

Biochar-based nanocomposites from waste biomass: a sustainable approach for wastewater treatment and renewable bioenergy

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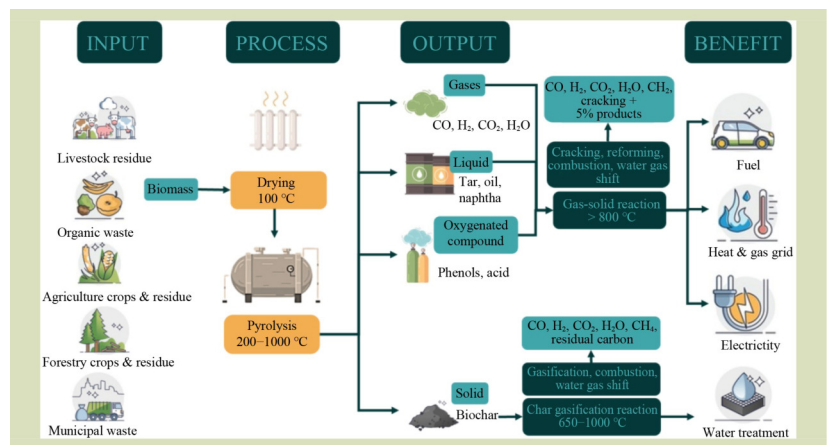
KEYWORDS

Biofuels, biomass, climate action, energy, sustainability, UN Sustainable Development Goals

HIGHLIGHTS

- Biochar-based nanocomposites are suitable for sustainable waste treatment
- Biochar contains 50% to 90% carbon, with a balance of oxygen and hydrogen.
- Biochar enhances water quality, soil health, carbon sequestration and agricultural productivity.
- Biochar can be used to address waste management issues and create materials for environmental cleanup and energy production.
- Biochar has removal efficiencies of 98.6% and 99.2% for lead and cadmium, respectively.

GRAPHICAL ABSTRACT



ABSTRACT

The study emphasizes the significance of biochar-based nanocomposites (BNCs) in tackling waste management challenges and developing valuable materials for environmental remediation and energy generation. BNCs have enhanced adsorption and catalytic properties by incorporating nanoparticles into a charcoal matrix, offering a dual benefit for waste treatment and environmental preservation. Using waste biomass for BNC production repurposes resources and reduces the ecological impact of waste disposal. This study also addresses the existing research gaps and uncertainties hindering the widespread use of biochar and BNCs. After almost a decade of extensive research, it is crucial to address and fill the gaps in knowledge, such as long-term impacts, carbon sequestration rates, potential deforestation and economic viability. Thoroughly analyzing the entire system and establishing adaptable governance is needed to realize the full benefits of BNCs. This article discusses the urgent need for sustainable technology and solutions to solve global concerns, including waste management, water quality, soil health, climate change and renewable energy. Its aim is to improve existing research

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by providing a comprehensive overview of the potential of biochar and BNCs in achieving sustainability objectives. It also identifies research gaps and challenges that must be addressed, directing future research directions. It extensively reviews biochar-based nanocomposites derived from waste biomass as a sustainable solution for wastewater treatment and renewable bioenergy. The constraints and future research directions have been highlighted, offering essential perspectives on the potential of biochar and BNCs in addressing global sustainability issues.

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1 Introduction

As the global population continues expanding toward 10 billion by 2050, there is a significant increase in waste generation that existing waste management systems cannot handle^[1]. The percentage of people living in urban areas in the Americas (excluding Canada and the USA), Asia and Africa is projected to rise from 46% in 2015 to over 60% by 2050^[2]. This unplanned urbanization has led to the sprawl of informal settlements and slums that lack access to municipal waste collection services and proper disposal infrastructure^[3]. However, contemporary industrial agriculture often degrades soil fertility, pollutes waterways, emits greenhouse gases and remains vulnerable to climate disruptions, including drought, flooding and extreme heat. Simply intensifying unsustainable practices would accelerate environmental decline and undermine long-term food security. There is an urgent need for technologies and management strategies that simultaneously enhance agricultural productivity, restore soil health, improve water quality, sequester carbon and strengthen resilience to shifting local climates^[4].

Biochar presents a potentially transformative solution that addresses multiple sustainability objectives across food systems and ecosystems. Biochar is derived from the Greek word *βίος*, meaning life, and *char*, provided with the meaning of charcoal carbonaceous substance generated from biomass via the pyrolysis process, wherein the organic material is heated in the absence of oxygen^[5]. The resulting material looks like charcoal, but it has unique properties that make it highly beneficial for improving soil health and carbon sequestration. Applying this highly stable carbon as a soil amendment provides viable option for large-scale carbon sequestration while generating valuable additional benefits for soil fertility and agricultural yields^[6]. However, despite over a decade of intensive research, uncertainties and knowledge gaps hinder widespread adoption of biochar.

The origins of biochar date back over 2500 years to the Amazon basin, where indigenous people amended the notoriously nutrient-poor soils with biochar^[7]. These ancient soils, known as *Terra Preta de Índios*, still contain high levels of organic carbon and nutrients, making them highly productive for agriculture^[8]. In the contemporary context, researchers rediscovered biochar in the late 1990s and early 2000s as a novel approach for enhancing soil fertility while sequestering carbon in a stable form^[9,10]. Modern researchers have since recognized the potential of biochar to address environmental and agricultural challenges, leading to a surge in interdisciplinary research. Despite these advancements, several research gaps must be addressed to fully realize the benefits of biochar.

Since this rediscovery, biochar research has rapidly expanded across disciplines, from soil sciences to engineering to climate modeling, exploring agronomic^[11–13], environmental^[14–16], and societal benefits associated with biochar application. However, understanding how biochar interacts with soil ecosystems over decades is crucial for confirming its long-term viability. Research must focus on longitudinal studies that monitor the impact of biochar on soil health, microbial communities and carbon sequestration over extended periods. More research is needed to understand the biochemical and physical processes involved in biochar application, including how biochar influences nutrient availability, water retention and soil microbial activity under various environmental conditions.

The fundamental aspect of biochar is that it provides a straightforward and multifaceted solution. By pyrolyzing organic wastes and waste biomass, which would otherwise be able to disintegrate and produce carbon monoxide, methane, hydrogen gases and C₁–C₂ hydrocarbons, not only is it possible to minimize emissions of greenhouse gases, but it also turns carbon into a stable form that can be stored in soils for hundreds to thousands of years^[17–19]. By enhancing essential

soil qualities such as water retention, pH levels, nutrient availability, microbial populations and other aspects, incorporating this carbon-rich material into soils results in many additional advantages^[20–22].

Biochar-based nanocomposites (BNCs), mainly derived from waste biomass, have been developed as a sustainable solution for wastewater treatment and renewable bioenergy production^[4]. This approach offers a dual benefit by addressing waste management challenges while producing valuable materials for environmental remediation and energy generation. BNCs are formed by incorporating nanomaterials into a biochar matrix, enhancing their adsorption and catalytic properties. Using waste biomass as a feedstock for BNC production further contributes to sustainability by repurposing materials that would otherwise be disposed of, reducing the environmental impact of waste disposal.

With such a wide range of potential advantages across multiple spheres, many prominent organizations have touted the BNC application as an accessible, scalable climate solution ready for investment and large-scale implementation. The UN Intergovernmental Panel on Climate Change highlighted BNC production and soil incorporation as a direct option for carbon dioxide removal in its 2018 report^[23]. Project Drawdown identifies BNCs as one of the most impactful technologies for reversing global warming^[24]. Groups such as the World Bank, World Economic Forum and UN Convention to Combat Desertification have all released reports emphasizing the importance of biochar for climate-smart agriculture and sustainable development priorities^[25].

Additionally, the production of BNCs from waste biomass can contribute to the UN Sustainable Development Goals for most of Goal 6 (Clean Water and Sanitation) and Goal 7 (Affordable and Clean Energy)^[1]. BNCs have provided promising performance in removing organic and inorganic pollutants, heavy metals and pathogens from wastewater, improving water quality and sanitation^[4,18]. Also, biochar produced from waste biomass can be used as a renewable energy source through bioenergy production processes, including pyrolysis and gasification, supporting the transition toward clean and sustainable energy sources.

However, some critics have also raised concerns about biochar systems needing to be more generally adopted before fully understanding potential long-term issues. Skeptics caution that carbon sequestration rates could decrease over time as soils reach saturation. Others warn that large-scale biochar application could indirectly drive further deforestation or

agricultural expansion if new land is cleared to produce feedstock biomass. Additional life cycle analyses are needed to compare trade-offs related to different biochar production systems, transportation methods and land management practices. There remain open questions surrounding economic incentives, appropriate regulatory policies and effective business models that value sustainability attributes.

A growing body of multidisciplinary evidence positions biochar solutions as uniquely promising tools to address multiple global challenges related to water and food systems, soil health, waste management, land degradation, climate change resilience and greenhouse gas mitigation. However, fully capitalizing on these potential benefits without underappreciated drawbacks will require holistic evaluation, system-level thinking and adaptive governance. There are still active debates regarding the realistic climate impact, ideal production methods, environmental trade-offs, socioeconomic barriers and scalability constraints of biochar. However, the past two decades of intensive biochar research offer an encouraging start. With continued investigation and strategic investment guided by sustainability science, biochar systems could foster wastewater, ecological and climate improvements for the 21st century and beyond.

This paper evaluates the potential of biochar and biochar nanocomposites (BNCs) as sustainable solutions to pressing environmental and agricultural challenges. Specifically, to examine how biochar improves soil health, enhances agricultural productivity and contributes to carbon sequestration, explore the dual benefits of BNCs in wastewater treatment and renewable energy production and trace the origins of biochar and its resurgence in contemporary research. Also, it addresses criticisms and knowledge gaps related to adoption and scalability of biochar, and its contributions to the UN Sustainable Development Goals and climate initiatives.

2 Production of biochar from waste biomass

2.1 Feedstock selection

Feedstock describes substances or raw materials used as inputs in manufacturing processes or to produce items^[26]. When discussing producing biochar, feedstock usually refers to organic resources converted into biochar by pyrolysis or other methods, such as biomass, forestry, agriculture, industrial waste or agricultural waste^[27]. The feedstock selection could

significantly impact the characteristics and caliber of the biochar generated.

Feedstock selection is a critical factor influencing the properties, performance and sustainability of biochar products. Different biomass sources can significantly impact biochar yields and characteristics, including nutrient levels and pH, contaminant profiles, production energy requirements, economics and life cycle environmental footprints^[28–30]. Strategically selecting appropriate low-cost, locally available and environmentally sound feedstocks is essential for optimizing biochar systems.

Abundant organic waste residues and byproducts often make attractive biochar feedstock. These include agricultural crop residues including straw, husks, bagasse, nut shells, orchard prunings, forestry thinnings, sawdust, urban green waste from tree trimmings, livestock manures, food processing wastes, biosolids and byproduct streams from pulp or paper or bioenergy industries^[19,31]. Using these under used biomass resources avoids additional land cultivation demands while creating value from materials destined for disposal, open burning or environmental liabilities.

However, waste biomass feedstocks often have high moisture content, dispersed availability across landscapes, heterogeneous soil or rock contamination compositions and variable qualities^[32]. These factors can increase biochar production costs through demands for extensive preprocessing, such as dewatering, densification and screening, and higher transportation requirements for centralized pyrolysis facilities^[33]. Contaminants such as heavy metals and salts concentrated during pyrolysis represent a risk for degrading biochar properties if feedstocks are not carefully selected and blended.

Alternatively, cleaner and more uniform woody biomass, including forestry residues and orchard trimmings, or dedicated energy crops circumvent many of these challenges but compete against other higher-value commodity markets for pulp, paper, lumber and bioenergy sectors^[32,34,35]. Deforestation or displacing food crop production with bioenergy plantations intended solely for biochar manufacture could undermine carbon sequestration and food security objectives if not sustainably implemented^[36].

According to Vochozka et al.^[33], blending various residual feedstock streams in optimized ratios synthesizes advantages while mitigating the downsides of single-source inputs. Mixing high- and low-nutrient biomass adjusts biochar nutrient

profiles for different applications^[37]. Clean, woody inputs with contaminated organic wastes can dilute heavy metal concentrations. Balanced feedstock selection, preprocessing and production configurations (distributed or centralized) are important systems-level design considerations.

Other critical feedstock criteria include energy density, ash content, fixed carbon levels and bio-oil or syngas (also known as synthesis gas) co-product potentials, collectively influencing the pyrolysis behavior, scalability and economic viability of an integrated biochar system. Comprehensive analytical characterization of feedstocks helps match ideal biomass inputs to custom biochar applications. However, in most cases, strategically leveraging affordable, locally abundant residues while avoiding biomass cultivation for biochar alone offers economic feasibility and environmental sustainability advantages^[28].

2.2 Pyrolysis process

The pyrolysis process transforms renewable organic matter into a stable form of carbon that can improve soil health and fertility while sequestering carbon^[38]. Pyrolysis is the thermochemical decomposition of organic material at elevated temperatures between 350 and 550 °C^[39,40]. The biomass feedstock is loaded into a pyrolysis reactor for biochar production and then heated to temperatures typically ranging from 700 to 800 °C^[39]. As the biomass is heated, volatile compounds are driven off, leaving behind a carbon-rich solid material that is the biochar product^[38]. The pyrolysis process transforms the organic compounds in the biomass into bio-oil and syngas as byproducts in addition to the biochar^[41].

The specific temperatures and heating rates used depend on the desired qualities of the output biochar. Lower process temperatures around 300–500 °C favor a higher biochar yield whereas temperatures above 700°C increase biochar carbon content^[42]. Slow pyrolysis with longer solid and vapor residence times yields higher biochar yields. In contrast, fast pyrolysis with short vapor residence times favors bio-oil production over biochar formation^[41,43–45]. Various reactor configurations can be used to control pyrolysis parameters.

Biochar is produced through pyrolysis, which thermally decomposes organic biomass feedstocks in an oxygen-limited environment. Key process factors such as temperature, heating rate, vapor residence time and feedstock selection determine biochar yields and properties. Optimizing these parameters allows the production of customized biochars for specific soil enhancement and carbon sequestration applications.

2.3 Pyrolysis stages for biochar production

Controlling the stages of pyrolysis is critical for obtaining high yields of quality biochar suitable for applications such as agriculture, carbon sequestration and environmental remediation. Figure 1 shows the stages of pyrolysis from the moisture removal process, torrefaction, exothermic pyrolysis, endothermic pyrolysis and gasification processes.

2.3.1 Moisture removal (drying)

The first crucial stage when pyrolyzing biomass is drying, conditioning or dewatering the feedstock^[46,47]. Most raw biomass sources, such as forestry wastes, agricultural residues and energy crops, contain relatively high moisture levels ranging from 40% to 60% wet when freshly harvested^[48]. However, according to Bridgwater^[47], for efficient and optimized pyrolysis reactions, the moisture content must be substantially reduced to about 15% or lower before the thermal decomposition process. The naturally high moisture levels present in raw biomass feedstocks pose several challenges. First, the excess water lowers the overall energy content and calorific value of the biomass, making it less suitable as a fuel source. Second, the high moisture complicates biomass handling, transportation and storage due to increased weight, potential for microbial degradation and other stability issues^[49].

To address these challenges, techniques, such as conditioning or dewatering and drying, are used to eliminate excess water from the biomass, raising its energy density, improving its stability and making it more amenable for pyrolysis^[47,48]. The drying process involves heating the biomass to temperatures above 100 °C, which causes the vaporization and removal of most of the free or unbound moisture^[47]. In addition to drying, an essential part of the conditioning process is the softening or torrefaction stage, typically around 150 °C. During this stage, the dried biomass becomes more brittle and undergoes mild pyrolysis, releasing chemically bound water, trace amounts of carbon dioxide, volatile organic compounds and aromatic carbon compounds^[38,50].

