Biochar-based composites as environmentally sustainable functional materials for wastewater treatment

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Abstract

Given the pressing global concerns surrounding water scarcity, it is imperative to explore innovative solutions for wastewater treatment. The current chapter delves into the potential of Biochar-based composites as promising tools in addressing this issue. It begins by elucidating the process of producing biochar from biomass, typically through methods like pyrolysis, emphasizing its utility in water treatment. Furthermore, it highlights the enhanced efficacy achieved by combining biochar with other materials. The chapter goes on to detail how these biochar-based composites play a crucial role in combatting water pollution and mitigating freshwater scarcity. Their eco-friendly nature is underscored as a transformative factor in reshaping conventional treatment approaches, which often come with inherent drawbacks. One of the key strengths of biochar lies in its surface properties and porous structure, and these attributes are elucidated with illustrative examples. Various production methods, primarily centered around pyrolysis, are discussed for their impact on biochar's properties. Functionalization through composite materials is explored as a means to address limitations. The chapter also showcases different types of composites, including polymers and nano-biochar composites, which excel in removing pollutants from water. The critical aspect of sustainability is emphasized, emphasizing the need to strike a balance between effectiveness, stability, safety, and cost-effectiveness. In summary, this chapter paints a comprehensive picture of biochar-based composites as promising and sustainable tools for mitigating water pollution, offering hope in the face of the global water crisis.

Key points

- Biochar Composites for Sustainable Wastewater Treatment: Biochar-based composites offer sustainable solutions for wastewater treatment.
- Economical and Eco-friendly Adsorbent: Biochar's cost-effectiveness and eco-friendliness make it a potent adsorbent for environmental issues.
- Pyrolysis in Biochar Production: Pyrolysis is the widely accepted method for biochar production.
- Feedstock Influence on Biochar: Different feedstocks significantly affect biochar's properties, including appearance, chemical, and physical attributes.
- Effectiveness of Biochar Adsorbent: Biochar's adsorption effectiveness depends on understanding and evaluating its unique characteristics.
- Biochar Composites for Environmental Challenges: Biochar composites provide customizable and sustainable solutions for environmental contamination.
- Enhanced Functionality: Combining biochar with other materials enhances its functional properties.

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- Complex Pollutant Removal Mechanisms: Pollutant removal involves intricate physical and chemical interactions for capturing and mitigating contaminants.
- Balanced Design for Sustainability: Designing biochar and its modified forms should prioritize sustainability.
- Biochar's Role in Sustainable Development: Utilizing biochar and its composites aligns with Sustainable Development Goals, emphasizing its importance.

1 Introduction

Water, essential for our existence, forms the very essence of life, providing vitality that sustains us. Within the realm of the planet's water supply, a mere 0.14% stands as the available resource. However, in the face of persistent growth in population and economic activities, the water demand is surging at approximately 1% each year. As the world's population continues to expand alongside urbanization and industrialization, the strain on water resources has become increasingly evident. This pressing challenge underscores the critical need for innovative approaches to wastewater treatment that can effectively manage and alleviate the burden on freshwater sources. The history of wastewater treatment spans millennia, originating in ancient civilizations like Rome and the Indus Valley. However, modern wastewater treatment emerged around the sixteenth century and progressed gradually, where physical, chemical, and biological treatment methods began to take shape—the twentieth century marked significant advancements, shaping our understanding of wastewater treatment from then until today. Early 1900s methods encompassed filtration, settling, and septic tanks, alongside disinfection through chlorination. Subsequent years saw the refinement of treatment techniques, particularly for odor, color, and solid removal. Techniques such as adsorption, ion exchange, coagulation, and chemical treatments gained prominence. Post-1950, wastewater treatment transformed markedly, spurred by rapid global industrialization, driven by the emergence of new technologies, novel materials, processes, and equipment configurations (Shojaei and Shojaei, 2021).

Biochar-based composites have emerged as a promising avenue in pursuing environmentally sustainable solutions. Biochar, a carbon-rich material derived from biomass through processes like pyrolysis and hydrothermal carbonization, possesses unique physicochemical properties, making it an excellent candidate for water treatment applications. Integrating biochar with other functional materials in composite structures further enhances its capabilities and widens its applicability.

This chapter aims to delve into the intricate realm of biochar-based composites for wastewater treatment. By understanding the synergistic effects of biochar and various composite constituents, we can harness their combined potential to address water pollution challenges effectively. The underlying motivation for this exploration lies in the urgent need to balance the escalating water demand with the limited availability of freshwater resources. Moreover, the drive toward sustainability and the desire to mitigate the adverse impacts of conventional treatment methods underscores the significance of biochar-based composites as an eco-friendly solution. Through an in-depth analysis of the background and current state of research, this chapter seeks to lay the foundation for comprehending the role of biochar-based composites in revolutionizing wastewater treatment. By exploring these materials' benefits, challenges, and potential applications, we can contribute to advancing sustainable practices that ensure clean water for present and future generations.

1.1 Emerging trends in sustainable materials for wastewater treatment

There is a critical need to embrace and develop sustainable water treatment techniques that integrate cutting-edge technologies to ensure the availability of safe and clean water resources for future generations (Kumar et al., 2022). Recently, physical, chemical, and biological techniques have been widely used to treat wastewater effectively (Piaskowski et al., 2018; Kumar et al., 2012). These traditional treatment methods are associated with drawbacks, including low efficiency, generation of toxic sludge, high cost and energy consumption, complex regeneration processes, poor reusability, and introduction of potentially harmful chemicals into the environment (Bilal et al., 2022). Consequently, there is a growing recognition of the need for environmentally friendly technologies to efficiently treat wastewater to mitigate adverse impacts on the environment, human health, and natural water resources, as emphasized by (Al-Tohamy et al., 2022).

Therefore, most researchers have paid attention to the adsorption method using various adsorbents, like activated carbon, non-conventional adsorbents like agricultural by-products and waste, industrial wastes, biomass-based materials, natural and synthetic bio adsorbents, nanomaterials, composites and their hybrids, metal-organic frameworks, polymeric substances, chitosan-based materials, polyaniline based materials, carbon nanotubes, and other novel materials have been reported that work effectively for wastewater treatment (Sabzehmeidani et al., 2021; Ahmad, 2023; Crini et al., 2019).

Given that current adsorbent materials are neither economically feasible nor environmentally friendly, the solution appears to lie in the fabrication, development, and reliance on eco-friendly and sustainable materials. This can be achieved through the valorization of locally-sourced waste materials, which can then be utilized as adsorbents, flocculants/coagulants, or photocatalysts in both current and future wastewater treatment facilities (Ngeno et al., 2022).

2 Biochar as an adsorbent

Biochar (BC) is a stable, fine-grained, and carbon-rich material formed during the thermochemical decomposition of feedstock material through different heating methods. The substantial presence of surface functional groups such as hydroxyl, carboxyl, and amino, coupled with their notable porosity and expansive surface area, contribute to the remarkable adsorption efficiency exhibited by biochar-based adsorbents. In addition to its exceptional adsorption capabilities, biochar offers several benefits, including sustainability, easy synthesis, facile functionalization, enduring structural integrity, improved physicochemical characteristics, and the potential for recycling (Akl et al., 2021).

