review articles have discussed specific aspects of biochar applications, most have focused on individual sectors such as environmental remediation, agriculture, energy storage, or catalysis. The novelty of the present review lies in its comprehensive and integrated evaluation of biochar across multiple application domains, including environmental remediation, energy generation and storage, catalysis, agriculture, biomedicine, animal nutrition, and advanced materials. In addition to summarizing recent developments, this review emphasizes the relationship between biochar's physicochemical properties such as surface area, porosity, surface functionality, and mineral composition and its performance in diverse applications. Furthermore, it critically examines how feedstock selection, pyrolysis conditions, and post-synthesis modification strategies influence these properties and ultimately determine the efficiency of application. The review also highlights current challenges, including variability in biochar characteristics, long-term stability, catalyst deactivation, economic feasibility, and scalability concerns, while identifying future research directions focused on process standardization, advanced modification technologies, and life-cycle sustainability assessment. By bringing together these diverse perspectives within a single framework, this review provides a broader understanding of biochar's multifunctional role in supporting circular economy principles and the transition toward sustainable, low-carbon technologies.

Abbreviations

HTC	Hydrothermal Carbonization
DT	Dry Torrefaction
WT	Wet Torrefaction
MT	Microwave Torrefaction
NB	Nanobiochar
SSA	Specific Surface Area
O/C	Oxygen-to-Carbon ratio
H/C	Hydrogen-to-Carbon ratio
BET	Brunauer–Emmett–Teller analysis
EDS	Energy Dispersive Spectroscopy
ID/IG	Intensity ratio of D-band to G-band (Raman spectroscopy)
HHV	Higher Heating Value
EF	Enhancement Factor
EY	Energy Yield
EMCI	Energy–Mass Coefficient Index
CEI	Carbon Enhancement Index
FC	Fixed Carbon
ROS	Reactive Oxygen Species
MB	Methylene Blue
IBI	International Biochar Initiative
EBC	European Biochar Certificate

Author contributions

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Competing interests

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