Removing moisture from biomass is energy-intensive, consuming a significant portion of the energy required for pyrolysis. Therefore, it is generally recommended to dry the biomass to moderate moisture levels between 15% and 20% before proceeding with pyrolysis to balance sufficient drying and minimize energy demands^[47,49]. Well-dried and properly conditioned biomass feedstocks with low moisture levels lead to higher biochar yields and improved quality during the subsequent pyrolysis stage. In summary, the drying and conditioning steps are essential preprocessing operations that ensure the biomass is optimal for efficient and productive pyrolysis by reducing moisture content, increasing energy density and improving overall stability and reactivity.

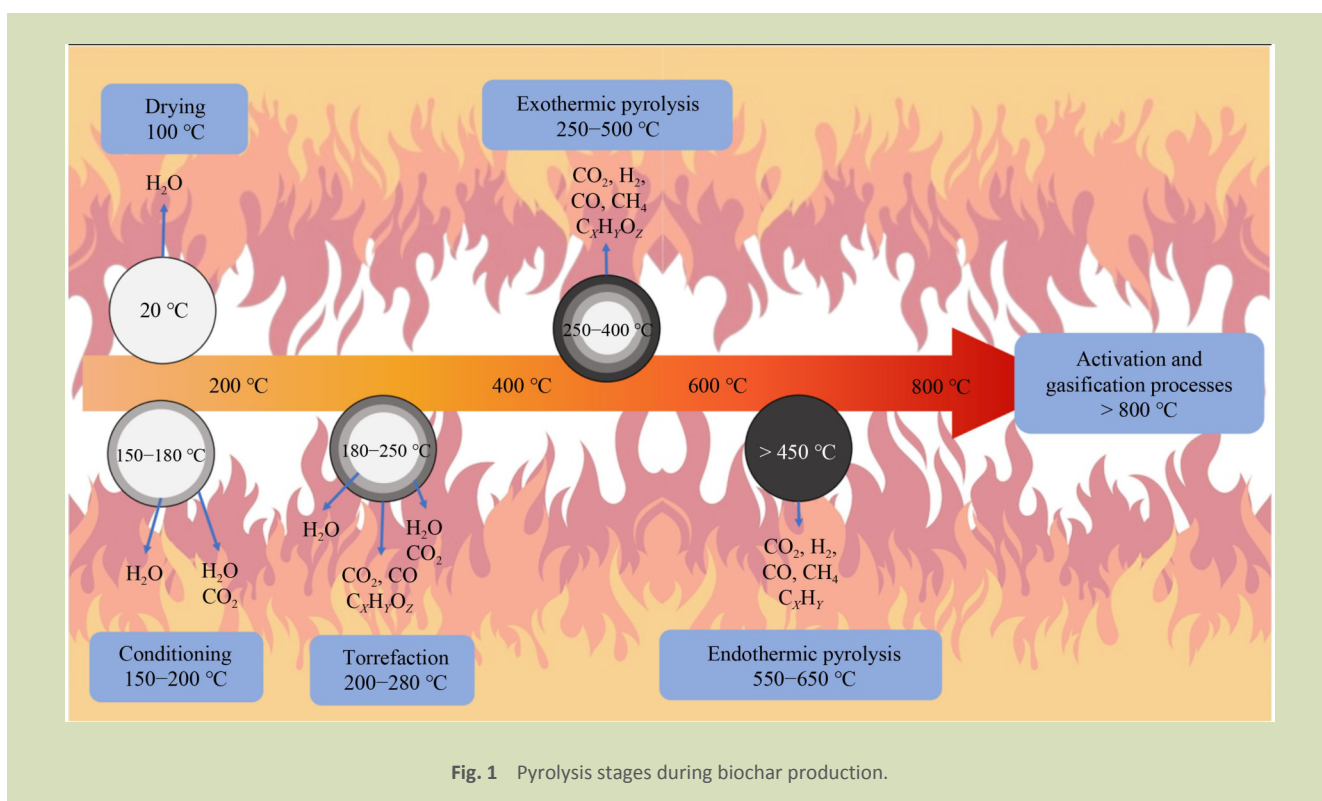


Fig. 1 Pyrolysis stages during biochar production.

2.3.2 Torrefaction

The following key stage in biomass pyrolysis is torrefaction, which occurs at temperatures approximately between 200 and 280 °C. Torrefaction is a mild thermochemical pretreatment process designed to reduce the moisture and volatile matter contents of the biomass feedstock before the main pyrolysis stage. This endothermic stage requires an external heat input to raise the temperature of the biomass sufficiently high to initiate the breakdown of the hemicellulose and cellulose components, which are two of the three major polymeric constituents of lignocellulose biomass^[49,51].

During torrefaction, the biomass undergoes partial decomposition through dehydration and depolymerization reactions involving the cleavage of weaker hydrogen, hydroxyl and ether bonds. This results in the liberation of various oxygenated organic volatiles such as methanol, acetic acid, carbon dioxide and carbon monoxide^[47,51]. These condensable gases can have value-added applications, such as producing smoke flavors for food or generating wood vinegar^[52].

A vital outcome of the torrefaction process is that the treated biomass develops increased brittleness and grindability and improved resistance to biological degradation and moisture reabsorption. This is attributed to the partial decomposition of the hemicellulose fraction, which acts as a binder in the biomass structure. Consequently, the energy requirements for subsequent grinding and milling operations are substantially lower than those for raw, untreated biomass^[49].

Torrefaction can be considered a relatively mild form of pyrolysis. It serves as a crucial intermediate step that dries and partially decomposes the biomass, preparing it for the subsequent higher-temperature pyrolysis stage, where the remaining solid undergoes further extensive thermal decomposition and devolatilization^[47,53]. Removing a portion of the moisture and volatile matter during torrefaction increases the energy density and calorific value of the biomass, making it a more concentrated and consistent fuel source for the main pyrolysis reactor.

2.3.3 Exothermic pyrolysis

The next critical stage in the biomass pyrolysis process is the exothermic phase, which occurs over a temperature range of 250–500 °C^[47,52,54]. During this stage, the biomass polymeric structures undergo more extensive chemical decomposition through the thermal scission and cleavage of the stronger carbon-carbon bonds in the remaining cellulose and lignin fractions^[51].

As these thermal decomposition reactions progress, a wide range of gaseous products, including methane, carbon dioxide, carbon monoxide, hydrogen and other condensable organic vapors, evolved from the solid biomass matrix^[47,52]. Significantly, the exothermic pyrolysis stage is characterized by releasing substantial amounts of heat as the volatile compounds are liberated from the solid biomass particles. This heat generation makes the process largely self-sustaining regarding energy requirements once initiated^[52].

The extensive devolatilization and thermal cracking reactions that occur during exothermic pyrolysis result in a significant portion of the original biomass feedstock being converted into gaseous products, condensable vapors and a solid carbonaceous residue known as biochar^[54,55]. Despite the self-heating nature of the reactions, some heat loss is inevitable, necessitating external heat input to maintain the optimal temperature range for efficient pyrolysis^[47,51].

The biochar produced during this stage is a carbon-rich solid fuel enriched in fixed carbon content compared to the original biomass. However, it retains some residual volatile matter and a low mineral ash content^[53,54]. Notably, the highest rates of biochar production occur toward the latter stages of the exothermic phase, just before the temperature ramps up further into the next phase^[47,52].

2.3.4 Endothermic pyrolysis

As the biomass pyrolysis process transitions past temperatures of 500 °C into the higher range of 550–650 °C, it enters the endothermic phase^[47,52,54]. Unlike the preceding exothermic stage, this high-temperature regime requires substantial external heat input as the decomposition rate and associated heat release decline from its earlier peak^[51].

At this stage, the residual biochar produced from the initial lower-temperature pyrolysis retains an appreciable amount of volatile matter trapped within its porous structure, along with some residual ash minerals and occluded tars^[54,55]. The further application of heat during the endothermic phase enables the cracking and devolatilization of these remaining volatile components to produce additional gaseous and vapor species, leaving behind a highly carbonaceous and purified char residue^[47,52].

Temperatures around 600 °C are typically used during the endothermic pyrolysis stage to facilitate these high-temperature cracking and devolatilization reactions. However, maintaining elevated temperatures requires substantial energy

inputs in the external heat supply^[52,54]. The high-temperature treatment reduces the volatile content of biochar to around 12% of its initial mass^[56].

Although biochar yields tend to decline during this endothermic stage compared to the previous exothermic phase, the purified char product generated is characterized by an enriched surface area, high fixed carbon content and enhanced carbon sequestration potential^[54]. These desirable properties result from the extensive devolatilization and aromatization reactions at higher pyrolysis temperatures.

However, the slow endothermic decomposition stage requires careful control and monitoring to optimize the biochar properties effectively. Factors such as heating rate, temperature, residence time and atmospheric conditions must be precisely regulated to achieve the desired characteristics in the final biochar product^[47,52].

2.3.5 Activation and gasification processes

The final stage of the biomass pyrolysis process consists of activation and gasification pathways, which emerge at temperatures above 600 °C^[47,52]. At this elevated temperature regime, the introduction of a controlled amount of oxidizing agents such as air, oxygen or steam enables a secondary reaction stage that facilitates the release of any remaining volatile matter from the biochar structure and further develops its porous characteristics through a process known as activation^[57–59].

During activation, the oxidizing agents selectively etch away specific carbon structures within the biochar matrix, creating new micropores and exposing active sites on the biochar surfaces. This porosity development and active site generation significantly enhance the adsorbent and catalytic capabilities of biochar^[58]. However, it is necessary to note that the biochar yields tend to drop substantially during this activation and gasification stage, as a significant portion of the remaining mass is lost due to the oxidative etching process^[47,52].

As the temperatures rise further, approaching and exceeding 800 °C, oxygen facilitates the complete breakdown and gasification of any residual volatile matter into syngas and other gaseous byproducts^[52]. The remaining solid residue at the end of this high-temperature gasification process is a highly activated and porous biochar material, representing only a fraction of the initial biomass feedstock.

Despite the lower yields, the biochar produced during this final

stage has a highly developed porous structure, large surface area and abundant active adsorption sites, making it well-suited for various environmental and filtration applications^[55,57–59]. By carefully controlling the process conditions, such as temperature, oxidant flow rates and residence times, it is possible to modify the properties of the final biochar product to meet specific requirements, whether it is intended for soil enhancement and carbon sequestration or use as an adsorbent material in environmental remediation applications^[47,52,58].

Understanding and controlling the stages of pyrolysis through drying, torrefaction, low-temperature exothermic decomposition, endothermic high-temperature pyrolysis and finally, activation or gasification enables the production of biochar suited for different purposes. Although high-yield soil enhancement biochar can be generated rapidly around 500 °C under faster pyrolysis rates, optimizing advanced adsorbent properties needs precise control through slow endothermic pyrolysis combined with activation. Preprocessing techniques such as pelletizing biomass can also aid the handling and uniformity of feedstocks. Pyrolysis offers a flexible process to take waste biomass and generate valuable biochar resources by targeting key thermal decomposition stages.

3 Biochar product distribution and properties

3.1 Causes affecting biochar production

Biochar production is influenced by various factors that affect process quality, yield and efficiency. These factors are crucial for optimizing biochar production and effectively harnessing its benefits. Feedstock selection, pyrolysis process parameters, feedstock particle size, feedstock moisture content, pyrolysis atmosphere, reactor design, and quenching and postprocessing treatments are vital factors influencing biochar production, as given in Table 1.

Feedstock selection is vital, as different biomass sources have varying chemical compositions and structural properties that impact the biochar yield and characteristics^[60,61,74]. The pyrolysis process parameters, including heating rate, temperature and residence time, significantly affect the biochar yield and quality^[51,54–56,61]. Feedstock particle size affects heat transfer and reaction kinetics, with smaller particles yielding faster pyrolysis rates^[46,63,75].

Table 1 Factors affecting biochar production

Factors affecting biochar production	Description	Reference
Feedstock selection	· Type and quality affect chemical composition and nutrient content	[60,61]
Pyrolysis process	· Temperature, heating rate, residence time influence yield and quality · Higher temperatures and longer residences enhance biochar stability and carbon sequestration potential	[47,51,52,54–56,62]
Feedstock particle size	· Size influences heat transfer and reaction kinetics · Smaller particles yield faster pyrolysis	[46,63–65]
Feedstock moisture content	· Higher moisture content requires more energy for drying · Lower biochar yields	[51,66–68]
Pyrolysis atmosphere	· Inert, oxidative, or reducing atmospheres affect chemical composition and surface area	[40,69,70]
Reactor design	· Size, shape and heating method affect efficiency · Designs suit different scales and feedstock types	[47,71]
Quenching and postprocessing treatment	· Impacts surface area, porosity and nutrient retention · Proper quenching enhances quality for specific applications	[72,73]

Feedstock moisture content is another critical factor, as higher moisture content requires more energy for drying and can lead to lower biochar yields^[51]. The pyrolysis atmosphere, whether inert, oxidative or reducing, can significantly impact the chemical composition and surface area of the resulting biochar^[61,76–78].

Reactor design, including size, shape and heating method, affects the efficiency of the process, and different designs are suitable for various scales and feedstock types^[47]. Quenching and postprocessing treatments can influence the surface area, porosity and nutrient retention of biochar, and modify its properties for specific applications^[72].

3.2 Types of biochar production systems

Biochar production involves various technologies and systems, each with unique characteristics and applications. Understanding the different types of biochar production systems is crucial for optimizing biochar production processes and harnessing their benefits effectively. Table 2 details various biochar production systems, ranging from small-scale, batch-type units to large-scale, continuous reactors. The choice of production system depends on factors such as the scale of production, the feedstock used and the desired properties of the biochar. By gaining insight into these systems, stakeholders in the biochar industry can make informed decisions about the most suitable production methods for their specific needs and goals.

Table 2 Types of biochar production system

Production system	Description	Reference
Batch pyrolysis systems	· Process limited feedstock · Require manual loading/unloading · Suitable for small-scale production · Could have lower efficiency/throughput compared to continuous systems	[40,46]
Continuous pyrolysis systems	· Process larger feedstock quantities · Offer higher efficiency and throughput · Require sophisticated control systems	[47,73]
Gasification systems	· Convert biomass feedstock into syngas · Use as fuel or biochar processing · Batch or continuous systems · Ideal for producing biochar and other bioenergy products	[72,79]
Microwave pyrolysis systems	· Use microwave radiation for faster, uniform heating · Offer efficient, controlled biochar production	[40,46]
Slow pyrolysis systems	· Operates at lower temperatures · Longer residence times · Ideal for soil amendment	[41,44,45]
Fast pyrolysis systems	· Rapid heating of biomass to high temperatures without oxygen · Unlike slow pyrolysis, it is designed to maximize bio-oil production · Requires careful control of operating conditions to optimize bio-oil quality and minimize byproducts	[44,45]

Table 3 Pyrolysis processes and product distribution

Process	Heating rate (°C·min ⁻¹)	Temperature (°C)	Residence time	Products			Reference
				Liquid (bio-oil) (%)	Gas (syngas) (%)	Solid (biochar) (%)	
Low pyrolysis	1–20	100–1000	Long residence time (mins–days)	30	35	35	[43,45,53]
Intermediate pyrolysis	100–500	500	Moderate (10–20 s)	50	25	25	[43,45,53]
Fast pyrolysis	> 300	300–1000	Short (< 2 s)	75	13	12	[43,45,53]
Gasification	2–100	> 800	Moderate (10–20 s)	5	85	10	[43,44]

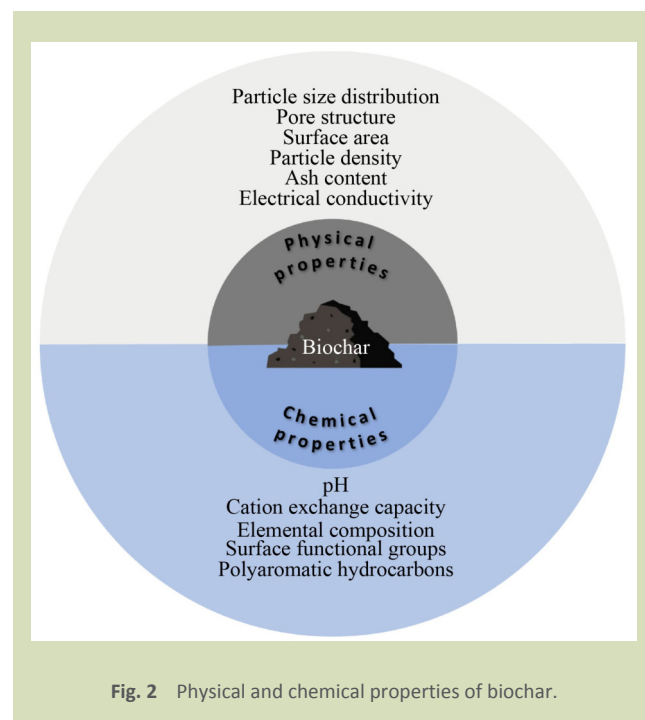
Table 3 provides a detailed overview of different pyrolysis processes and their corresponding product distributions, highlighting the versatility of thermochemical conversion technologies. Slow pyrolysis, with low heating rates and moderate temperatures, produces solid biochar as the primary output, accounting for 35% of the product distribution. It also generates liquid bio-oil (30%) and syngas (35%), offering opportunities for co-product valorization and integrated biorefineries^[41,44,45]. Fast pyrolysis, with rapid heating rates and short vapor residence times, maximizes liquid bio-oil yields, reaching up to 75% of the product stream^[44,45]. According to Hornung^[53], intermediate pyrolysis balances these processes, resulting in a relatively even distribution of products: 50% liquid bio-oil, 25% syngas, and 25% solid biochar. Gasification, operating at higher temperatures and longer residence times, prioritizes syngas production, accounting for 85% of the product distribution^[43]. This process is crucial for generating renewable energy, and the synthesis of gas for chemical production and hydrogen for various applications.