Various techniques can be employed to manufacture biochar, including pyrolysis, flash carbonization, hydrothermal carbonization, gasification, and torrefaction (Fig. 1).

However, pyrolysis is the most commonly used and widely accepted method for biochar production. In pyrolysis, high temperatures (above 300 °C) are applied to heat biomass without oxygen (O^2). The organic components undergo thermal decomposition and vaporize during this procedure, while the remaining solid phase transforms into biochar. There are two types of pyrolysis based on the variation in the heating rate:

(i) ***Fast pyrolysis*** - Fast pyrolysis entails rapidly heating the biomass or feedstock at a high rate (typically exceeding 300 °C/min) for a short residence time, usually less than 60 min, without oxygen. This process typically yields a low-energy-density gas called syngas (5% to 20%) and a high-energy-density liquid called bio-oil (50% to 70%) and biochar1 (0% to 30%). (ii) ***Slow pyrolysis***- Slow pyrolysis, in contrast, entails gradually heating the biomass or feedstock within a range of temperatures spanning from 300 °C to 800 °C, utilizing a slower heating rate, typically exceeding 5 °C to 7 °C per minute. This method involves a prolonged residence time, typically more than 60 min, in an oxygen-deprived environment. As a result, slow pyrolysis generally yields a higher proportion of biochar than fast pyrolysis. Typically, slow pyrolysis results in an approximate composition of 35% syngas, 30% bio-oil, and 35% biochar.

Biochars derived from the thermal degradation of various biological feedstocks exhibit different compositions and chemistry. Thus, we can say that features of biochar are notably shaped by factors such as the feedstock's nature and type, as well as the pyrolysis conditions, which encompass elements like time and temperature. The basic feedstock materials significantly influence the properties of the resultant biochar. It is primarily produced using waste materials from various industries like agriculture, aquaculture, wood processing, and fiber processing, making it eco-friendly. Organic waste sources like weeds, slaughterhouse waste, and municipal waste can be used as feedstocks for biochar production (Fig. 2). Different feedstocks significantly

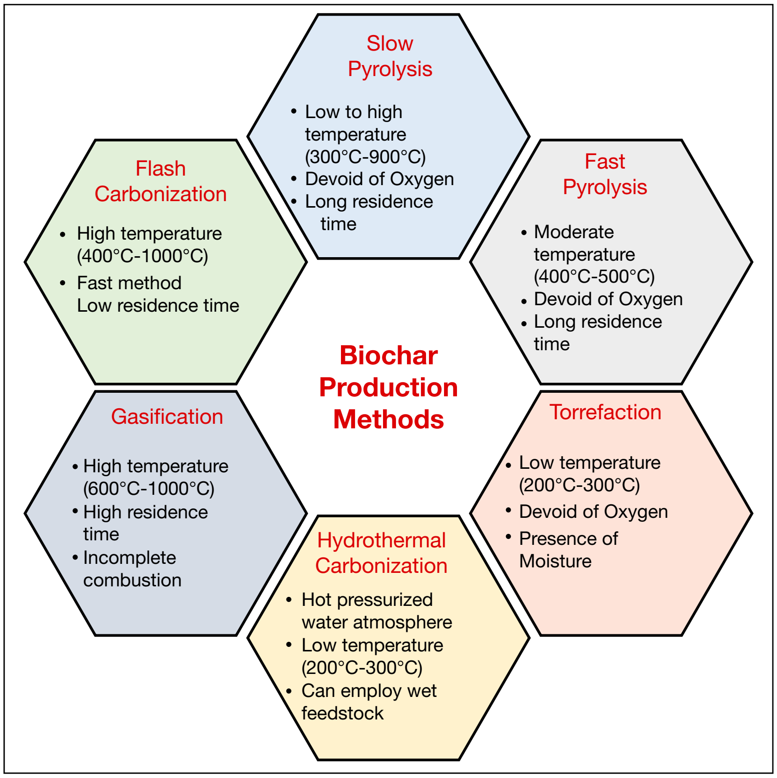

Fig. 1 Biochar production methods and their features.

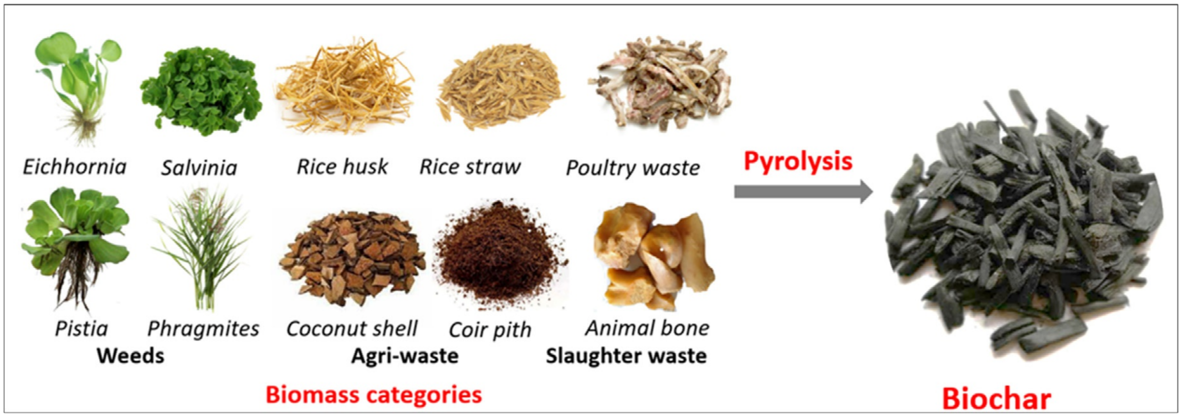

Fig. 2 Biochar preparation.

Fig. 3 Biochar prepared from various feedstocks.

influence biochar's physical appearance apart from its chemical and physical properties, as shown in Fig. 3. Wood-based biochars have higher carbon content and lower levels of plant-available nutrients. In contrast, manure-based biochars exhibit opposite trends, while grass-based biochars generally exhibit intermediate characteristics between woody and manure biochars (Ippolito et al., 2020).

Increasing pyrolysis temperature also influences final biochar composition and characteristics. As observed by previous studies, there was an augmentation in the specific surface area as the pyrolysis temperature rose. This phenomenon results from the solid matrix contracting, which reduces the size of relatively large pores, consequently elevating the overall specific surface area. Additionally, the higher pyrolysis temperature was evident in the increased ash content and pH of the biochar, owing to the increased presence of solid-phase hydroxide and carbonate components within the ash, resulting in a concurrent increase in pH values (Ippolito et al., 2020).

3 Biochar characterization

Characterizing biochar is crucial for assessing its inherent properties because adsorption efficiency is directly linked to physicochemical features like functional groups, surface area, cation exchange capacity, and more. In other words, the effectiveness of biochar as an adsorbent depends on understanding and evaluating its specific characteristics.

The International Biochar Initiative (IBI), a United States-based NGO that operates globally to support a sustainable biochar industry, has developed and established systematic frameworks with standardized methods for characterizing biochar materials to enhance product quality uniformity across the biochar industry. Various methods can be employed to quantitatively and qualitatively characterize biochar. One common approach is proximate analysis, which follows the ASTM Standard Practice for Proximate Analysis of Coal and Coke (D 3172) and provides information on moisture (M), Volatile Matter (VM), Ash content (AC), and Fixed Carbon (FC) percentage in the biochar samples. In addition to proximate analysis, sophisticated and modern techniques like field emission scanning electron microscopy (Fe-SEM), Fourier Transform Infrared Spectrometer (FTIR), Thermo Gravimetric Analysis (TGA), X-ray diffraction (XRD), Brunauer Emmett Teller (BET), and Atomic Force Microscope (AFM), inductively coupled plasma mass spectrometry (ICP-MS) are employed for the comprehensive characterization of biochar and related sample s.

For better understanding, we provide the critical characterization details of biochar prepared from water hyacinth (*Eichhornia crassipes*) (Viswanathan et al., 2022). The biochar produced from Eichhornia weed stems, referred to as ECBC, displayed noticeable variations based on the type of feedstock and the pyrolysis temperature used. A thorough analysis of ECBC unveiled its distinct chemical and physical characteristics.

The proximal and ultimate analyses of the resulting biochar are summarized in Table 1. ECBC exhibits a notably high alkaline nature, with a pH of approximately 8.2, a typical characteristic of biochar derived from biomass sources. The biochar contains approximately 28.3% volatile matter (VM), 9.6% ash content (AC), and 65.35% fixed Carbon (FC). The abundance of biomass components, particularly hemicellulose, cellulose, and lignin, significantly contributes to the high FC content, with variations in thermal stability among these components. The FC content serves as an indicator of the aromatic nature of the biochar, and this characteristic is closely linked to both the pyrolysis temperature and the lignocellulosic composition of the initial feedstock (Fig. 4).

The images clearly show an increase in surface area and pore volumes, likely attributable to the gradual breakdown of organic materials like hemicelluloses, cellulose, and lignin, as well as the development of vascular bundles or channel structures during the pyrolysis process. The appearance of micro and macro-pores is distinctly seen. EDX spectrum verified the presence of various organic and inorganic elements in the biochar. Strong signals of inorganic elements (Si, K, Cl, Ca, Fe, Na, and S) were detected in the EDS spectra.

Table 1 pH, Electrical conductivity (EC), and proximate analysis of *Eichhornia* biochar.

Parameters	*Value*
pH	8.2 ± 0.5
EC(μScm^{-1})	532.4 ± 0.9
Proximate analysis	
Moisture (%)	2.3 ± 0.85
Volatile matter (%)	28.3 ± 0.5
Fixed carbon (%)	65.35 ± 1.2
Ash Content (%)	9.6 ± 0.65

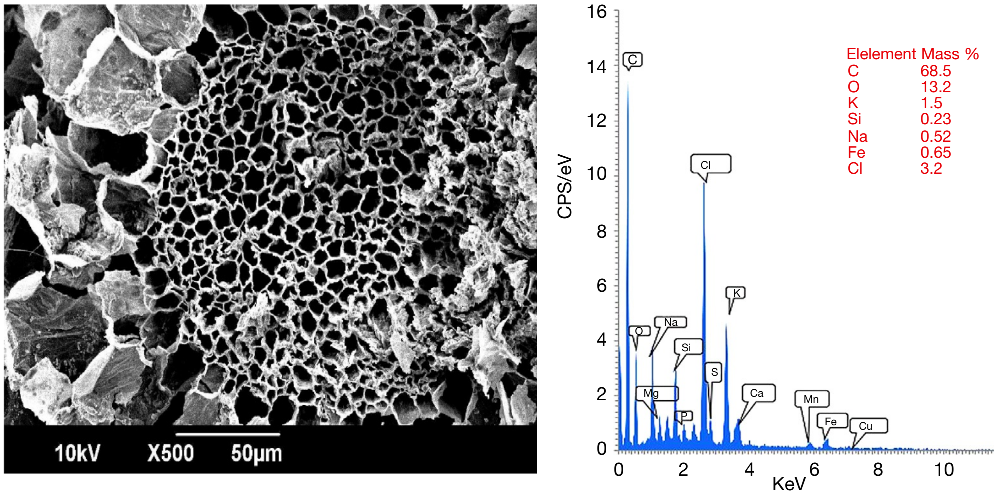

Fig. 4 SEM images of *Eichhornia* biochar and EDS spectrogram.

The carbonization process induced the emergence of major peaks signifying aromatic structures and polymerization (Fig. 5). These include the aromatic C—H out-of-plane deformation at 782 cm^{-1}, C—C stretching vibrations at 1400 cm^{-1}, and robust aromatic C═C and C═O stretching modes indicating conjugated ketones and quinones at 1600 cm^{-1}. The presence of lignocellulosic content in the biochar was evident through the specific band at 1450 cm^{-1}. Thus, the FTIR spectrum of Eichhornia biochar prior to adsorption highlights the presence of diverse functional groups.

The thermal analysis of weed biomass reveals its stability through three distinct weight loss phases from 100 to 600 °C (Fig. 6). Phase I (25–150 °C) involves initial weight loss due to moisture removal. Phase II (peak at 313.89 °C) represents devolatilization and biochar combustion, characterized by a broad peak between 250 and 420 °C, indicating the breakdown of hemicellulose and

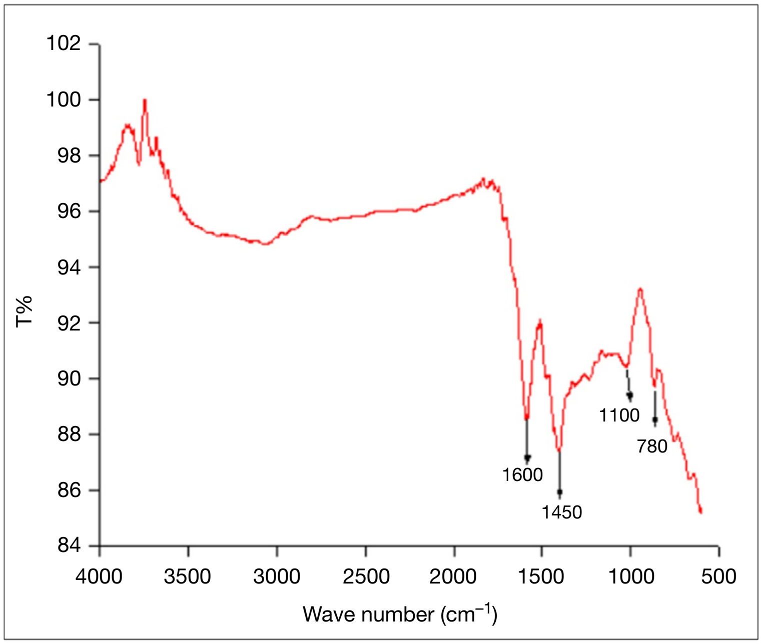

Fig. 5 FTIR spectra of *Eichhornia* biochar.