3.3 Properties of biochar

The physical, chemical and biological properties of biochar are crucial in determining its effectiveness and suitability for various applications. Figure 2 shows the physical and chemical properties of biochar.

3.3.1 Physical properties

The physical properties of the resulting biochar are influenced by critical parameters in production, including choice of particle size, pore structure, surface area, density, ash content and conductance^[63,65,80]. These physical attributes, in turn, directly impact the potential applications for biochar. Understanding and controlling these physical properties is crucial for maximizing the benefits of biochar in various

**Fig. 2** Physical and chemical properties of biochar.

environmental and agricultural applications. Table 4 presents the physical properties of biochar.

The diverse physical properties of biochar suit different soil, agricultural, environmental and industrial uses. Determining appropriate production conditions and treatments to achieve target particle size, pore distribution, surface area, density, ash content, and conductance maximizes the effectiveness of tailored biochar formulations.

3.3.2 Chemical properties

Beyond its physical attributes, biochar has unique chemical characteristics that determine its potential applications in carbon sequestration, soil enhancement and contaminant remediation^[38]. Basic chemical properties include pH, which typically ranges from neutral to alkaline due to the

Table 4 Physical properties of biochar

Physical property	Description	Reference
Particle size distribution	<ul style="list-style-type: none"> · Depends on initial biomass feedstock properties and postpyrolysis reduction · Smaller particles for soil amendments: greater surface area interaction · Larger particles improve soil aeration and drainage · Particle sizes tailored to the application maximize effectiveness 	[41,63]
Pore structure	<ul style="list-style-type: none"> · Pore structure provides channels for water, gases, nutrients and soil microbes retention · Higher pyrolysis temperatures increase porosity · Fast pyrolysis conditions preserve pore structure · Pore structure depends on feedstock and production parameters 	[44,45,80]
Surface area	<ul style="list-style-type: none"> · Biochar surface area relates to accessibility to pores for adsorption of water, nutrients, pollutants, or soil organic matter · As pyrolysis temperature rises, surface area increases due to porosity development, reaching maximums around 600 °C · High surface area biochars aid environmental remediation, lower surface areas reduce nutrient retention 	[32,81,82]
Particle density	<ul style="list-style-type: none"> · Bulk material density is crucial for handling and processing facilities · Biochar energy density increases with treatment temperature · Biochar particle density ranges from 1.2 to 1.8 g·cm⁻³, decreasing with pyrolysis temperature · Lower density improves soil aeration, higher density enhances water retention · Density influences biochar application rates 	[81]
Ash content	<ul style="list-style-type: none"> · Influences potential uses based on quantity and nature of inorganic substances · High ash concentration can hinder high-grade industrial applications · Ash-related issues during thermochemical conversion of biomass can be exacerbated · Ash content is determined by the type of biomass and harvesting methods · Woody feedstocks have lower ash contents (1% to 5%) than manures, biosolids, or waste biomass (10% to 80% ash) · Nutrient value relates to ash composition 	[41,80]
Electrical conductivity	<ul style="list-style-type: none"> · Varieties from 5 to 20 dS·m⁻¹ · Based on concentration and composition of inorganic minerals postpyrolysis · Salt enrichment and lime activation increase conductivity · High conductivity aids electromagnetic applications 	[81,83,84]

concentration of essential minerals during pyrolysis^[40] cation exchange capacity (CEC), with wood biochars ranging from 20 to 90 mol·kg⁻¹ due to increased surface area from high-temperature pyrolysis^[85] elemental composition rich in carbon (50% to 90%) with decreasing oxygen and hydrogen at higher temperatures^[80] surface functional groups, including carboxyl and phenolic groups, that impart hydrophilicity and reactivity while contributing to alkalinity^[82] and potential for polyaromatic hydrocarbon formation during partial combustion, which can be minimized through proper production controls^[86,87]. These chemical features interact with the physical structure of biochar to influence nutrient availability, microbial interactions, contaminant sorption and overall performance in various environmental and industrial applications. Table 5 details the chemical properties of biochar.

The various chemical characteristics of biochars, such as their alkalinity or acidity, surface functionality, ability to exchange cations and anions, elemental composition and presence of polyaromatic hydrocarbons, underlie their distinctive interactions with soils, waste effluents, decomposing biomass and agricultural environments.

4 Nanocomposites in wastewater treatment

Clean water is essential for life and vital to public health, industrial processes and agriculture. However, the growing human population and increasing industrialization have led to a significant rise in wastewater generation. Contaminated wastewater can contain harmful pollutants, including pathogens, heavy metals, organic compounds and pharmaceuticals^[1,90,91]. These pollutants seriously threaten human health and the environment if not adequately treated.

Conventional wastewater treatment methods, such as sedimentation, coagulation, filtration and biological treatment processes, efficiently eliminate a broad spectrum of contaminants^[92,93]. However, they often struggle to remove emerging pollutants, such as pharmaceuticals and microplastics, which can be energy-intensive or generate significant quantities of sludge that require further treatment^[1,4].

Using nanocomposites has become a viable strategy for

Table 5 Chemical properties of biochar

Chemical property	Description	Reference
pH	<ul style="list-style-type: none"> · Biochar pH depends on feedstock and production conditions · pH ranges from neutral to alkaline, 5 to 7.5 · Pyrolysis concentrates minerals, increasing alkalinity · Hardwoods and nutshells produce more alkaline biochars · pH affects nutrient availability, microbial ecology and contaminant interactions 	[60,86]
Cation exchange capacity	<ul style="list-style-type: none"> · CEC indicates cation retention capacity · High temperature pyrolysis increases pore development, enhancing cation exchange surface area · Nutrient-rich manure feedstocks yield biochars with abundant anion exchange capacity 	[85,87]
Elemental composition	<ul style="list-style-type: none"> · Enhances elemental carbon content · Increases inorganic ash components · Biochars: 50% to 90% carbon, balance of oxygen and hydrogen · Nutrient composition varies with feedstock 	[80,88]
Surface functional groups	<ul style="list-style-type: none"> · Oxygen-containing functional groups including carboxyl, phenolic and lactonic groups enhance hydrophilicity and reactivity · Carbonization, a heat degradation process, removes functional groups and releases oxygen and hydrogen · Biochar with low H/C ratios have more aromatic structures and fewer functional groups · Functional groups serve as sites for adsorption, microbial ecology and contaminant interactions · Alkalinity of biochar affects its capacity to counteract soil acids · Alkalinity can be categorized into organic functional groups surface, soluble organic compounds, carbonate and inorganic alkalis · Higher treatment temperatures result in elevated alkalinity 	[82,89]
Polyaromatic hydrocarbons	<ul style="list-style-type: none"> · Partial pyrolytic combustion and toxic polyaromatic hydrocarbons · High pyrolysis temperatures and slow heating reduce polyaromatic hydrocarbon formation · Monitoring based on applications is crucial 	[43–45,86]

overcoming these obstacles and improving the effectiveness of wastewater treatment. Materials made up of two or more phases, at least one of which has a dimension in the nanoscale (1–100 nm), are called nanocomposites^[94,95]. Typically, nanocomposites in the wastewater treatment context are made of a polymeric matrix with nanoparticles incorporated, which helps decrease the antimicrobial effectiveness of catalyzing^[96,97].

In recent years, there has been an increasing interest in developing more sustainable and efficient methods for wastewater treatment. Nanomaterials have appeared as a promising approach for wastewater remediation due to their unique properties, including high surface area, porosity and reactivity^[19,38,96,98,99]. BNCs, which combine biochar with nanoparticles, represent a particularly attractive class of nanomaterials for wastewater treatment applications.

4.1 Role of nanocomposites in enhancing wastewater treatment efficiency

Wastewater treatment is crucial for protecting the environment and human health by removing contaminants and pollutants from various sources, including industrial, municipal and agricultural discharges^[100,101]. Traditional wastewater

treatment methods, such as physical and chemical processes, have been widely used but often face limitations regarding efficiency, economic, sociology and environmental impact^[19,58,97,99,102]. In recent years, the application of nanotechnology in wastewater treatment has gained significant attention due to its potential to enhance treatment efficiency and address the challenges associated with conventional methods^[97,103,104].

Nanocomposites, composed of a matrix and nanoscale reinforcements, have arisen as promising for improving wastewater treatment processes^[100,105,106]. These nanocomposites have unique properties, such as high surface-to-volume ratios, enhanced reactivity and tailored surface functionalities, which make them attractive for various wastewater treatment applications^[100,107].

One of the primary roles of nanocomposites in wastewater treatment is their ability to eliminate various contaminants, including heavy metals, organic pollutants, dyes and pathogens^[93]. Nanocomposites can effectively adsorb and immobilize these contaminants through various mechanisms, such as electrostatic interactions, complexation and redox reactions^[93,108]. Additionally, nanocomposites can catalyze chemical reactions that degrade or transform pollutants into less harmful compounds^[106].

Also, nanocomposites can improve the efficiency of existing wastewater treatment processes. For example, incorporating nanocomposites into membrane filtration systems can improve permeability, fouling resistance and selectivity, resulting in more efficient separation and purification of water^[106,108]. Nanocomposites can also be used as catalysts or adsorbents in advanced oxidation processes (AOPs), which encompass the generation of highly reactive oxidizing species (ROS) for the degradation of organic pollutants^[106,108,109].

Another significant advantage of nanocomposites in wastewater treatment is their potential for catalytic reusability and regeneration. Many nanocomposites are quickly recovered and reused multiple times, reducing the overall economic and environmental impact of the treatment process^[106,107,110].

4.2 Nanocomposites used in wastewater treatment

Several nanocomposites are used in wastewater treatment, each with unique properties and applications. Some common types are carbon-based nanocomposites, metal-based nanocomposites, polymer-based nanocomposites and hybrid nanocomposites.

Carbon-based nanocomposites are typically formed by combining two or more solid phases^[83]. These nanocomposites display exceptional properties, including significantly improved toughness, mechanical strength and thermal or electrochemical conductivity. Research has shown carbon base nanocomposites, such as carbon nanotubes and graphene oxide, can be used in wastewater treatment due to their high surface area and adsorption capacity^[83,111–113]. Activated carbon and biochar benefit water treatment due to their absorption capacities and prosperity^[90,114,115]. These nanocomposites can effectively remove heavy metals, organic pollutants and dyes from wastewater. The type and application of carbon-based nanocomposites are given in Table 6.

In addition, metal-polymer nanocomposites represent an advanced material category characterized by a synergistic blend of metal nanoparticles and polymer matrices^[116,117]. The selection of specific metals and polymers influences the range of properties of nanocomposites, such as iron oxide nanoparticles and silver nanoparticles, which show antimicrobial properties and catalytic activity, effectively removing organic pollutants and pathogens from wastewater^[117]. Polymer-based nanocomposites, such as polymer-clay nanocomposites and polymer-metal oxide nanocomposites, are used in wastewater treatment for their dye adsorption capacity, mechanical strength and permeability^[110]. These nanocomposites can effectively remove organic pollutants and heavy metals from wastewater. Hybrid nanocomposites combine two or more types of nanoparticles to create materials with enhanced properties. Hybrid nanocomposites are used in wastewater treatment for their synergistic effects, which can improve treatment efficiency and reduce costs.

Nanocomposites can enhance wastewater treatment efficiency by increasing the adsorption capacity, selectively adsorbing contaminants, providing catalytic activity and allowing for regeneration and reuse. These nanocomposites offer an economical and sustainable solution for improving treated water quality and protecting the environment^[106,107,110].

4.3 Biochar-based nanocomposites for wastewater treatment

Nanomaterials in a biochar matrix are a promising approach for wastewater remediation as their unique properties, such as porosity, tailored functionalities, high surface area and unique physicochemical properties of nanomaterials, can enhance the adsorption and catalytic capabilities of BNCs^[57,58,102,107,110]. Also, the synergistic effects between biochar and nanomaterials can improve selectivity and specificity toward target pollutants^[101]. The tailored surface functionalities of BNCs can

Table 6 Types of carbon-based nanocomposites

Nanocomposite	Description	Application	Reference
Carbon nanotubes	Cylindrical structures made of carbon atoms	Widely used in wastewater treatment due to their high surface area and adsorption capacity	[83,84]
Graphene oxide	Single-layered sheet of carbon atoms	Effective in removing heavy metals, organic pollutants and dyes from wastewater	[111,112]
Activated carbon	Carbon material processed to have high porosity and surface area	Used in wastewater treatment for its adsorption properties	[90]
Biochar	Charcoal-like material produced from biomass	Used in wastewater treatment for its adsorption capacity and environmental benefits	[114,115]

facilitate the removal of an extensive range of contaminants, including organic and inorganic pollutants, heavy metals and pathogens^[101].

BNCs, a specific type of nanomaterial, are particularly suitable for wastewater treatment applications. They combine the beneficial properties of biochar, derived from pyrolyzed waste biomass, with the functionalities of nanoparticles, resulting in enhanced performance.

4.3.1 Preparation of biochar-based nanocomposites

BNCs represent an emerging class of advanced materials synthesized by integrating nanoscale additives into porous biochar matrices^[102,110]. The choice of preparation technique significantly influences their properties and performance, and interactions between constituent components within the nanocomposite structure^[57,58,110]. Several synthesis strategies have been developed and explored for fabricating BNCs, each with their own advantages and disadvantages^[57,58,102]. Figure 3 illustrates the preparation methods for biochar-based nanocomposites.

4.3.1.1 Pre-pyrolysis treatment

Pre-pyrolysis treatment is a sophisticated technique that integrates biochar production with the incorporation of nanomaterials, offering a novel approach to enhance the

properties of BNCs^[35,47]. Before the pyrolysis process, pre-pyrolysis treatment methods are used on biomass feedstock to improve its characteristics and elevate the quality of the resultant biochar. These methods are tailored to eliminate impurities, amplify yield, improve the attributes of biochar and expand its range of applications. Pre-pyrolysis impregnation stands out for its effectiveness in synthesizing BNCs that host metal or metal oxide nanoparticles. Initially, the precursor biomass is impregnated or blended with desired metal salts or precursors, which are then subjected to pyrolysis under controlled conditions. During this process, the metal precursors undergo thermal decomposition or reduction, forming nanoparticles entrenched within the biochar matrix^[57,58].

The process begins with drying biomass feedstock to eliminate moisture, thereby enhancing the pyrolysis efficiency and preventing the formation of undesirable byproducts such as tar. Since biomass is often too large for efficient pyrolysis, mechanical reduction techniques such as grinding or chopping are used^[19,99]. Subsequently, the biomass undergoes treatment with metal oxide salts or iron ion functional nanoparticles before pyrolysis. The biomass is immersed in a solution of desired metal salts for a specific duration to facilitate the attachment of metals to the surface of biochar. Following this, the devolatilization process involves heating the biomass at low temperatures to drive off volatile compounds such as water and

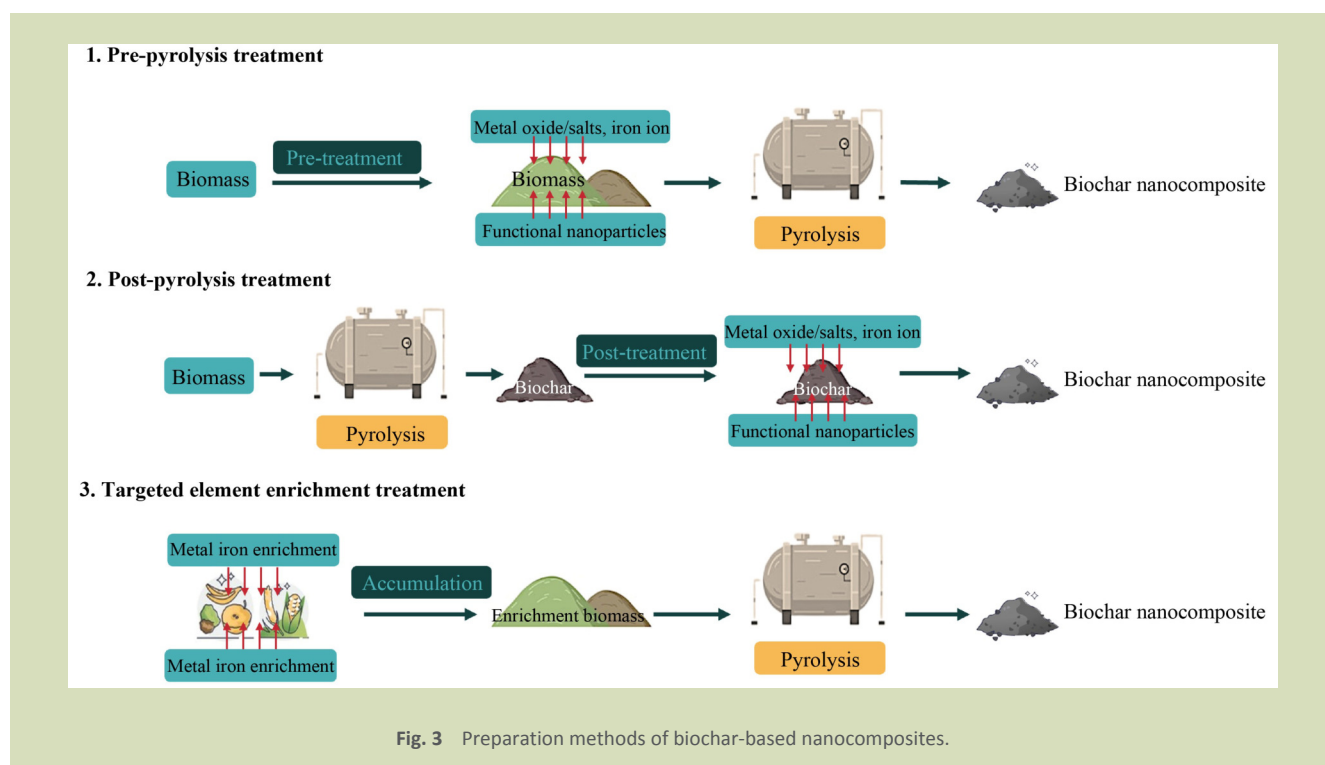


Fig. 3 Preparation methods of biochar-based nanocomposites.

organic solvents, thereby enhancing pyrolysis efficiency and minimizing tar formation. Chemical treatments involving inorganic acids (sulfuric acid, hydrochloric acid, phosphoric acid and nitric acid), alkalis or solvents (sodium hydroxide and potassium hydroxide) and inorganic salts (potassium carbonate and zinc chloride) can be used to refine biomass, thereby removing impurities, enhancing biochar yield and altering its properties^[19,99].

Torrefaction, a mild pyrolysis process conducted at temperatures between 200 and 300 °C in an inert atmosphere, enhances biomass energy density and stability, rendering it more suitable for transport and storage^[70].

During the devolatilization and torrefaction processes, biomass is converted into char. In contrast, the attached metal ions are converted into nanometal oxides or hydroxides, forming a biomass matrix with embedded metal ions and a biochar nanocomposite. Another notable technique, hydrothermal carbonization, involves converting biomass into biochar through heating in a pressurized aqueous environment, thereby improving its properties and reducing ash content. Biomass efficacy and selectivity in pyrolysis can be further enhanced through steam explosion techniques, microwave-assisted pyrolysis and ultrasonic pretreatment. Combining different pretreatment methods can be a strategic approach to achieving specific goals, including enhancing biochar yield, quality and properties^[19,99].

These pre-pyrolysis treatment methods are pivotal role for influencing the quality and properties of biochar, making them indispensable considerations in producing biochar for many applications.

4.3.1.2 Postpyrolysis treatment

Post-pyrolysis treatment methods are vital for enhancing the properties and performance of biochar for wastewater treatment applications^[58,102]. After the pyrolysis process, biochar can undergo various modifications to improve its porosity, surface area and chemical composition, making it more effective for removing pollutants from wastewater.

In these methods, biochar is produced through the normal pyrolysis or gasification processes. Then nanomaterials, such as metal oxides or metal salts, are introduced onto the biochar surface through techniques including wet impregnation, chemical vapor deposition or hydrothermal synthesis^[35,102]. These treatments can enhance the adsorption and catalytic properties of biochar for wastewater treatment applications.

According to Chausali et al.^[35], biochar can be impregnated with metal salt solutions, followed by drying and calcination, to form metal or metal oxide nanoparticles on its surface. These nanoparticles can act as catalysts for the degradation of organic pollutants or facilitate the adsorption of heavy metals from wastewater^[118]. Alternatively, chemical vapor deposition can deposit carbon-based nanomaterials, such as carbon nanotubes or graphene, onto the biochar surface, enhancing its adsorption capacity for organic contaminants^[58].

Also, treating biochar with activating agents, including steam, carbon dioxide, or chemicals (e.g., potassium hydroxide and phosphoric acid), increases its porosity and surface area, making it more effective for adsorption and catalysis processes in wastewater treatment^[31,100].

Chemical modification of biochar using acids, bases or other chemicals can alter its surface chemistry and enhance its functionality for specific wastewater treatment applications, such as heavy metal adsorption or removing organic pollutants^[57]. Physical methods, including milling, sieving and pelletizing, can also modify the size, shape and texture of biochar particles, improving their compatibility with different wastewater treatment systems^[31]. Biochar surfaces can also be functionalized with various functional groups (e.g., amino, hydroxyl and carboxyl groups) to improve their reactivity and selectivity for specific adsorption or catalytic reactions in wastewater treatment processes^[35,102].

These postpyrolysis treatment methods can significantly enhance the properties and performance of biochar for wastewater treatment applications, making it a valuable and versatile material for sustainable water resource management^[58,100].

4.3.1.3 Targeted element enrichment treatment

Targeted element enrichment on biochar-based nanocomposites involves deliberately incorporating specific elements into the biochar matrix to enhance its properties and tailor its functionality for various applications^[102,103]. This process can be achieved through different methods, such as impregnation, ion exchange and co-precipitation^[104].

Impregnation is a standard method where biochar is enriched with desired metal elements or their precursors, allowing for the absorption of these elements into the biochar structure^[101,104]. Ion exchange involves the exchange of ions between the biochar surface and a solution containing the target elements, leading to their enrichment on the biochar surface^[6,105].

Targeted element enrichment on biochar-based nanocomposites can significantly enhance their properties and make them suitable for various applications, such as wastewater treatment, soil remediation and catalysis^[58,103]. By controlling the type and number of elements incorporated, researchers can tailor the properties of biochar-based nanocomposites to meet specific requirements for different applications.

Similarly, enriching biochar with phosphorus or potassium can enhance its effectiveness as a soil amendment for agricultural applications^[100]. These elements can be incorporated into the biochar matrix through ion exchange or impregnation methods, leading to nanocomposites that release nutrients slowly, improving soil fertility and crop yield.

Targeted element enrichment on biochar-based nanocomposites can also enhance their magnetic properties for magnetic separation applications^[105]. According to Tan et al.^[57], incorporating iron nanoparticles into the biochar matrix can enable the nanocomposite to be easily separated from water using a magnet, making it useful for water treatment and environmental remediation. However, the targeted element enrichment on biochar-based nanocomposites offers a versatile and practical approach to tailor the properties of biochar for a wide range of applications, including water treatment, soil remediation, catalysis and magnetic separation.

Table 7 highlights the key benefits and challenges of each treatment method, in order to understand their suitability for different applications and contexts.

When BNCs are combined with other adsorbents, such as

activated carbon or zeolites, the composite material benefits from a broader range of surface functional groups and pore structures. This diversity enhances the adsorption capacity and selectivity for various pollutants. For example, adding activated carbon can improve the removal of organic contaminants through increased π - π interactions and hydrophobic effects.

Also, integrating BNCs with AOPs such as photocatalysis or Fenton reactions, can significantly improve the kinetics of pollutant degradation. BNCs can serve as catalysts or supports, facilitating the generation of ROS that rapidly oxidize contaminants^[113]. For example, TiO₂-modified biochar has been shown to enhance the photodegradation of dyes under UV light^[106,108,109].

4.4 Properties and characteristics of biochar-based nanocomposites

BNCs have received greater interest due to their unique properties and characteristics, particularly in wastewater treatment^[102,103]. These materials are formed by incorporating nanomaterials into a biochar matrix, resulting in enhanced properties that make them highly effective in various applications^[57,58]. Understanding the properties and characteristics of BNCs is essential for maximizing their potential in environmental remediation and other fields^[6].

Characterization of biochar is crucial for assessing its effectiveness in pollutant removal and other applications. Structural and elemental analyses help predict the environmental impact of biochar and its interactions with pollutants^[100]. The pH-dependent nature of biochar-metal interactions is significant, as it influences both the functional

Table 7 Advantages and disadvantages of treatments for preparation methods of biochar-based nanocomposites

Treatment	Advantage	Disadvantage	Reference
Pre-pyrolysis treatment	<ul style="list-style-type: none"> Enhances feedstock quality by removing contaminants Can improve biochar yield and quality Allows for the addition of valuable additives before pyrolysis 	<ul style="list-style-type: none"> Adds extra processing steps, increasing overall costs Could result in the loss of some beneficial volatiles Requires additional infrastructure and equipment 	[19,35,47,99]
Post-pyrolysis treatment	<ul style="list-style-type: none"> Allows for modification of biochar properties after production (e.g., activation and doping) Can enhance specific functionalities including adsorption or nutrient retention Flexibility to tailor biochar to specific applications 	<ul style="list-style-type: none"> Increases complexity and cost of biochar production Could require additional processing facilities Potentially less effective if initial biochar properties are unsuitable 	[31,35,101,102]
Targeted element enrichment treatment	<ul style="list-style-type: none"> Improves the ability of biochar to address specific environmental or agricultural needs (e.g., nutrient supply and heavy metal adsorption) Can increase the efficiency of biochar in targeted applications Tailored enhancements based on end-use requirements 	<ul style="list-style-type: none"> Potentially high cost and complexity in customizing biochar Could require precise control over processing conditions Risk of uneven distribution of added elements 	[57,101,103-105]

changes of biochar and the speciation of metal contaminants^[103]. These properties highlight the efficacy of biochar as an adsorbent for soil contaminants^[38,101].

4.4.1 High surface area and porosity

The most significant advantages of BNCs are high surface area and porosity, originating from the intrinsic properties of biochar and the incorporation of nanomaterials^[38,103]. Their ability to adsorb pollutants and facilitate catalytic reactions in wastewater treatment processes is greatly enhanced by their high surface area and porosity^[96,97]. The surface area of a material is crucial for its reactivity and interaction with other substances. BNCs have exceptionally high surface areas due to the intimate integration of nanomaterials, such as carbon nanotubes, graphene or metal oxides^[83,84]. These nanomaterials occupy interstitial spaces within the biochar matrix, creating additional external surfaces. A greater surface area translates to higher adsorption capacities, making biochar-based nanocomposites effective in water purification and gas storage applications.

BNCs include diverse surface functional groups, including hydroxyl, carboxyl and carbonyl, that have a crucial impact on adsorption. These groups can engage with adsorbates via hydrogen bonding, electrostatic interactions and van der Waals forces. Research suggests that the existence of these functional groups increases the attraction of BNCs to both organic and inorganic contaminants. The adsorption capacity of BNCs can be significantly increased by functionalization^[101]. Treatment with acid or base can increase the number of active sites. In contrast, impregnation with metals such as iron and zinc can improve specific adsorption processes including ion exchange and complexation.

Biochar owns a porous structure with a high specific surface area, typically ranging from 100 to 1000 m²·g⁻¹^[31,58]. Adding nanomaterials, such as carbon nanotubes, graphene, or metal oxide nanoparticles, further increases the surface area and porosity of the resulting BNCs^[102]. BNCs can adsorb and retain a widespread spectrum of pollutants ranging from heavy metals to organic contaminations due to the increased availability of binding sites.

Porosity is closely related to surface area, the volume of void spaces within a material. The intrinsic porosity of biochar is significantly uplifted when combined with nanomaterials. This is because biochar is structurally porous and nanomaterials can introduce additional nanopores. This enhanced porosity facilitates the diffusion of molecules throughout the BNC

structure. In catalysis, this means improved access of reactants to catalytic sites and efficient removal of products^[57]. This improved porosity for energy storage applications, such as supercapacitors and batteries, allows more room for ion exchange and storage, which is imperative for device efficiency.

The high surface area and porosity of BNCs contribute to enhanced adsorption capacities and catalytic activities, effectively removing various pollutants from wastewater^[57]. Additionally, the porous structure facilitates the transport and diffusion of reactants and products during catalytic reactions, improving the inclusive efficiency of BNCs in wastewater treatment processes^[103].

4.4.2 Tailored surface functionalities

BNCs can tailor their surface functionalities by incorporating different types of nanomaterials or functional groups^[102,119]. These can include chemical functionalization, physical treatments and the incorporation of nanoparticles. Chemical functionalization can introduce specific functional groups onto the biochar surface to enhance its reactivity and interaction with other materials. According to Tan et al.^[58] and Kant Bhatia et al.^[120], incorporating metal or metal oxide nanoparticles can give catalytic properties to the BNCs, enabling them to catalyze various reactions for pollutant degradation or transformation.

Additionally, the surface functionalization of BNCs with specific functional groups, such as amine, carboxyl or thiol groups, can enhance their selectivity and affinity toward certain types of pollutants^[103,120]. This chemical functionalization involves introducing specific functional groups onto the biochar surface, improving its reactivity and enabling it to interact more effectively with other materials.

Physical treatments such as plasma or heat treatment can also modify the surface properties of biochar. These treatments can improve performance in specific applications, making biochar-based nanocomposites more versatile and practical in diverse fields. Also, incorporating nanoparticles onto the biochar surface can further enhance its functionality and performance in nanocomposite materials. This approach opens up opportunities to tailor the properties of biochar-based nanocomposites based on specific application requirements.

The tailored surface functionalities of BNCs make them versatile materials for addressing a wide range of wastewater treatment challenges, including removing organic and inorganic contaminants, heavy metals and pathogens^[101]. These tailored surface functionalities expand the potential

applications of biochar-based nanocomposites and highlight their significant role in addressing complex challenges across various industries.