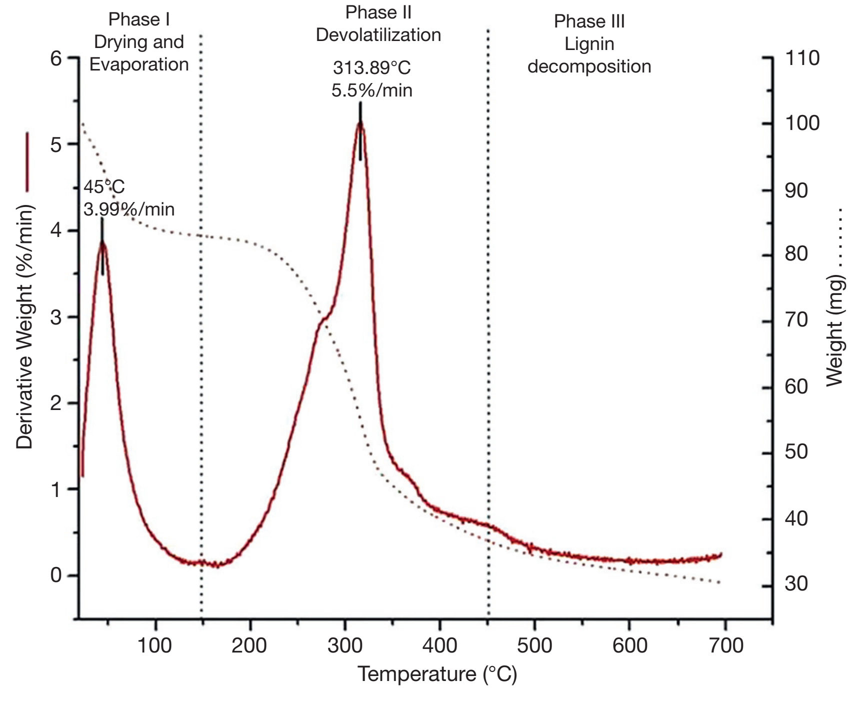

Fig. 6 TGA spectra of *Eichhornia* biochar.

cellulose content. Phase III signifies the degradation of remaining lignin and cellulose, contributing to thermal stability. The low ash content (28.6%) indicates high-quality biochar, representing the percentage of biochar remaining after organic fraction decomposition at a constant 550 °C temperature.

4 Functionalization of biochar

Biochar is commonly used for removing dyes, heavy metals, and inorganic pollutants from wastewater, acting as a sorbent or catalyst. Despite its affordability and versatility in source materials, biochar has limitations in adsorption capacity. Pollutant removal efficiency depends on raw material properties, pyrolysis conditions, pollutant types, and reaction conditions. Furthermore, biochar, especially in crushed form with small particle size, lacks stability and reusability, making recovery from aqueous mixtures challenging. These constraints hinder its practical application in wastewater treatment despite its potential to reduce treatment costs. Introducing or loading functional materials onto biochar is employed to overcome these issues and create composites.

The term "biochar composite" generally denotes a material formed by blending biochar with other substances or materials, resulting in an amalgamated material designed for particular characteristics or intended uses. These composites aim to enhance biochar's performance and functionality for various applications. The selection of composite materials and proportions is tailored to the desired characteristics and intended use, taking advantage of biochar's unique attributes while mitigating inherent limitations such as finite adsorption capacity, specificity for certain pollutants, slow adsorption kinetics, regeneration challenges, competition with other ions, sensitivity to pH, potential effectiveness decline over time, and associated costs.

4.1 Advantages of biochar composites as adsorbent materials in water treatment

Biochar composites offer several advantages as adsorbents, making them an attractive choice for water treatment applications:

i. *Enhanced Adsorption Capacity*: Biochar composites often have a higher adsorption capacity than pristine biochar. This is because the additional materials in the composite can provide active sites and surface functionalities that increase the adsorption of target pollutants.
ii. *Tailored Properties:* The composition of biochar composites can be customized to target specific pollutants or contaminants. The composites can be designed to have optimal properties for a particular application by selecting appropriate additives or materials.
iii. *Improved Selectivity:* Biochar composites can be engineered to adsorb specific pollutants while ignoring others selectively. This selectivity can be crucial in water and air purification processes.
iv. *Reduced Leaching*: Some contaminants may leach from pure biochar over time, potentially contaminating the treated water or soil. Biochar composites can reduce this leaching by providing a protective matrix around the biochar.
v. *Enhanced Durability:* Composites can enhance biochar's structural integrity and stability, making it more durable. This is particularly important for long-term adsorption applications.
vi. *Versatility*: Biochar composites can be used in various environmental remediation processes, including wastewater treatment, soil remediation, and air purification, making them versatile solutions for environmental challenges.
vii. *Cost-Efficiency:* Depending on the choice of composite materials, biochar composites can be cost-effective, especially when using locally available or waste materials as additives.
viii. *Sustainability:* Biochar itself is often produced from renewable biomass sources, and by using waste materials in composites, the overall environmental footprint can be reduced, making these adsorbents more sustainable.
ix. *Regeneration*: Some biochar composites can be regenerated and reused, increasing their cost-effectiveness and sustainability.
x. *Scalability:* The production of biochar composites can be scaled up to meet the demands of large-scale environmental remediation projects.

Thus, biochar composites offer a promising solution for addressing environmental contamination and pollution challenges while providing performance, customization, and sustainability advantages.

4.2 Types, preparation, properties, application, and challenges of biochar composites

Biochar is a superior adsorbent due to its cost-effectiveness, eco-friendly nature, and versatile properties. It outperforms many polymeric and commercial adsorbents in pollutant removal. Its unique sorption properties, stemming from disordered valence sheets with active sites and a negatively charged surface, make it effective in attracting and removing contaminants. Additionally, its oxygen and nitrogen functional groups enhance adsorption through chemical interactions. Moreover, biochar's carbon matrix and electrical conductivity make it ideal for photocatalytic reactions, reducing electron/hole recombination and improving oxidation rates. These attributes position biochar as a compelling alternative to activated carbon in adsorption and photocatalysis applications. Despite these qualities, pristine biochar has limitations, including poor adsorption capacity for anionic pollutants, extended equilibrium times due to limited surface functional groups, and variability in properties based on biomass source and processing conditions. Separating biochar powders after use poses challenges and can lead to secondary pollution. To enhance its suitability for environmental applications, chemical methods like acid/base modification, metal salt or oxidizing agent treatment, and carbonaceous material modification are commonly employed, forming biochar composite materials. The major types of biochar composites are described as follows.