4.4.3 Enhanced adsorption and catalytic Properties

Introducing nanoparticles into the biochar matrix increases surface area and the development of a hierarchical pore structure. This enhances the adsorption capacity and facilitates the diffusion of adsorbates into the interior of the material^[119,121]. Combining biochar and nanomaterials in BNCs gives enhanced adsorption and catalytic properties compared to their components^[58,95]. The high surface area and porosity of BNCs contribute to their improved adsorption capacities. Concurrently, incorporating catalytic nanomaterials, such as metal or metal oxide nanoparticles, provides catalytic activity for pollutant degradation or transformation^[35,101].

The adsorption properties of BNCs can be further enhanced through surface functionalization of carbon material or the incorporation of specific nanomaterials with high affinities toward target pollutants^[81,101]. It has a larger specific surface area, increased porosity and higher density of functional groups, all contributing to its superior adsorption capabilities^[121]. These properties allow them to adsorb various pollutants, ranging from heavy metals to organic compounds, more efficiently than traditional adsorbents^[32]. For example, BNCs containing graphene or carbon nanotubes have excellent adsorption capacities for organic pollutants whereas those incorporating metal oxide nanoparticles have been shown to have high adsorption affinities for heavy metals^[32,58,122]. Functional groups such as hydroxyl, carboxylic and amine groups can be engineered onto the surface of biochar-based nanocomposites to target specific pollutants^[121]. This selective adsorption is crucial for applications in complex mixtures where specific contaminants must be removed preferentially^[119,121].

The catalytic performance of biochar is significantly augmented when incorporated with nanoparticles. These nanocomposites can catalyze various reactions, including the degradation of environmental pollutants and the synthesis of fine chemicals^[4]. The nanoparticles within biochar-based nanocomposites provide active sites for catalysis. Also, thermal stability of biochar supports the durability of composites under various reaction conditions^[4]. Their enhanced adsorption properties make them suitable for water and air purification, whereas their catalytic capabilities are advantageous in waste treatment and pollution control.

4.4.4 Synergistic effects

The advantage of BNCs is the synergistic effects that arise from combining biochar and nanomaterials^[57,123]. Compared to the individual components alone, these synergistic effects can improve the performance of wastewater treatment. According to Amdeha^[123], incorporating metal oxide nanoparticles into biochar can enhance the generation of ROS during catalytic oxidation processes, leading to more efficient degradation of organic pollutants.

Additionally, the interaction between biochar and nanomaterials can create unique active sites or interfacial regions that facilitate adsorption or catalytic reactions^[101]. These synergistic effects contribute to the overall effectiveness of BNCs in various wastewater treatment applications. BNCs provide a synergistic enhancement in adsorption capacity due to the combined action of the large surface area of biochar and the high reactivity of nanoparticles^[123]. This results in a material that can adsorb pollutants more effectively than either component could individually^[123,124]. The study by Liu et al.^[125] showed that biochar functionalized with magnetic nanoparticles provides an increased surface for adsorption and easy separation from aqueous solutions using an external magnetic field, making the composite ideal for water treatment applications.

The incorporation of nanoparticles significantly augments the catalytic performance of biochar. This is due to the high dispersion of catalytically active nanoparticles on the biochar surface, which increases the availability of active sites for reactions^[57]. Additionally, the carbonaceous matrix of biochar can stabilize the nanoparticles, preventing agglomeration and maintaining their catalytic efficiency over time.

Adding nanoparticles into the biochar matrix improves the mechanical properties of the resulting composite. Nanoparticles can act as reinforcing agents that enhance the tensile strength and durability of biochar, making it more suitable for construction materials and high-stress environmental applications^[126].

The judicious amalgamation of nanotechnology with the absorptive prowess of biochar gives rise to BNCs that are far superior in purifying water and capable of tackling complex mixtures of industrial effluents and domestic sewage with unprecedented effectiveness. By capitalizing on the intrinsic properties of biochar and nanomaterials, BNCs are a clear advancement in addressing the urgent demand for cleaner water and sustainable treatment methods. The multifaceted synergistic effects observed in BNCs solidify their role as a

transformative option in wastewater treatment landscapes. These materials offer a significant boost in performance, underscoring their potential to revolutionize environmental remediation and establish new benchmarks in treatment efficiency.

4.4.5 Stability and reusability

Stability in BNCs refers to the ability of these materials to maintain their structure and functionality under the intended application conditions over time. The stability is influenced by the inherent properties of biochar and the nature of the nanoparticles incorporated into the matrix. BNCs often have improved stability and reusability compared to their components^[34,61]. The biochar matrix can enhance the strength and dispersion of the incorporated nanomaterials, preventing their aggregation or leaching during wastewater treatment processes^[42,57].

Conversely, nanomaterials can improve the structural integrity and thermal stability of the biochar matrix, increasing the overall durability of the BNCs^[102,123]. Biochar is known for its high carbon content and aromatic structure confer excellent thermal stability. Nanocomposites derived from biochar inherit this property, making them suitable for high-temperature applications. Inorganic nanoparticles can further enhance thermal stability, acting as heat sinks and evenly distributing thermal energy throughout the material^[119,127]. The chemical stability of biochar-based nanocomposites is crucial when exposed to corrosive or reactive environments. The carbon matrix of biochar provides a protective barrier around the nanoparticles, preventing leaching or degradation. Additionally, modifying biochar with nanoparticles can provide in a material that is less prone to oxidation and other chemical changes that might compromise its integrity^[121,123].

The reusability of BNCs is an essential consideration for practical applications, as it can reduce operational costs and minimize waste generation^[121,128]. Many BNCs have demonstrated the ability to regenerate and reuse multiple times without significant performance loss, making them economically and environmentally attractive for wastewater treatment^[58,121]. Reusability is a property of paramount importance, especially from an economic and environmental perspective. The capability to regenerate and reuse biochar-based nanocomposites without significant performance loss is beneficial for sustainable practices.

Biochar nanocomposites can often be regenerated through simple thermal or chemical treatment, which removes the adsorbed

species and restores its adsorptive capacity. Díaz et al.^[121] mention that metal-impregnated biochar nanocomposites used in catalysis recovered and reactivated, thus extending their life cycle and reducing the need for fresh materials. Their reusability enhances the sustainable life cycle of biochar-based nanocomposites. They can be used in cyclic processes, such as water treatment plants and catalytic reactors, and were reused multiple times before disposal. This cyclical use reduces the environmental footprint of the material and contributes to the circular economy^[123,129].

4.5 Performance of biochar nanocomposites in wastewater treatment

BNCs have emerged as highly effective materials for wastewater treatment, demonstrating promising performance in removing organic and inorganic pollutants, heavy metals and pathogens^[35,121,123]. These nanocomposites are formed by incorporating nanomaterials into a biochar matrix, enhancing their adsorption and catalytic properties.

The performance of BNCs in wastewater treatment is attributed to structure and composition. The porous nature of biochar provides a large surface area for adsorption whereas the incorporated nanomaterials further enhance adsorption capacity and catalytic activity^[130]. This synergistic effect between biochar and nanomaterials makes BNCs highly efficient in removing many contaminants from wastewater.

Chausali et al.^[35], have reported the successful application of BNCs in wastewater treatment. For example, BNCs have been used to remove organic pollutants, such as dyes, phenols and pharmaceuticals, from wastewater, with high adsorption capacities and excellent removal efficiencies. Additionally, BNCs have been shown to have great potential in removing heavy metals from wastewater, including lead, cadmium and copper, through adsorption and precipitation mechanisms^[97]. For example, biochar modified with iron oxides has been shown to enhance adsorption for arsenic due to the formation of stable complexes.

Also, BNCs have effectively removed pathogens from wastewater, including bacteria, viruses and protozoa, through adsorption and inactivation processes^[38]. The antimicrobial properties of some nanomaterials incorporated into BNCs further enhance their performance in pathogen removal.

The performance of BNCs in wastewater treatment highlights their potential as sustainable and practical materials for

addressing water pollution challenges. Further research and development in this field is needed to optimize their performance and explore their applications in various wastewater treatment scenarios.

4.5.1 Adsorption of organic pollutants

BNCs have demonstrated excellent adsorption capacities for various organic pollutants, including pharmaceuticals and personal care products, making them suitable for treating industrial and municipal wastewater^[57,58]. As a sorbent, biochar is used to eliminate organic pollutants from wastewater. Compound dyes and phenols are the most significant organic pollutants that are difficult to eradicate. The high surface area, porosity and tailored surface functionalities of BNCs contribute to their enhanced adsorption properties^[103,121]. According to Park et al.^[131], the dye wastewater discharged from dyeing operations in the garment sector accounts for 10%–15% of all dyes used, equivalent to 1.5–108 m³·yr⁻¹.

Díaz et al.^[121] mention that BNCs incorporating carbon-based nanomaterials, such as carbon nanotubes or graphene, have been shown to have remarkable adsorption capacities for organic dyes and personal care products^[19]. The π - π interactions between the carbon-based nanomaterials and the aromatic rings of organic pollutants facilitate their adsorption onto the BNC surface^[57,58]. Additionally, incorporating functional groups, such as amine or carboxyl groups, can further enhance the adsorption of specific organic pollutants through electrostatic interactions or hydrogen bonding^[100,103].

Also, BNCs possess various surface functional groups, such as hydroxyl, carboxyl and carbonyl, that are important for adsorption. These groups can interact with adsorbates through hydrogen bonding, electrostatic interactions and van der Waals forces. Studies indicate that the presence of these functional groups enhances the affinity of BNCs for both organic and inorganic pollutants^[101].

4.5.2 Removal of heavy metals

BNCs have also demonstrated promising performance in removing heavy metals from wastewater, a critical concern due to the toxic, carcinogenic and persistent nature of these pollutants^[101]. Incorporating metal oxide nanoparticles or functional groups with high affinities for heavy metal ions can significantly enhance the adsorption capacity and selectivity of BNCs^[57,58].

The adsorption properties of biochars from peat moss were examined using various carbonization settings to remove lead, zinc, copper and cadmium. According to Nadarajah et al.^[103], BNCs containing iron oxide nanoparticles have been shown to have excellent adsorption capacities for heavy metals such as lead, cadmium and chromium. The absorption removes efficiencies of 98.6% and 99.2% for lead and cadmium, respectively. The high surface area and porosity of the BNCs, combined with the affinity of iron oxide for heavy metal ions, contribute to their improved performance in heavy metal removal^[19,101] with several factors, including contact duration and solution pH, impacting adsorption. According to Frišták et al.^[132], the biochar included oxidizable fractions of copper, and exchangeable fractions of cadmium and zinc.

4.5.3 Catalytic degradation of organic pollutants

BNCs have been extensively studied for their catalytic activity in degrading organic pollutants through AOPs^[58,121,123]. Incorporating catalytic nanomaterials, such as metal or metal oxide nanoparticles, into the biochar matrix can enhance the generation of ROS and facilitate the oxidative degradation of organic pollutants^[103,133].

According to a study by Zeng et al.^[105], BNCs containing iron or manganese oxide nanoparticles have demonstrated excellent catalytic activity in degrading organic dyes, pharmaceuticals and other persistent organic pollutants through Fenton-like reactions or photocatalytic oxidation processes. The synergistic effects between the biochar matrix and the catalytic nanomaterials contribute to the improved performance of BNCs in these catalytic degradation processes^[57,121,123].

4.5.4 Disinfection and pathogen removal

BNCs have also been shown to have potential for disinfecting wastewater and removing pathogens, such as bacteria and viruses^[100]. Incorporating nanomaterials with antimicrobial properties, such as silver or copper nanoparticles, into the biochar matrix can enhance the disinfection capabilities of BNCs^[101].

The mechanism of pathogen removal by BNCs can involve a combination of adsorption, inactivation and the release of antimicrobial agents^[58]. The porous structure and high surface area of BNCs facilitate the adsorption of pathogens. Concurrently, antimicrobial nanomaterials exert their biocidal effects through various mechanisms, such as the generation of ROS or the disruption of cell membranes^[103,133].

4.5.5 Integration with other treatment processes

BNCs are integrated with other wastewater treatment processes, including membrane filtration, AOPs or biological treatment systems^[62,101]. For example, BNCs are used as adsorbents or catalysts in membrane bioreactors to enhance the removal of organic pollutants and mitigate membrane fouling^[58].

Additionally, BNCs can be used as catalysts or adsorbents in AOPs, such as Fenton-like reactions or photocatalytic oxidation processes, for the efficient degradation of persistent organic pollutants^[101,103,133]. Also, BNCs can be incorporated into biological treatment systems, such as activated sludge processes or constructed wetlands, to improve the removal of specific pollutants or enhance the overall treatment efficiency^[62,101].

Despite the promising performance of BNCs in various wastewater treatment applications, challenges such as scalability, cost-effectiveness, and potential environmental impacts still need to be addressed^[58]. Additionally, further research is required to understand better the mechanisms underlying the interactions between BNCs and pollutants and the long-term stability and reusability of these materials^[133].

5 Bioenergy production from biochar nanocomposites

Biochar has received significant attention for its potential applications in bioenergy production. Integrating nanomaterials into biochar matrices, which form BNCs, has provided new opportunities for enhancing bioenergy generation processes. BNCs offer opportunities to optimize energy conversion efficiencies, improve process stability and mitigate the environmental impacts of traditional bioenergy production methods.

One of the primary applications for BNCs in bioenergy production is through direct combustion for heat and electricity generation. Biochar has a high calorific value and low moisture content, making it a suitable solid alternative to fossil fuels^[86]. However, incorporating nanomaterials into biochar can further enhance its combustion properties. The BNCs containing metal oxide nanoparticles, such as iron (III) oxide or copper oxide, have been shown to improve the ignition properties, combustion kinetics and thermal stability of biochar during combustion processes^[126]. The presence of these nanoparticles can catalyze oxidation reactions, leading to

higher energy release rates and more efficient heat transfer^[62,127].

Gasification is another thermochemical process in which BNCs can significantly contribute in bioenergy production. During gasification, biochar is converted into a combustible gas mixture (i.e., syngas) composed primarily of hydrogen, carbon monoxide and methane^[127]. This syngas can be used for various applications, including heat and power generation, or further processed into liquid biofuels. Incorporating nanomaterials into biochar matrices can enhance the gasification process by improving the reactivity and catalytic properties of the resulting BNCs. For example, BNCs containing nickel or iron nanoparticles have demonstrated improved tar cracking and reforming abilities, leading to higher-quality syngas production^[130]. Additionally, BNCs with oxygen-containing functional groups, such as graphene oxide-biochar composites, can facilitate the gasification reactions and improve syngas yield^[101].

Also, BNCs contribute to mitigating environmental impacts associated with bioenergy production processes. For example, BNCs can be used as adsorbents or catalysts to remove pollutants and contaminants from gaseous emissions or wastewater streams generated during bioenergy production^[58]. The high surface area and tailored surface chemistry of BNCs make them effective in adsorbing and catalyzing the degradation of various pollutants, such as volatile organic compounds, nitrogen oxides and sulfur oxides^[134].

Despite the promising potential of BNCs in bioenergy production, several challenges remain. One of the main challenges is the scalability and cost-effectiveness of BNC production. Although laboratory-scale synthesis of BNCs has been widely explored, the transition to large-scale production remains a hurdle. Additionally, the economic feasibility of incorporating nanomaterials into biochar matrices must be carefully evaluated, considering the benefits of improved energy conversion efficiencies and environmental impact mitigation^[101].

Another challenge is the potential environmental and health implications of using nanomaterials in BNCs. Although nanomaterials can enhance bioenergy production processes, their possible toxicity and ecological persistence raise concerns^[134]. Rigorous risk assessments and environmental impact studies are necessary to ensure the safe and sustainable use of BNCs in bioenergy applications.

Biochar-based nanocomposites offer exciting opportunities to

enhance bioenergy production processes and mitigate environmental impacts. Their unique properties, such as improved combustion characteristics, enhanced gasification reactivity, increased biogas yields and pollutant removal capabilities, make them attractive for various bioenergy applications. However, addressing the challenges related to scalability, cost-effectiveness, and potential environmental and health implications is crucial for successfully implementing BNCs in bioenergy production systems.