4.2.1 Polymer biochar composites

Polymer composites are multiphase materials reinforced with a filler, resulting in improved mechanical properties due to the synergistic effect of the two (Das et al., 2021). Biochar polymer composites represent a promising innovation in the realm of water treatment. Both natural and synthetic polymers can be employed to fabricate biochar polymer composites. They have also been classified based on their structural attributes, encompassing linear, branched, and crosslinked polymers (Berber, 2020). These materials leverage the exceptional adsorption capacity of biochar, derived from renewable biomass sources while integrating the structural stability and mechanical properties of polymers like nano cellulose (Fig. 7). Blending polymers with biochar can yield composite material with desired properties such as reduced density, increased toughness, enhanced stiffness, specific thermal characteristics, chemical and mechanical stability, and other traits tailored to their intended applications. In a pioneering study (Ghaffar et al., 2018), wood-derived biochar was blended with polymer polyvinylidene fluoride (PVdF) through a distinctive thermal phase inversion technique. The result was robust biochar polymer composite membranes with remarkable mechanical strength and a well-defined porous structure. These adaptable membranes addressed issues linked to using biochar particles directly as sorbents and showcased the potential for large-scale production, making them highly suitable for practical use.

Commonly used methods for preparing these composite materials include solution processing, melt processing, and *in-situ* polymerization techniques (Rahaman et al., 2019).

- Solution Processing: This processing method includes the dispersion of carbons within the polymer matrix, followed by the subsequent elimination of the solvent or dispersing agent from the mixture like in vacuum filtration
- Melt Processing: Instead of a solvent, the polymer substrate is melted and then intermixed with carbons like biochar using techniques such as shearing, extrusion, etc.
- In Situ Polymerization Process: In situ polymerization achieves even biochar filler dispersion in the polymer matrix. This method is especially valuable for creating unsuitable polymers for production using solution (for insoluble polymers) or melt mixing (for thermally unstable polymers) techniques.

Beyond their adsorption capabilities, these composites can be regenerated and reused, making them cost-effective and environmentally friendly options for water treatment. By tailoring their properties to specific needs and utilizing sustainable feedstocks, biochar polymer composites offer a compelling solution to enhance water quality and address environmental challenges while

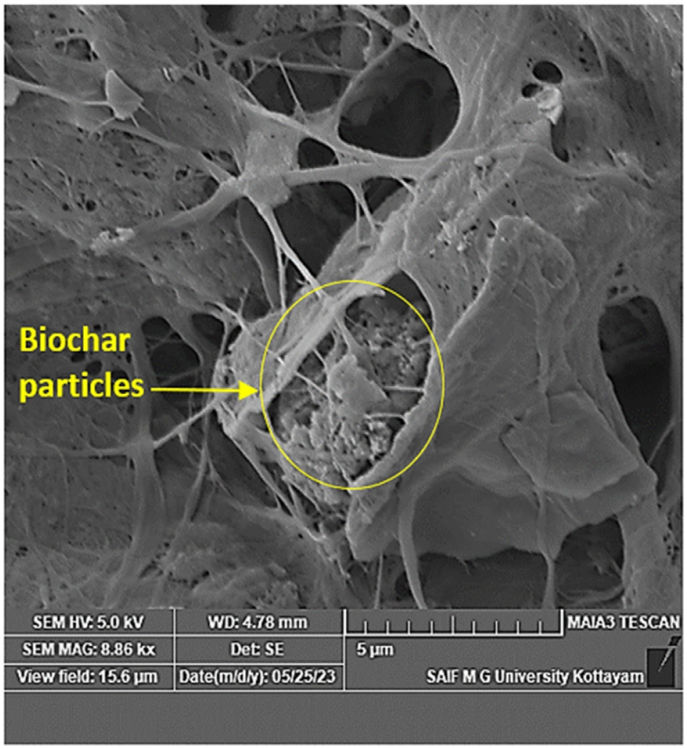

Fig. 7 SEM image of biochar nano cellulose membrane.

aligning with principles of resource efficiency and sustainability in water treatment processes. However, the extended environmental impact of these composites remains unclear, leading to concerns about the possible leaching of pollutants from the material into the environment.

4.2.2 Metal-biochar composites

Metal-biochar composites, integrating the best features of both materials, can be achieved by modifying biochar with specific metallic oxides and hydroxides. These composites address the limitations of using pristine biochar for contaminant removal from an aqueous medium. The main types of composites in this category include nano zero-valent iron (nZVI)–biochar, iron oxide–biochar, and iron sulfide–biochar composites. Metals such as Fe_3O^4 and $BiFeO_3$ possess unique attributes like ferromagnetism and catalytic capabilities. Besides, composites like MgO–biochar, MnO_x–biochar, and MoS_2–biochar composites are also innovative candidates (Wang et al., 2022). Combining biochar with metal or nanometallic oxides/hydroxides can impart additional functionalities to biochar or enhance its advantages through synergistic effects. Consequently, incorporating various metallic oxides/hydroxides into biochar has been recognized as a prudent approach for constructing highly efficient hybrid biochar materials.

Three distinct synthesis techniques are employed for the production of metal oxide/hydroxide-biochar composites:

- Bio-Accumulation for Target Element Enrichment: The first approach is that bio-accumulation within biomass allows for the concentration of specific chemical elements, which can then be harnessed to produce tailored biochar with the intended characteristics.
- Metal Salt Pretreatment of Biomass: The second approach involves the pretreatment of biomass using metal salts before the pyrolysis stage.
- Post-Pyrolysis Insertion of Metal Oxide Particles: The third method entails the introduction of metal oxide particles into the biochar after the pyrolysis process has taken place.

Depending on the composite's intended use, many types of metal may be used. Iron, copper, silver, and manganese are common metals utilized, although other metals can also be added depending on the desired function. Metal-biochar composites are promising materials for eliminating oxyanionic pollutants from wastewater when particular metals (in elemental, oxide/hydroxide, or layered double hydroxide form) are added to biochar (Li et al., 2018). Metal biochar composites exhibit high oxyanion removal capacities. The metal component can absorb impurities, promote chemical reactions, and improve remediation. For instance, groundwater contaminated with heavy metals or chlorinated chemicals is remedied using iron biochar composites (Li et al., 2018).

The creation and use of metal biochar composites present several difficulties, such as ensuring optimal metal dispersion within the biochar matrix, limiting the release of metals into the environment, and determining the long-term consequences on ecosystem health.

4.2.3 Magnetic-biochar composites

Biochar has demonstrated its promise as a proficient adsorbent for eliminating pollutants. Nevertheless, the challenge lies in separating powdered biochar from aqueous solutions. Magnetic biochar offers the advantage of easy separation from a solution using an external magnetic field and the potential for improved adsorption capacity by incorporating magnetic iron oxides. Moreover, the hybrid nature of magnetic biochar enables improved sorption of various inorganic and organic pollutants (Wang et al., 2018). The composition and properties of magnetic biochar can be tailored to target specific contaminants or applications, optimizing its effectiveness. Magnetic biochar can be regenerated and reused in some cases, enhancing its cost-effectiveness and sustainability.

Biochar can undergo conversion into magnetic materials through two distinct synthesis methods.

- Pre-treating biomass using iron ion: The initial approach involves saturating biomass with Fe^{3+}/Fe^{2+} ions or chemical co-precipitation of these ions onto the biomass and then pyrolyzing it. The resultant composite material exhibits impressive ferromagnetic characteristics and effective adsorption capabilities in aqueous solutions (Liang et al., 2022).
- Chemical co-precipitation: Another method for magnetic biochar composites production is direct chemical co-precipitation of Fe3+/Fe2+ on already prepared biochar (Wang et al., 2018).

Fig. 8 shows the Fe- SEM images of the magnetic biochar synthesized. Magnetic biochar is advantageous due to its easy recovery under a magnetic field, sustainable reuse after regeneration, effective photocatalytic carrier, and efficient recovery of precious metals through adsorption and enrichment (Li et al., 2020). However, challenges with magnetic biochar as an adsorbent include addressing potential environmental toxicity, understanding its transformation during remediation, and preventing the release of adsorbed pollutants to avoid secondary pollution (Yi et al., 2020) (Fig. 9).

4.2.4 Nano-biochar composites

Numerous experiments have focused on developing innovative biochar-based nanocomposites to expand the application scope of biochar. These involve loading biochar with diverse functional nanoparticles such as chitosan, graphene, graphene oxide, carbon nanotubes, ZnS nanocrystals, layered double hydroxides, nanoscale zero-valent iron, and graphitic C3N4, utilizing biochar as a

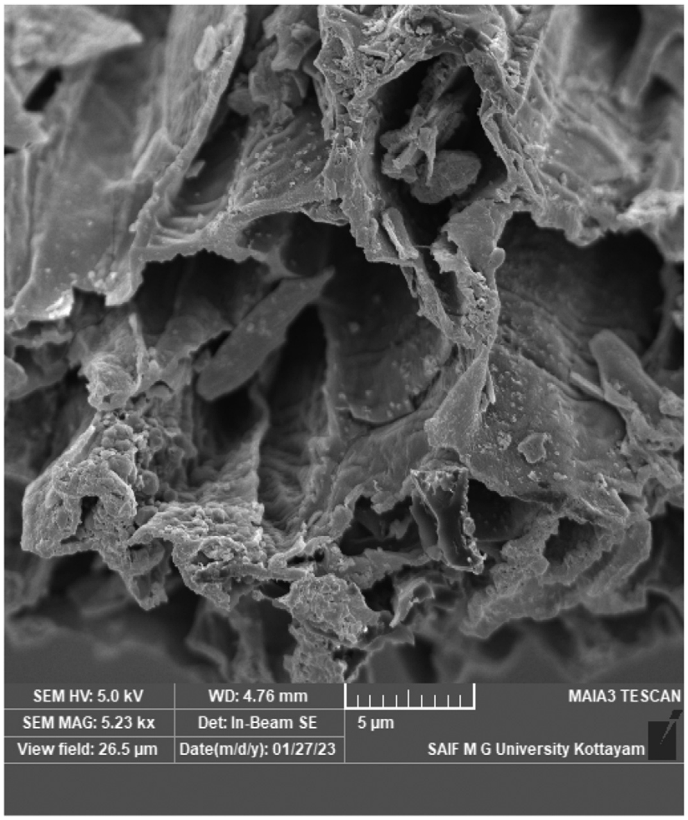

Fig. 8 Sem image of Ag/Zn biochar composite.

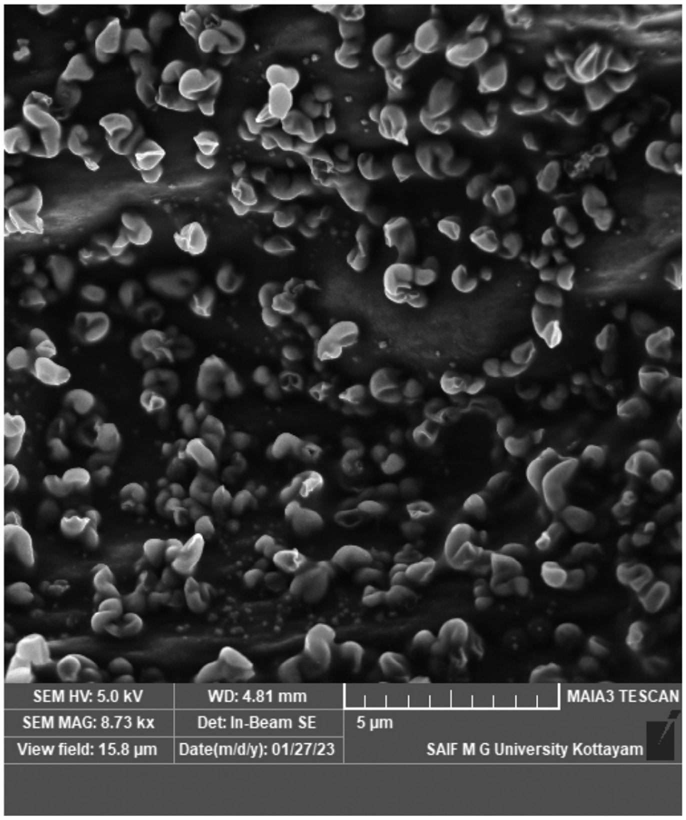

Fig. 9 SEM image of Fe-biochar composite.

supporting matrix. These composite materials exhibit enhanced physicochemical properties compared to raw biochar, featuring increased surface-active sites, higher specific surface area, improved porosity, enhanced stability, and more excellent reusability (Amdeha, 2023). These composites harness the combined strengths of biochar and nanoparticles to remove a wide range of contaminants efficiently (Tan et al., 2016).

Biochar nanocomposites are synthesized using innovative, practical, sustainable, and facile approaches, with varying properties depending on precursor materials and synthesis methods. The most common techniques for preparing these nanocomposites are sol-gel, hydrothermal, mechanical mixing, and sonication treatment.

- Mechanical Mixing: This technique has performed best in creating biochar-based nanocomposites.
- Hydrothermal Method: It is a versatile solution-based reaction method operating across a wide temperature range, offering control over the morphology, composition, size, and crystalline forms of nanomaterials. However, it requires costly autoclave equipment and high-temperature/pressure conditions.
- Sol-Gel Technique: This wet chemical process can produce various high-quality biochar-based nanomaterials. It allows for operation at different temperatures and for fabricating homogeneous, pure nanomaterials. However, it involves a prolonged processing time and high precursor costs.
- Sonication Techniques: The sonochemical reduction rate depends on the ultrasonic frequency used.

These methods have become increasingly popular due to their simplicity, environmental friendliness, rapidity, and the ability to produce smaller nanomaterials and diverse nanostructures. These synthesis techniques offer a range of choices for customizing biochar nanocomposites for specific applications, each with its own set of benefits and drawbacks. By incorporating various functional groups present in pyrolyzed biochar, it is possible to enhance the properties of biochar nanocomposites (Fig. 10).