5.1 Use of biochar in renewable bioenergy production and power generation

In the biofuel industry, BNCs have demonstrated their potential as catalysts in biomass conversion processes. By incorporating metal or metal oxide nanoparticles onto the biochar surface, BNCs can be given catalytic properties that facilitate reactions involved in the production of biofuels, such as gasification, pyrolysis and catalytic upgrading^[120]. These catalytic BNCs can enhance the yield and selectivity of desired biofuel products, improving process efficiency and economic viability^[47].

The pulp and paper industry, a significant energy consumer, has also recognized the potential of BNCs in bioenergy production. The abundant availability of biomass residues, such as sawdust and bark, makes this industry a prime candidate for implementing BNC-based bioenergy solutions. BNCs can be used as efficient adsorbents to purify biogas generated from the anaerobic digestion of these biomass residues^[101]. By selectively adsorbing impurities, including hydrogen sulfide and carbon dioxide, BNCs can enhance the calorific value and combustion efficiency of the biogas, leading to improved energy recovery and reduced emissions^[135].

In addition, the agricultural industry has grown interested in applying BNCs for bioenergy production. Agricultural residues, such as crop residues, animal manure and food waste, represent valuable feedstocks for bioenergy production. BNCs can be used as catalysts to convert residues into value-added chemicals and biofuels through processes including pyrolysis and gasification^[39,47]. Additionally, BNCs can serve as adsorbents for the purification of biogas generated from the anaerobic digestion of agricultural waste, further contributing to the overall sustainability and efficiency of bioenergy production in this industry.

In the wastewater treatment sector, BNCs have been shown to have promising applications in energy recovery from wastewater streams. By incorporating conductive

nanomaterials, such as carbon nanotubes or graphene, into the biochar matrix, BNCs can have enhanced electrical conductivity and improved electrochemical performance^[83]. These properties make BNCs suitable for use as electrode materials in microbial fuel cells (MFCs), which harness the energy generated by bacteria during the breakdown of organic matter in wastewater^[100]. Implementing BNC-based MFCs in wastewater treatment plants can lead to the simultaneous treatment of wastewater and recovery of renewable energy.

The transportation industry, which is a significant contributor to greenhouse gas emissions, has also recognized the potential of BNCs in bioenergy production. BNCs can be used as catalysts in converting biomass-derived compounds, such as alcohols or plant oils, into biofuels suitable for transportation applications^[47]. Additionally, BNCs can contribute to the purification of biogas, enabling its use as a renewable fuel for vehicles or as a feedstock for producing other transportation fuels.

5.2 Applications of biochar nanocomposites for supercapacitors

Supercapacitors, also known as electrochemical capacitors, are energy storage devices that have received significant interest due to their high power density, fast charge or discharge rates and long cycle life^[136]. Biochar-based nanocomposites have emerged as promising electrode materials for supercapacitors, offering several advantages over traditional carbon-based electrodes.

Incorporating conductive nanomaterials, such as carbon nanotubes (CNTs) or graphene, into the biochar matrix can significantly enhance the electrical conductivity and electrochemical performance of BNCs^[83,84]. The high surface area and porosity of biochar provide an excellent platform for the uniform dispersion of these conductive nanomaterials, resulting in improved charge transfer and ion transport^[135].

Also, the surface functionalization of BNCs with specific functional groups, such as oxygen-containing groups or nitrogen-doping, can increase the pseudocapacitance and overall capacitance of the electrode material^[101]. This enhancement in capacitance contributes to higher energy density and improved performance in supercapacitor applications.

BNCs have been found to provide superior electrochemical performance compared to pristine biochar or other carbon-

based materials, making them attractive candidates for energy storage devices in various applications, including renewable energy systems, electric vehicles and portable electronics^[57].

5.3 Use of biochar nanocomposites in fuel manufacturing

The use of biochar-based nanocomposites in fuel production technology has gained significant attention due to their potential as catalysts in biomass conversion processes and their ability to enhance the quality of biofuels.

One promising application of BNCs is their use as catalysts in the pyrolysis and gasification of biomass to produce bio-oils and syngas^[44,47]. By incorporating metal or metal oxide nanoparticles onto the biochar surface, BNCs can have catalytic properties that facilitate biomass conversion into valuable fuels and chemicals^[120]. These catalytic BNCs can be used to improve the desired yield, selectivity and quality of its products, making the process more efficient and economically viable.

Also, BNCs can purify and upgrade biofuels. They can serve as adsorbents for removing impurities, such as sulfur compounds, from bio-oils or biogas, thereby enhancing fuel quality and reducing emissions^[102,137]. Also, BNCs can be used as catalysts in upgrading bio-oils through hydrodeoxygenation, cracking or isomerization, improving the fuel properties and compatibility with existing infrastructure^[47].

The modifiable surface chemistry and porosity of BNCs also make them suitable for hydrogen storage and production applications, which are essential for various energy-related applications, including fuel cell technologies^[38,100].

5.4 BNCs for microbial fuel cell technology electrodes for power generation

MFCs are a promising technology that harnesses microbial energy during organic matter oxidation to produce electricity. In MFCs, biochar-based nanocomposites have been shown to have great potential as electrode materials, offering several advantages over traditional carbon-based electrodes.

The high surface area and porosity of biochar provide an ideal environment for the attachment and growth of electrochemically active bacteria, which are responsible for generating electrons in MFCs^[100,103]. Additionally, incorporating conductive nanomaterials, such as CNTs or

graphene, into the biochar matrix can significantly enhance the electrical conductivity of the electrode, facilitating efficient electron transfer and improving the overall power output of the MFC^[83,84].

Also, the surface functionalization of BNCs can enhance their interaction with the microorganisms, promoting better biofilm formation and increasing the overall performance of the MFC^[102,103]. For example, introducing nitrogen-containing functional groups can improve the affinity of the electrode surface for bacterial attachment and growth^[112].

Using BNCs as electrodes in MFCs contributes to renewable power generation. It offers a sustainable solution for treating organic waste streams, as the organic matter is converted into electricity during the process^[43,100]. This dual benefit of waste valorization and energy production makes MFCs with BNC electrodes attractive for various applications, such as wastewater treatment plants, industrial facilities and remote or off-grid communities.

5.5 Biochar nanocomposites in farming systems

The application of biochar and biochar-based nanocomposites in farming systems has gained significant attention due to their potential to improve soil quality, nutrient retention and crop productivity while contributing to renewable bioenergy production.

Biochar applied to agricultural soils can improve soil fertility by improving water-holding capacity, nutrient availability and soil structure^[15,22,33]. Additionally, biochar can sequester carbon in the soil, contributing to climate change mitigation efforts^[23].

Incorporating biochar into a farming system also provides opportunities for renewable bioenergy production. Agricultural residues, such as crop residues, animal manures and forestry wastes, can serve as feedstocks for biochar production through pyrolysis^[25,26,33]. The biochar produced can then be applied to agricultural soils. Concurrently, the energy generated during the pyrolysis process can be used for various purposes, such as heating, electricity generation, or biofuel production.

Also, the development of BNCs has provided new ways for enhancing the performance of biochar in farming systems. BNCs are engineered to improve nutrient retention, water-holding capacity and soil structure by incorporating specific

nanomaterials or functional groups^[36,37]. For example, incorporating clay or metal oxide nanoparticles into the biochar matrix can enhance nutrient sorption and availability, improving crop productivity^[35,110].

Additionally, BNCs can be used as carriers for controlled release of fertilizers, pesticides and plant growth regulators, reducing the environmental impact and improving the efficiency of these agricultural inputs^[19,27].

Integrating biochar and biochar-based nanocomposites into farming systems contributes to sustainable agricultural practices. It provides opportunities for producing renewable bioenergy, advancing the transition toward a more sustainable and circular economy.

5.6 Benefits and challenges of using biochar for bioenergy production

Despite the promising potential of BNCs in renewable bioenergy production across various industries, several challenges must be tackled to facilitate their widespread implementation. One of the critical challenges is the scalability and cost-effectiveness of BNC production processes^[33]. Researchers and industry stakeholders are actively exploring strategies to optimize production processes and reduce the associated costs, making BNCs more economically viable for large-scale applications.

5.6.1 Benefits of using biochar nanocomposites for bioenergy production

The availability and renewability of these feedstocks make BNCs a sustainable alternative to fossil fuels, contributing to reducing greenhouse gas emissions and promoting a circular economy^[18]. Also, the production and application of BNCs contribute to carbon sequestration, as a significant portion of the carbon in the biomass feedstock is retained in the biochar structure^[23]. This stable form of carbon can remain sequestered in the soil for extended periods, potentially mitigating the effects of climate change^[20]. Applying biochar to agricultural soil has improved soil quality by increasing water retention, nutrient availability and microbial activity^[9,10]. These benefits can enhance crop yields and agricultural productivity, contributing to food security and sustainable farming practices^[13].

Also, BNCs are used in various bioenergy applications, including biofuel production, energy storage systems and MFCs. Its unique properties, including high surface area,

porosity and electrical conductivity, make it suitable for catalytic applications, supercapacitor electrodes and MFC anodes^[47,83,100]. Additionally, the production of BNCs from waste biomass, such as agricultural residues, municipal solid waste and sewage sludge, offers opportunities for waste management and resource recovery^[43]. By converting these waste streams into biochar, valuable resources can be recovered and used for bioenergy production or other applications^[5,6].

5.6.2 Challenges for using biochar nanocomposites in bioenergy production

Depending on the feedstock source and the production parameters (e.g., the temperature of the pyrolysis process, the rate of heating and the amount of time that biochar is allowed to remain in the atmosphere), the characteristics of biochar, such as its surface area, porosity, and chemical composition, can vary considerably^[11,41]. Consequently, this variability can affect the performance of biochar in various bioenergy applications, presenting challenges for standardization and quality control. Also, large-scale production and application of biochar for bioenergy purposes currently need economic challenges. The costs associated with feedstock procurement, biochar production and transportation can be significant, potentially hindering the widespread adoption of biochar-based bioenergy technologies^[25,33]. Although biochar is generally considered a stable material, its long-term stability and resistance to degradation can be influenced by various factors, such as environmental conditions, soil characteristics and biochar properties^[34,42]. Therefore, understanding and optimizing biochar stability is crucial to ensure its effectiveness in carbon sequestration and soil amendment applications.

Additionally, the production and application of biochar can raise environmental and health concerns, such as the potential release of pollutants (e.g., polycyclic aromatic hydrocarbons and dioxins) during the pyrolysis process or the leaching of contaminants from biochar into the soil or water^[60,86]. Proper controls and mitigation strategies are necessary to address these concerns. Also, the lack of comprehensive regulatory frameworks and policies governing biochar production, characterization and application can hinder its widespread adoption^[25]. Establishing clear guidelines and standards for biochar quality, safety and sustainability is crucial for promoting its use in bioenergy and other applications. Despite significant progress in understanding the properties and applications of biochar, knowledge gaps still exist in areas such as biochar-soil interactions, long-term environmental impacts and optimization of biochar production processes^[76]. Due to the lack of regulations in this area, voluntary standards for

biochar quality have been established in Europe via the European Biochar Certificate, in the UK through the Biochar Quality Mandate and in the USA through the International Biochar Initiative standards, designed for worldwide usage^[138,139]. Simultaneously, biochar producers and consumers in some EU nations partially integrated the novel biochar product within the current national fertilizers, soil enhancers and composts regulations. The proposed amendment to EC Regulation 2003/2003 on fertilizers presents the chance to establish rules for using biochar at the EU level^[140].

5.7 By-products of biochar nanocomposites

BNCs have been shown to have substantial potential in addressing global challenges across various industries, including environmental remediation, energy storage and catalysis. These nanocomposites are distinguished by their unique physicochemical properties, including high surface area, porosity and chemical stability^[52,58,125].

However, producing these innovative materials is accompanied by generating various byproducts in gaseous, liquid and solid forms. These by-products possess specific characteristics and potential applications, presenting challenges and opportunities for developing sustainable and eco-friendly processes^[141,142]. The effective management and valorization of these by-products are crucial for minimizing waste, maximizing resource use efficiency and promoting the transition toward a circular economy.

As the demand for BNCs grows, a comprehensive understanding of the nature, composition and use of the associated by-products becomes increasingly essential.

By exploring innovative approaches to byproduct valorization, the biochar-based nanocomposite industry can contribute to achieving global sustainability goals, fostering a harmonious balance between technological advancements, environmental preservation and economic prosperity. This paper aims to provide a comprehensive overview of the by-products generated during the production of biochar-based nanocomposites, laying the foundation for future research, policy development and industrial implementation.

5.7.1 Gaseous byproducts

During the thermochemical conversion of biomass, a mixture of combustible gases, including hydrogen, methane, carbon monoxide and carbon dioxide, is generated as a

byproduct^[99,141,143]. These gaseous byproducts can be used as a fuel source for energy generation, contributing to the overall energy efficiency of the process^[99,142]. Additionally, captured carbon dioxide can be sequestered or used in various industrial processes, such as enhanced oil recovery or producing carbonates and other valuable chemicals^[99,143].

However, the management and treatment of these gaseous byproducts present challenges. The composition and concentration of the gases can vary depending on the feedstock and production conditions, necessitating tailored treatment strategies^[59]. Also, contaminants, such as particulate matter, tar and other impurities, require additional purification steps to ensure safe and efficient use^[57,58].

5.7.2 Liquid byproducts

Bio-oils, or pyrolysis liquids, are the liquid byproducts generated during biochar-based nanocomposites^[142]. These byproducts are formed through the condensation of volatile organic compounds released during the thermochemical conversion of biomass. Bio-oils are complex mixtures of water, organic acids, phenolic compounds and other oxygenated hydrocarbons^[52,99].

Bio-oils are highly calorific and can be used as a fuel source for heat and power generation^[59]. Additionally, they can serve as precursors for producing valuable chemicals, such as phenolic resins, adhesives and other specialty chemicals^[144]. However, the use of bio-oil has challenges, including their high acidity, viscosity and instability, which can lead to corrosion, fouling and polymerization^[57]. Upgrading and refining processes, including catalytic cracking, hydrogenation and emulsification, are often required to improve the properties and stability of bio-oils for specific applications^[99,142].

5.7.3 Solid byproducts

The solid byproducts of biochar-based nanocomposites comprise ash and unreacted carbonaceous materials^[99]. The composition and properties of these solid byproducts are highly dependent on the feedstock and the production conditions used.

One potential application of these solid byproducts is their use as soil amendments or fertilizers in agricultural practices^[52]. The ash content, rich in essential plant nutrients, including phosphorus, potassium and calcium, can improve soil fertility and plant growth^[144]. The carbonaceous materials of solid byproducts can also improve soil structure, water retention and cation exchange capacity^[59].

However, using solid byproducts in agriculture requires careful consideration and monitoring due to the potential presence of contaminants, such as heavy metals and organic pollutants^[57]. These contaminants can accumulate in the soil or be taken up by plants, posing risks to human health and the environment^[145].

Alternative applications for solid byproducts include their use as feedstock for producing construction materials, such as bricks and cement, or as an energy source through combustion or gasification processes^[52,144].

6 Conclusions and recommendations

BNCs have emerged as highly effective materials for wastewater treatment and renewable bioenergy production. These nanocomposites, formed by incorporating nanomaterials into a biochar matrix, have unique properties that enhance their adsorption and catalytic capabilities, making them versatile and efficient in addressing water pollution challenges.

Key findings suggest that BNCs have demonstrated promising performance in removing many contaminants from wastewater, including organic pollutants, heavy metals and pathogens. Their porous structure provides a large surface area for adsorption whereas the incorporated nanomaterials further enhance their adsorption capacity and catalytic activity. This synergistic effect between biochar and nanomaterials makes

BNCs highly effective in various wastewater treatment applications.

The implications for future research in this field are substantial. To improve their performance and cost-effectiveness, further studies are needed to optimize the production processes of BNCs, including the selection of feedstocks, pyrolysis conditions and nanomaterial incorporation methods. Additionally, research focusing on the long-term stability and environmental impacts of BNCs is essential to ensure their sustainability and safety in practical applications.