Extensive research has demonstrated that incorporating functional nanoparticles into biochar has unlocked its capacity for wastewater treatment through the adsorption of harmful metals and other contaminants (Chausali et al., 2021). Consequently, these nanocomposites based on biochar have established themselves as highly effective, environmentally friendly, and cost-efficient solutions for wastewater remediation. Limited research on biochar nanocomposite material toxicity necessitates addressing potential biological and environmental risks.

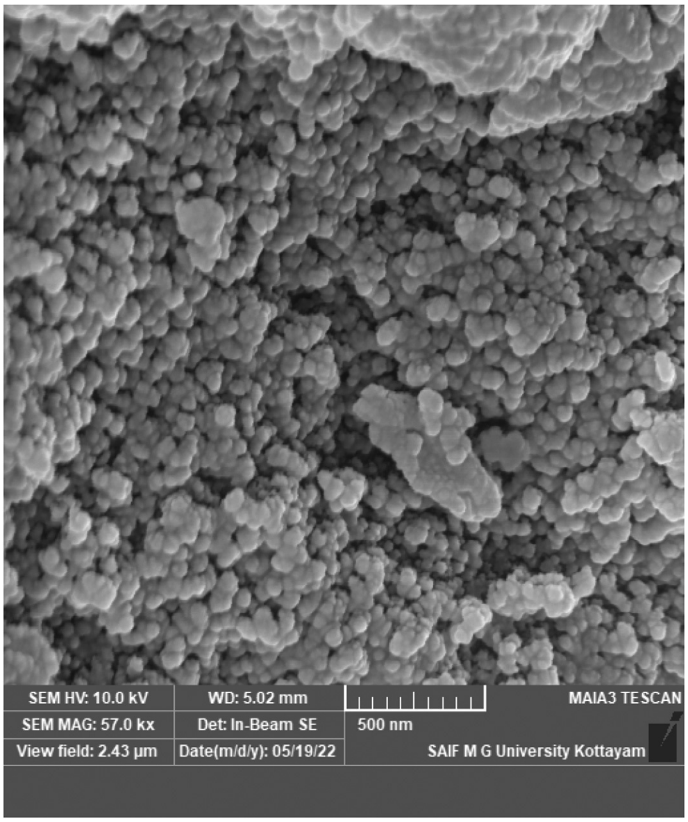

Fig. 10 SEM images of bone-derived -biochar nanocomposite.

4.3 Functional properties of biochar composites

Biochar composites, which combine biochar's unique properties with other materials, have garnered significant attention in various fields due to their enhanced functional properties. These composites are engineered to harness the benefits of biochar, such as its high surface area, alkalinity, and adsorption capabilities while addressing its limitations. By integrating biochar with other substances, these composites offer improved performance and versatility, making them valuable in applications ranging from environmental remediation especially wastewater treatment. The functional properties of biochar composites represent a promising avenue for addressing the current complex wastewater treatment challenges.

Biochar composites as adsorbents offer several improved functionalities compared to pure biochar. Some of these enhanced functionalities include:

i. *Increased Adsorption Capacity*: Incorporating other materials, such as nanoparticles or polymers, into biochar composites can significantly increase their adsorption capacity. This means they can remove more pollutants from a given solution (Ahmad et al., 2023).
ii. *Enhanced Selectivity*: Biochar composites can be designed to exhibit selectivity for specific pollutants. Functionalization with specific groups or materials can make them highly effective at targeting particular contaminants while leaving others unaffected (Tan et al., 2016; Premarathna et al., 2019).
iii. *Improved Kinetics*: Biochar composites often have faster adsorption kinetics, meaning they can adsorb pollutants more rapidly, which is particularly useful in time-sensitive applications (Han et al., 2016)
iv. *Enhanced Surface Area*: As mentioned earlier, biochar composites can have a larger surface area, providing more active sites for adsorption. This increased surface area can improve adsorption performance (Pan et al., 2021).
v. *Tailored Porosity*: By carefully designing the composition and structure of biochar composites, their porosity can be tailored to suit specific adsorption requirements (Ahuja et al., 2022). This can lead to better access to active sites and improved adsorption efficiency.
vi. *Enhanced strength and durability*: Encapsulating biochar particles with robust matrixes or supports like polymers can offer excellent mechanical strength, increased durability, and favorable hydraulic properties and hence can be employed as better adsorbents (Afzal et al., 2018).
vii. *Reusability*: Some biochar composites are designed to be reusable, allowing for multiple cycles of adsorption and regeneration without a significant loss of adsorption capacity (Alam et al., 2020).
viii. *Magnetic responsiveness and separability*: Biochar ferromagnetic composites show this property and can be easily manipulated and separated from the solution using an external magnetic field (Bopda et al., 2022). This feature simplifies the recovery and reuse process, making these composites highly practical and cost-effective adsorbents
ix. *Synergistic Effects*: Combining biochar with other materials can result in synergistic effects, where the composite's overall performance is greater than the sum of its components. This can lead to highly efficient pollutant removal (Kaur and Kaur, 2022).

5 Possible removal mechanism of pollutants by biochar composites

Biochar composites combine biochar's adsorption capabilities with other materials, enhancing pollutant removal. This process involves a multifaceted mechanism that utilizes physical and chemical interactions to capture and mitigate contaminants. Mechanisms include surface adsorption, chemical reactions, complexation, and physical entrapment. Understanding these mechanisms is crucial for designing effective pollutant removal strategies using biochar composites in various environmental applications.

5.1 Adsorption mechanism of emerging contaminants

Emerging Contaminants (ECs) encompass endocrine-disrupting compounds (EDCs), microplastics (MPs), pesticides, flame retardants, nanomaterials, pharmaceuticals, and personal care products (PPCPs). Some of these emerging contaminants are persistent organic pollutants, resisting easy degradation and persisting in the aquatic environment for extended periods, creating a quasi-permanent presence and causing numerous detrimental environmental impacts (Dong et al., 2023).