The potential applications and benefits of BNCs extend beyond wastewater treatment. Due to their specific properties, such as high surface area, porosity and electrical conductivity, these nanocomposites can be used in bioenergy production, energy storage systems and microbial fuel cells. Also, producing BNCs from waste biomass offers waste management and resource recovery opportunities, contributing to a circular economy and sustainable development.

In summary, the use of biochar-based nanocomposites provides promising opportunities for sustainable water treatment and bioenergy production. Their unique properties, potential applications and benefits make them a valuable solution for addressing water pollution challenges and advancing renewable energy technologies. Continued research and development efforts in this field are crucial to unlocking the full potential of BNCs and promoting their widespread adoption in various environmental and energy applications.

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Compliance with ethics guidelines

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REFERENCES

1. United Nations (UN). The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water. Available at UN Water website on September 7, 2024
2. United Nations Environment Programme (UNEP). Plastic Pollution. UNEP (UN Environment Programme), 2024. Available at UNEP website on September 7, 2023
3. Kaza S, Yao L C, Bhada-Tata P, Van Woerden F. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. *Urban Development*, 2018, 141–180
4. Noreen S, Abd-Elsalam K A. Biochar-based nanocomposites: a sustainable tool in wastewater bioremediation. *Aquananotechnology*, 2021, 185–200

5. Yuan H R, Lu T, Huang H Y, Zhao D D, Kobayashi N, Chen Y. Influence of pyrolysis temperature on physical and chemical properties of biochar made from sewage sludge. *Journal of Analytical and Applied Pyrolysis*, 2015, **112**: 284–289
6. Wang M Y, Lan X F, Xu X P, Fang Y Y, Singh B P, Sardans J, Romero E, Peñuelas J, Wang W Q. Steel slag and biochar amendments decreased CO₂ emissions by altering soil chemical properties and bacterial community structure over two-year in a subtropical paddy field. *Science of the Total Environment*, 2020, **740**: 140403
7. Neves E G, Petersen J B, Bartone R N, Augusto Da Silva C. Historical and Socio-cultural Origins of Amazonian Dark Earth. *Amazonian Dark Earths*, 2003, 29–50
8. Kern D C, D'aquino G, Rodrigues T E, Frazao F J L, Sombroek W, Myers T P, Neves E G. Distribution of Amazonian Dark Earths in the Brazilian Amazon. *Amazonian Dark Earths*, 2003, 51–75
9. Jeffery S, Verheijen F G A, Van Der Velde M, Bastos A C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 2011, **144**(1): 175–187
10. Biederman L A, Harpole W S. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *Global Change Biology. Bioenergy*, 2013, **5**(2): 202–214
11. Enders A, Hanley K, Whitman T, Joseph S, Lehmann J. Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology*, 2012, **114**: 644–653
12. Akoto-Danso E K, Manka'abusi D, Steiner C, Werner S, Häring V, Nyarko G, Marschner B, Drechsel P, Buerkert A. Agronomic effects of biochar and wastewater irrigation in urban crop production of Tamale, northern Ghana. *Nutrient Cycling in Agroecosystems*, 2019, **115**(2): 231–247
13. Pandit N R, Mulder J, Hale S E, Zimmerman A R, Pandit B H, Cornelissen G. Multi-year double cropping biochar field trials in Nepal: finding the optimal biochar dose through agronomic trials and cost-benefit analysis. *Science of the Total Environment*, 2018, **637–638**: 1333–1341
14. DeLuca T H, Gundale M J, MacKenzie M D, Jones D L. Biochar effects on soil nutrient transformations. *Biochar for Environmental Management: Science, Technology and Implementation*, 2015, **2**: 421–454
15. Igalavithana A D, Ok Y S, Usman A R A, Al-Wabel M I, Oleszczuk P, Lee S S. The Effects of Biochar Amendment on Soil Fertility. *SSSA Special Publications*, 2015, 123–144
16. Igalavithana A D, Yang X, Zahra H R, Tack F M G, Tsang D C W, Kwon E E, Ok Y S. Metal(loid) immobilization in soils with biochars pyrolyzed in N₂ and CO₂ environments. *Science of the Total Environment*, 2018, **630**: 1103–1114
17. Hersh B, Mirkouei A. Life Cycle Assessment of Pyrolysis-Derived Biochar From Organic Wastes and Advanced Feedstocks. Volume 4: 24th Design for Manufacturing and the Life Cycle Conference. *13th International Conference on Micro- and Nanosystems*, 2019
18. Teh J S, Teoh Y H, How H G, Le T D, Jason Y J J, Nguyen H T, Loo D L. The potential of sustainable biomass producer gas as a waste-to-energy alternative in Malaysia. *Sustainability*, 2021, **13**(7): 3877
19. Gupta M, Savla N, Pandit C, Pandit S, Gupta P K, Pant M, Khilari S, Kumar Y, Agarwal D, Nair R R, Thomas D, Thakur K. Use of biomass-derived biochar in wastewater treatment and power production: a promising solution for a sustainable environment. *Science of the Total Environment*, 2022, **825**: 153892
20. Sheng Y Q, Zhu L Z. Biochar alters microbial community and carbon sequestration potential across different soil pH. *Science of the Total Environment*, 2018, **622–623**: 1391–1399
21. Paetsch L, Mueller C W, Kögel-Knabner I, Von Lützow M, Girardin C, Rumpel C. Effect of *in-situ* aged and fresh biochar on soil hydraulic conditions and microbial C use under drought conditions. *Scientific Reports*, 2018, **8**(1): 6852
22. Hossain M Z, Bahar M M, Sarkar B, Donne S W, Ok Y S, Palansooriya K N, Kirkham M B, Chowdhury S, Bolan N. Biochar and its importance on nutrient dynamics in soil and plant. *Biochar*, 2020, **2**(4): 379–420
23. de Coninck H, Revi A, Babiker M, Bertoldi P, Buckeridge M, Cartwright A, Dong W, Ford J, Fuss S, Hourcade J, Ley D. Chapter 4: Strengthening and implementing the global response. In: Global Warming of 1.5 °C an IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Dtrengthening the Global Response to the Threat of Climate Change. *International Panel and Climate Change*, 2018
24. Project Drawdown. Biochar Production. *Project Drawdown*, 2023. Available at Project Drawdown website on March 10, 2024
25. Scholz S B, Sembres T, Roberts K, Whitman T, Wilson K, Lehmann J. Biochar Systems for Smallholders in Developing Countries: Leveraging Current Knowledge and Exploring Future Potential for Climate-Smart Agriculture. *The World Bank*, 2014
26. Rynk R, Schwarz M, Richard T L, Cotton M, Halbach T, Siebert S. Compost Feedstocks. *The Composting Handbook*, 2022, 103–157
27. Filiberto D, Gaunt J. Practicality of biochar additions to enhance soil and crop productivity. *Agriculture*, 2013, **3**(4): 715–725
28. 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
29. Hou R J, Li T X, Fu Q, Liu D, Li M, Zhou Z Q, Li Q L, Zhao H, Yu P F, Yan J W. Effects of biochar and straw on greenhouse gas emission and its response mechanism in seasonally frozen farmland ecosystems. *Catena*, 2020, **194**: 104735

30. Farhangi-Abriz S, Torabian S, Qin R J, Noulas C, Lu Y Y, Gao S D. Biochar effects on yield of cereal and legume crops using meta-analysis. *Science of the Total Environment*, 2021, **775**(12): 145869
31. Das R, Panda S N. Preparation and applications of biochar based nanocomposite: a review. *Journal of Analytical and Applied Pyrolysis*, 2022, **167**(8): 105691
32. Sanchez-Monedero M A, Cayuela M L, Roig A, Jindo K, Mondini C, Bolan N. Role of biochar as an additive in organic waste composting. *Bioresource Technology*, 2018, **247**: 1155–1164
33. Vochozka M, Maroušková A, Váchal J, Straková J. Biochar pricing hampers biochar farming. *Clean Technologies and Environmental Policy*, 2016, **18**(4): 1225–1231
34. Leng L J, Huang H J. An overview of the effect of pyrolysis process parameters on biochar stability. *Bioresource Technology*, 2018, **270**: 627–642
35. Chausali N, Saxena J, Prasad R. Nanobiochar and biochar based nanocomposites: advances and applications. *Journal of Agriculture and Food Research*, 2021, **5**(3): 100191
36. Ramadan M M, Asran-Amal, Abd-Elsalam K A. Micro/nano Biochar for Sustainable Plant Health: Present Status and Future Prospects. *Carbon Nanomaterials for Agri-Food and Environmental Applications*, 2020, 323–357
37. El-Naggar A, Lee S S, Rinklebe J, Farooq M, Song H, Sarmah A K, Zimmerman A R, Ahmad M, Shaheen S M, Ok Y S. Biochar application to low fertility soils: a review of current status, and future prospects. *Geoderma*, 2019, **337**: 536–554
38. Ahmad M, Rajapaksha A U, Lim J E, Zhang M, Bolan N, Mohan D, Vithanage M, Lee S S, Ok Y S. Biochar as a sorbent for contaminant management in soil and water: a review. *Chemosphere*, 2014, **99**(9): 19–33
39. Bridgwater T, Peacocke C. Fast pyrolysis processes for biomass. *Renewable & Sustainable Energy Reviews*, 2000, **4**(1): 1–73
40. Lehmann J, Joseph S. Biochar for Environmental Management. 2nd ed. *Routledge*, 2015, 235–282
41. Mukome F N D, Zhang X M, Silva L C R, Six J, Parikh S J. Use of chemical and physical characteristics to investigate trends in biochar feedstocks. *Journal of Agricultural and Food Chemistry*, 2013, **61**(9): 2196–2204
42. Singh B P, Cowie A L, Smernik R J. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology*, 2012, **46**(21): 11770–11778
43. Bolan N S, Thangarajan R, Seshadri B, Jena U, Das K C, Wang H L, Naidu R. Landfills as a biorefinery to produce biomass and capture biogas. *Bioresource Technology*, 2013, **135**: 578–587
44. Glushkov D, Nyashina G, Shvets A, Pereira A, Ramanathan A. Current status of the pyrolysis and gasification mechanism of biomass. *Energies*, 2021, **14**(22): 7541
45. Jerzak W, Reinmüller M, Magdziarz A. Estimation of the heat required for intermediate pyrolysis of biomass. *Clean Technologies and Environmental Policy*, 2022, **24**(10): 3061–3075
46. Demirbas A. Effects of temperature and particle size on biochar yield from pyrolysis of agricultural residues. *Journal of Analytical and Applied Pyrolysis*, 2004, **72**(2): 243–248
47. Bridgwater A V. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy*, 2012, **38**: 68–94
48. McKendry P. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, 2002, **83**(1): 37–46
49. Shankar Tumuluru J, Sokhansanj S, Wright C T, Hess J R, Boardman R D. A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, 2011, **7**(5): 384–401
50. Singh Y, Strezov V, Negi P. Biowaste and Biomass in Biofuel Applications (1st ed). Boca Raton: *CRC Press*, 2023
51. Chen W H, Lin B J, Lin Y Y, Chu Y S, Ubando A T, Show P L, Ong H C, Chang J S, Ho S H, Culaba A B, Pétrissans A, Pétrissans M. Progress in biomass torrefaction: principles, applications and challenges. *Progress in Energy and Combustion Science*, 2021, **82**: 100887
52. Basu P, Kaushal P. Biomass Gasification, Pyrolysis, and Torrefaction. 4th ed. *Megan Ball*, 2023
53. Hornung A. Intermediate Pyrolysis of Biomass. *Biomass Combustion Science, Technology and Engineering*, 2013, 172–186
54. Khater E S, Bahnasawy A, Hamouda R, Sabahy A, Abbas W, Morsy O M. Biochar production under different pyrolysis temperatures with different types of agricultural wastes. *Scientific Reports*, 2024, **14**(1): 2625
55. Kan T, Strezov V, Evans T J. Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. *Renewable & Sustainable Energy Reviews*, 2016, **57**: 1126–1140
56. Angin D. Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake. *Bioresource Technology*, 2013, **128**: 593–597
57. Tan X F, Liu Y G, Gu Y L, Xu Y, Zeng G M, Hu X J, Liu S B, Wang X M, Liu S M, Li J. Biochar-based nano-composites for the decontamination of wastewater: a review. *Bioresource Technology*, 2016, **212**: 318–333
58. Tan X, Liu S B, Liu Y G, Gu Y L, Zeng G, Hu X J, Wang X, Liu S H, Jiang L. Biochar as potential sustainable precursors for activated carbon production: multiple applications in environmental protection and energy storage. *Bioresource Technology*, 2017, **227**: 359–372
59. Cha J S, Park S H, Jung S C, Ryu C, Jeon J K, Shin M C, Park Y K. Production and utilization of biochar: a review. *Journal of Industrial and Engineering Chemistry*, 2016, **40**: 1–15
60. Weber K, Quicker P. Properties of biochar. *Fuel*, 2018, **217**: 240–261
61. Leng L J, Huang H J, Li H, Li J, Zhou W G. Biochar stability assessment methods: a review. *Science of the Total Environment*, 2019, **647**: 210–222

62. Han L F, Ro K S, Wang Y, Sun K, Sun H R, Libra J A, Xing B S. Oxidation resistance of biochars as a function of feedstock and pyrolysis condition. *Science of the Total Environment*, 2018, **616-617**: 335–344
63. Hernández J J, Saffe A, Collado R, Monedero E. Recirculation of char from biomass gasification: effects on gasifier performance and end-char properties. *Renewable Energy*, 2020, **147**: 806–813
64. Shen Q Q, Liaw S B, Costa M, Wu H W. Rapid pyrolysis of pulverized biomass at a high temperature: the effect of particle size on char yield, retentions of alkali and alkaline earth metallic species, and char particle shape. *Energy & Fuels*, 2020, **34**(6): 7140–7148
65. Várhegyi G, Wang L, Skreiberg Ø. Empirical kinetic models for the CO₂ gasification of biomass chars. Part I. Gasification of wood chars and forest residue chars. *ACS Omega*, 2021, **6**(41): 27552–27560
66. Chen W H, Peng J, Bi X T. A state-of-the-art review of biomass torrefaction, densification and applications. *Renewable & Sustainable Energy Reviews*, 2015, **44**: 847–866
67. Labbé R, Paczkowski S, Knappe V, Russ M, Wöhler M, Pelz S. Effect of feedstock particle size distribution and feedstock moisture content on pellet production efficiency, pellet quality, transport and combustion emissions. *Fuel*, 2020, **263**: 116662
68. Khaledi S, Delbari M, Galavi H, Bagheri H, Chari M M. Effects of biochar particle size, biochar application rate, and moisture content on thermal properties of an unsaturated sandy loam soil. *Soil & Tillage Research*, 2023, **226**: 105579
69. Mun J S, Mun S P. Structural and thermal characterization of milled wood lignin from bamboo (*Phyllostachys pubescens*) grown in Korea. *Molecules*, 2023, **29**(1): 183
70. Premchand P, Demichelis F, Chiaramonti D, Bensaid S, Fino D. Biochar production from slow pyrolysis of biomass under CO₂ atmosphere: a review on the effect of CO₂ medium on biochar production, characterisation, and environmental applications. *Journal of Environmental Chemical Engineering*, 2023, **11**(3): 110009
71. Prabha B, Pugalendhi S, Subramanian P. Design and development of semi-indirect non-electric pyrolytic reactor for biochar production from farm waste. *Indian Journal of Agricultural Sciences*, 2015, **85**(4): 585–591
72. Thomas S C. Post-processing of biochars to enhance plant growth responses: a review and meta-analysis. *Biochar*, 2021, **3**(4): 437–455
73. Osman A I, Fawzy S, Farghali M, El-Azazy M, Elgarahy A M, Fahim R A, Maksoud M A, Ajlan A A, Yousry M, Saleem Y, Rooney D W. Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: a review. *Environmental Chemistry Letters*, 2022, **20**: 2385–2485
74. Ronsse F, Van Hecke S, Dickinson D, Prins W. Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *Global Change Biology. Bioenergy*, 2013, **5**(2): 104–115
75. Deng Y X, Zhang T, Wang Q M. Biochar adsorption treatment for typical pollutants removal in livestock wastewater: a review. In: Huang Wujang, ed. *Engineering Applications of Biochar. InTech*, 2017
76. 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
77. Zhang H, Voroney R P, Price G W. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. *Soil Biology & Biochemistry*, 2015, **83**: 19–28
78. Premchand P, Demichelis F, Fino D, Chiaramonti D, Bensaid S. Study on the effects of carbon dioxide atmosphere on the production of biochar derived from slow pyrolysis of organic agro-urban waste. *Waste Management*, 2023, **172**: 308–319
79. Klasson K T, Boiher L L Jr, Uchimiya M, Lima I M. Influence of biochar pyrolysis temperature and post-treatment on the uptake of mercury from flue gas. *Fuel Processing Technology*, 2014, **123**: 27–33
80. 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
81. Jindo K, Mizumoto H, Sawada Y, Sanchez-Monedero M A, Sonoki T. Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeosciences*, 2014, **11**(23): 6613–6621
82. Suliman W, Harsh J B, Abu-Lail N I, Fortuna A M, Dallmeyer I, Garcia-Perez M. Influence of feedstock source and pyrolysis temperature on biochar bulk and surface properties. *Biomass and Bioenergy*, 2016, **84**: 37–48
83. Aslam M M A, Kuo H W, Den W, Usman M, Sultan M, Ashraf H. Functionalized carbon nanotubes (CNTs) for water and wastewater treatment: preparation to application. *Sustainability*, 2021, **13**(10): 5717
84. Baratta M, Nezhdanov A V, Mashin A I, Nicoletta F P, De Filipo G. Carbon nanotubes buckypapers: a new frontier in wastewater treatment technology. *Science of the Total Environment*, 2024, **924**: 171578
85. Joseph S D, Camps-Arbestain M, Lin Y, Munroe P, Chia C H, Hook J M, Van Zwielen L, Kimber S, Cowie A L, Singh B P, Lehmann J, Foidl N, Smernik R J, Amonette J E J. An investigation into the reactions of biochar in soil. *Soil Research*, 2010, **48**(7): 501–515
86. Hale S E, Lehmann J, Rutherford D, Zimmerman A R, Bachmann R T, Shitumbanuma V, O'Toole A, Sundqvist K L, Arp H P H, Cornelissen G. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. *Environmental Science & Technology*, 2012, **46**(5): 2830–2838
87. Weber K, Heuer S, Quicker P, Li T, Løvås T, Scherer V. An

- alternative approach for the estimation of biochar yields. *Energy & Fuels*, 2018, **32**(9): 9506–9512
88. Mukherjee A, Zimmerman A R. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. *Geoderma*, 2013, **193–194**: 122–130
89. Fidel R B, Laird D A, Thompson M L, Lawrinenko M. Characterization and quantification of biochar alkalinity. *Chemosphere*, 2017, **167**: 367–373
90. Patel A, Sharma D, Kharkar P, Mehta D. Application of activated carbon in waste water treatment. *International Journal of Engineering Applied Sciences and Technology*, 2019, **3**(12): 63–66
91. Weiss-Hortala E, Chesnaud A, Haurie L, Lyczko N, Munirathinam R, Nzihou A, Patry S, Pham Minh D, White C E. Handbook on Characterization of Biomass, Biowaste and Related By-products. In: Nzihou A, ed. Berlin: Springer International Publishing, 2020, 1307–1387
92. Garbisu C, Garaiyurrebaso O, Lanzén A, Álvarez-Rodríguez I, Arana L, Blanco F, Smalla K, Grohmann E, Alkorta I. Mobile genetic elements and antibiotic resistance in mine soil amended with organic wastes. *Science of the Total Environment*, 2018, **621**: 725–733
93. Nguyen D D D, Phan Quang H H, Nguyen X H, Nguyen T P. The treatment of real dyeing wastewater by the electro-Fenton process using drinking water treatment sludge as a catalyst. *RSC Advances*, 2021, **11**(44): 27443–27452
94. Naghdi M, Taheran M, Brar S K, Kermanshahi-pour A, Verma M, Surampalli R Y. Immobilized laccase on oxygen functionalized nanobiochars through mineral acids treatment for removal of carbamazepine. *Science of the Total Environment*, 2017, **584–585**: 393–401
95. Naghdi M, Taheran M, Pulicharla R, Rouissi T, Brar S K, Verma M, Surampalli R Y. Pine-wood derived nanobiochar for removal of carbamazepine from aqueous media: adsorption behavior and influential parameters. *Arabian Journal of Chemistry*, 2019, **12**(8): 5292–5301
96. Savage N, Diallo M S. Nanomaterials and water purification: opportunities and challenges. *Journal of Nanoparticle Research*, 2005, **7**(4-5): 331–342
97. Anjum M, Miandad R, Waqas M, Gehany F, Barakat M A. Remediation of wastewater using various nano-materials. *Arabian Journal of Chemistry*, 2019, **12**(8): 4897–4919
98. Mohan D, Sarswat A, Ok Y S, Pittman C U Jr. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent—A critical review. *Bioresource Technology*, 2014, **160**: 191–202
99. Rangabhashiyam B. The potential of lignocellulosic biomass precursors for biochar production: performance, mechanism and wastewater application—A review. *Industrial Crops and Products*, 2019, **128**: 405–423
100. Singh A. A review of wastewater irrigation: environmental implications. *Resources, Conservation and Recycling*, 2021, **168**: 105454
101. Rajapaksha A U, Chen S S, Tsang D C W, Zhang M, Vithanage M, Mandal S, Gao B, Bolan N S, Ok Y S. Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. *Chemosphere*, 2016, **148**: 276–291
102. Zhang A, Li X, Xing J, Xu G. Adsorption of potentially toxic elements in water by modified biochar: a review. *Journal of Environmental Chemical Engineering*, 2020, **8**(4): 104196
103. Nadarajah K, Asharp T, Jeganathan Y. Biochar from waste biomass, its fundamentals, engineering aspects, and potential applications: an overview. *Water Science and Technology*, 2024, **89**(5): 1211–1239
104. Yao Y, Gao B, Chen J, Zhang M, Inyang M, Li Y, Alva A, Yang L. Engineered carbon (biochar) prepared by direct pyrolysis of Mg-accumulated tomato tissues: characterization and phosphate removal potential. *Bioresource Technology*, 2013, **138**: 8–13
105. Zeng H P, Qi W, Zhai L X, Wang F S, Zhang J, Li D. Preparation and characterization of sludge-based magnetic biochar by pyrolysis for methylene blue removal. *Nanomaterials*, 2021, **11**(10): 2473
106. Kefeni K K, Mamba B B, Msagati T A M. Application of spinel ferrite nanoparticles in water and wastewater treatment: a review. *Separation and Purification Technology*, 2017, **188**: 399–422
107. Rayhan T H, Yap C N, Yulisa A, Rubiyatno, Popescu I, Alvarez J A, Kristanti R A. Engineered nanoparticles for wastewater treatment system. *Civil and Sustainable Urban Engineering*, 2022, **2**(2): 56–66
108. Amusat S O, Kebede T G, Dube S, Nindi M M. Ball-milling synthesis of biochar and biochar-based nanocomposites and prospects for removal of emerging contaminants: a review. *Journal of Water Process Engineering*, 2021, **41**: 101993
109. Khader E H, Muslim S A, Saady N M C, Ali N S, Salih I K, Mohammed T J, Albayati T M, Zendeheboudi S. Recent advances in photocatalytic advanced oxidation processes for organic compound degradation: a review. *Desalination and Water Treatment*, 2024, **318**: 100384
110. Hnamte M, Pulikkal A K. Clay-polymer nanocomposites for water and wastewater treatment: a comprehensive review. *Chemosphere*, 2022, **307**: 135869
111. Liu Y C. Application of graphene oxide in water treatment. *IOP Conference Series. Earth and Environmental Science*, 2017, **94**: 012060
112. Anegebe B, Ifijen I H, Maliki M, Uwidia I E, Aigbodion A I. Graphene oxide synthesis and applications in emerging contaminant removal: a comprehensive review. *Environmental Sciences Europe*, 2024, **36**: 15
113. Panigrahy S K, Nandha A, Chaturvedi M, Mishra P K. Novel nanocomposites with advanced materials and their role in waste water treatment. *Next Sustainability*, 2024, **4**: 100042
114. Xiang W, Zhang X Y, Chen J J, Zou W X, He F, Hu X, Tsang D C W, Ok Y S, Gao B. Biochar technology in wastewater treatment: a critical review. *Chemosphere*, 2020, **252**: 126539

115. Enaime G, Baçaoui A, Yaacoubi A, Lübken M. Biochar for wastewater treatment—Conversion technologies and applications. *Applied Sciences*, 2020, **10**(10): 3492
116. Nicolais L, Carotenuto G. Metal-Polymer Nanocomposites. Canada: *John Wiley & Sons*, 2004
117. Sahu A, Dosi R, Kwiatkowski C, Schmal S, Poler J C. Advanced polymeric nanocomposite membranes for water and wastewater treatment: a comprehensive review. *Polymers*, 2023, **15**(3): 540
118. Wang S G, Xu Y, Norbu N, Wang Z. Remediation of biochar on heavy metal polluted soils. *IOP Conference Series. Earth and Environmental Science*, 2018, **108**: 042113
119. Conte P, Bertani R, Sgarbossa P, Bambina P, Schmidt H P, Raga R, Lo Papa G, Chillura Martino D F, Lo Meo P. Recent developments in understanding biochar's physical–chemistry. *Agronomy*, 2021, **11**(4): 615
120. Kant Bhatia S, Palai A K, Kumar A, Kant Bhatia R, Kumar Patel A, Kumar Thakur V, Yang Y H. Trends in renewable energy production employing biomass-based biochar. *Bioresource Technology*, 2021, **340**: 125644
121. Díaz B, Sommer-Márquez A, Ordoñez P E, Bastardo-González E, Ricaurte M, Navas-Cárdenas C. Synthesis methods, properties, and modifications of biochar-based materials for wastewater treatment: a review. *Resources*, 2024, **13**(1): 8
122. Rajapaksha P, Power A, Chandra S, Chapman J. Graphene, electrospun membranes and granular activated carbon for eliminating heavy metals, pesticides and bacteria in water and wastewater treatment processes. *Analyst*, 2018, **143**(23): 5629–5645
123. Amdeha E. Biochar-based nanocomposites for industrial wastewater treatment via adsorption and photocatalytic degradation and the parameters affecting these processes. *Biomass Conversion and Biorefinery*, 2024, **14**(19): 23293–23328
124. Wang J L, Wang S Z. Preparation, modification and environmental application of biochar: a review. *Journal of Cleaner Production*, 2019, **227**: 1002–1022
125. Liu W J, Jiang H, Yu H Q. Emerging applications of biochar-based materials for energy storage and conversion. *Energy & Environmental Science*, 2019, **12**(6): 1751–1779
126. Zhao B, O'Connor D, Zhang J L, Peng T Y, Shen Z T, Tsang D C W, Hou D Y. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. *Journal of Cleaner Production*, 2018, **174**: 977–987
127. Shan R, Han J, Gu J, Yuan H R, Luo B, Chen Y. A review of recent developments in catalytic applications of biochar-based materials. *Resources, Conservation and Recycling*, 2020, **162**: 105036
128. Olugbenga O S, Adeleye P G, Oladipupo S B, Adeleye A T, John K I. Biomass-derived biochar in wastewater treatment- a circular economy approach. *Waste Management Bulletin*, 2023, **1**(4): 1–14
129. Mishra E, Kapse S, Jain S. Consideration About Regeneration, Reactivity, Toxicity, and Challenges of Biochar-Based Nanocomposites. *Biochar-Based Nanocomposites for Contaminant Management*. Cham: *Springer International Publishing*, 2023, 107–118
130. Huang Q, Song S, Chen Z, Hu B W, Chen J R, Wang X K. Biochar-based materials and their applications in removal of organic contaminants from wastewater: state-of-the-art review. *Biochar*, 2019, **1**(1): 45–73
131. Park J H, Wang J J, Meng Y L, Wei Z, DeLaune R D, Seo D C. Adsorption/desorption behavior of cationic and anionic dyes by biochars prepared at normal and high pyrolysis temperatures. *Colloids and Surfaces. A, Physicochemical and Engineering Aspects*, 2019, **572**: 274–282
132. Frišták V, Pipiška M, Lesný J, Soja G, Friesl-Hanl W, Packová A. Utilization of biochar sorbents for Cd²⁺, Zn²⁺, and Cu²⁺ ions separation from aqueous solutions: comparative study. *Environmental Monitoring and Assessment*, 2015, **187**(1): 4093
133. Fang G D, Liu C, Wang Y J, Dionysiou D D, Zhou D M. Photogeneration of reactive oxygen species from biochar suspension for diethyl phthalate degradation. *Applied Catalysis B: Environmental*, 2017, **214**: 34–45
134. Reza M S, Afroze S, Bakar M S A, Saidur R, Aslfattahi N, Taweekun J, Azad A K. Biochar characterization of invasive *Pennisetum purpureum* grass: effect of pyrolysis temperature. *Biochar*, 2020, **2**(2): 239–251
135. Zhang K M, Deng Y P, Liu Z Q, Feng Y P, Hu C, Wang Z. Biochar facilitated direct interspecies electron transfer in anaerobic digestion to alleviate antibiotics inhibition and enhance methanogenesis: a review. *International Journal of Environmental Research and Public Health*, 2023, **20**(3): 2296
136. Zhang J, Gu M, Chen X. Supercapacitors for renewable energy applications: a review. *Micro and Nano Engineering*, 2023, **21**: 100229
137. Dai Y J, Wang W S, Lu L, Yan L L, Yu D Y. Utilization of biochar for the removal of nitrogen and phosphorus. *Journal of Cleaner Production*, 2020, **257**: 120573
138. European Biochar Foundation. European Biochar Certificate—Guidelines for a Sustainable Production of Biochar: Version 6.1 of 19th June 2015, Arbaz, Switzerland. 2012, Available at European Biochar Foundation website on September 7, 2023
139. British Biochar Foundation. Biochar Quality Mandate(BQM) v. 1.0: Version for public consultation, Edinburgh, United Kingdom. Available at European Biochar Foundation website on September 7, 2023
140. European Commission. Roadmap: Revision of the Fertilisers Regulation (EC) No 2003/2003, 2016. Available at European Commission website on September 7, 2023
141. Shackley S, Carter S, Knowles T, Middellink E, Haefele S M, Sohi S, Cross A, Haszeldine R S. Sustainable gasification–biochar systems? A case-study of rice-husk gasification in Cambodia, Part I: context, chemical properties, environmental and health and safety issues. *Energy Policy*,

- 2012, **42**: 49–58
142. Gonzalez J M, Shipitalo M J, Smith D R, Warnemuende-Pappas E, Livingston S J. Atrazine sorption by biochar, tire chips, and steel slag as media for blind inlets: a kinetic and isotherm sorption approach. *Journal of Water Resource and Protection*, 2016, **8**(13): 1266–1282
143. Siwal S S, Zhang Q B, Devi N, Saini A K, Saini V, Pareek B, Gaidukovs S, Thakur V K. Recovery processes of sustainable energy using different biomass and wastes. *Renewable & Sustainable Energy Reviews*, 2021, **150**: 111483
144. Carvalho J, Nascimento L, Soares M, Valério N, Ribeiro A, Faria L, Silva A, Pacheco N, Araújo J, Vilarinho C. Life cycle assessment (LCA) of biochar production from a circular economy perspective. *Processes*, 2022, **10**(12): 2684
145. Gonzalez J, Sargent P, Ennis C J. Sewage treatment sludge biochar activated blast furnace slag as a low carbon binder for soft soil stabilisation. *Journal of Cleaner Production*, 2021, **311**(6): 127553