The adsorption of organic pollutants by biochar typically involves a mix of interactions, including π-π interactions with biochar's graphene layers, direct electrostatic forces, intermolecular hydrogen bonding, hydrophobic interactions, pore filling, and acting as a catalyst for pollutant degradation. π-π EDA interactions occur during the adsorption of aromatic compounds on biochar's graphene-like surface. These interactions depend on pyrolysis temperature and affect biochar's electron density, influencing its electron acceptor or donor role (Wang et al., 2010). Electrostatic interactions are crucial in adsorbing ionizable and ionic organic compounds onto biochar. The pH of the solution predominantly dictates the impact of these interactions during adsorption (Ambaye et al., 2021). Highly electronegative organic pollutants can form bonds with the polar hydrogen groups on the biochar surface (Qiu et al., 2022). Higher pyrolysis temps make biochar less polar, increasing its hydrophobicity. This enables it to adsorb non-polar organics, often through pore-based partitioning, which demands less hydration energy due to competition with water

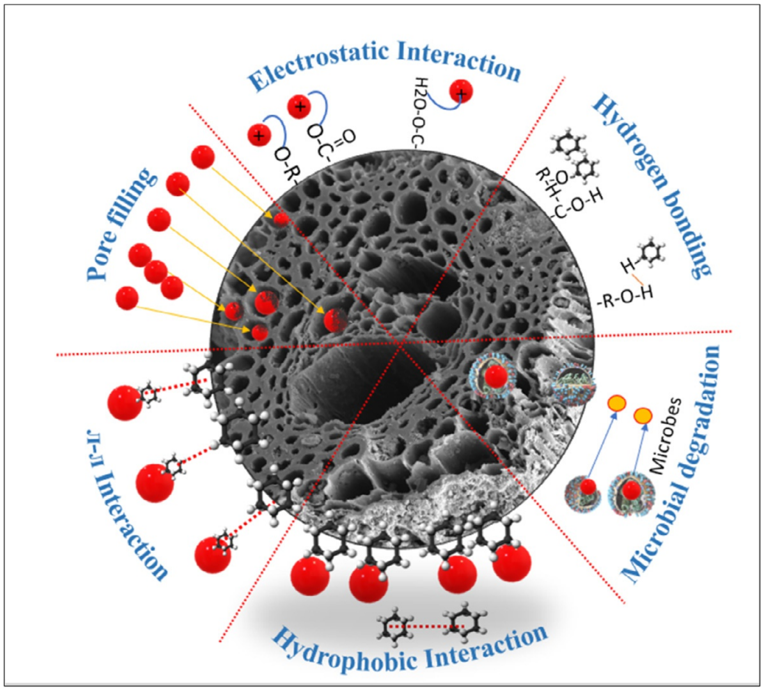

Fig. 11 Possible adsorption mechanism of Emerging Contaminants by biochar composites.

molecules. Biochar's pores and large surface area are crucial for adsorbing small organic molecules through pore-filling. However, larger molecules are excluded due to size limitations. Biochar's porous structure has a dual effect on microbial degradation: it can impede microbial access to pollutants, slowing degradation while also serving as a habitat for microorganisms, boosting their activity and changing the microbial community structure in pollutant-rich environments (Mukherjee et al., 2022) (Fig. 11).

5.2 Adsorption mechanism of heavy metals

Heavy metal pollution, encompassing a range of pollutants like As(III), Cr(VI), Ni(II), Zn(II), Cu(II), Cd(II), Hg(II), U(VI), Pu(IV), as well as metal-like elements such as As(III), Se(IV), and As(V), poses a significant and pressing environmental challenge (Liu et al., 2022).

The treatment processes involving biochar and its composite materials for heavy metal removal involve various adsorption mechanisms. This includes a series of interconnected removal mechanisms: co-precipitation, where heavy metals form insoluble compounds; complexation, involving functional groups on biochar's surface binding to the π electron-rich regions on aromatic structures; surface adsorption, where the porous structure of biochar captures and immobilizes heavy metal ions; electrostatic adsorption, stemming from interactions between the biochar surface and metal ions with differing electrostatic charges; and ion exchange, where cations, such as metal ions, exchange with protons or other alkali metals on the biochar surface.

The intrinsic oxygen-containing anions in biochar and its compounds further contribute to heavy metal fixation through co-precipitation, electrostatic adsorption, or complexation. Biochar also exhibits reductive activity, facilitating electron transfer and altering the oxidation states of bound heavy metal ions. In practical applications, these multiple reactions often occur concurrently, highlighting the multifaceted nature of biochar's heavy metal removal mechanisms (Cheung et al., 2023) (Fig. 12).

6 Sustainable fabrication of biochar composites

Balanced consideration in the design of biochar and its modified versions encompasses several critical aspects to ensure the sustainability of this technology (Zhang et al., 2022). One crucial balance to strike is between effectiveness and stability. While biochar offers stability over its feedstock, it can change the environment, affecting its functionality. Evaluating the persistence of functions, especially in modified biochar composites used for pollutant removal, is vital. This involves assessing their long-term effectiveness in removing contaminants and the stability of the biochar structure itself.

Another balance to achieve is between desired functions and potential risks. While biochar modification aims to enhance pollutant removal performance, it is essential to evaluate associated environmental risks carefully (Das et al., 2016). Modifications

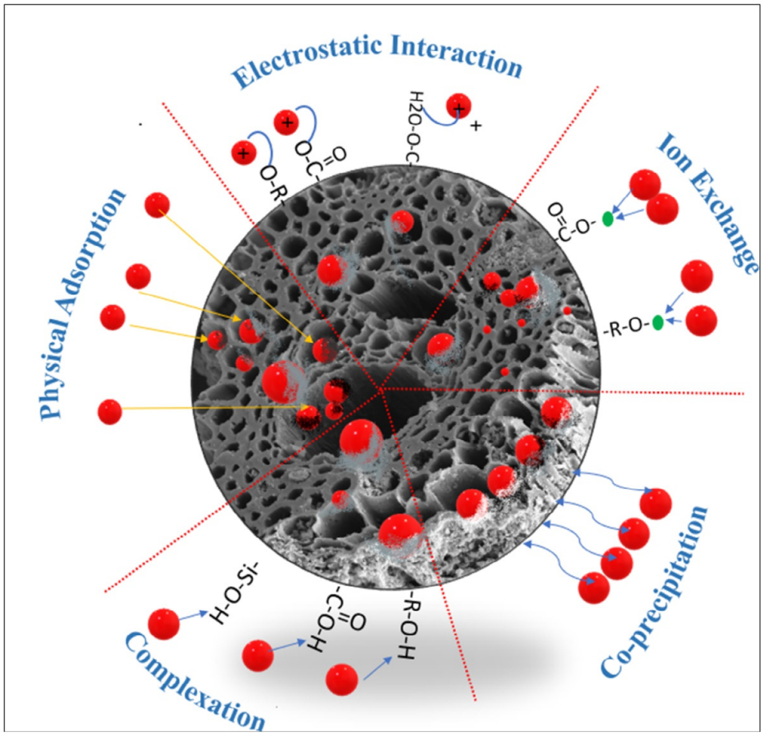

Fig. 12 Possible adsorption mechanism of Heavy metal pollutants adsorption by biochar composites.

may increase the reactivity of biochar, potentially introducing chemical stress to organisms. Releasing chemicals, nanoparticles, heavy metals, or organic compounds from biochar composites can pose unforeseen environmental risks. Proper assessment and environmentally friendly modification methods are encouraged, using non-toxic agents and reducing waste.

Finally, a balance between effectiveness and cost is crucial from an economic perspective. Biochar manufacturers must weigh the effectiveness of modification techniques against their costs. Various factors, including feedstock expenses and production conditions, influence the cost of biochar production. Biochar often remains more cost-effective than commercial alternatives like activated carbon, even after modification. Optimizing production methods and considering resource recovery from waste materials can help manage costs effectively.

The utilization of biochar and its composite applications holds paramount importance in the context of Sustainable Development Goal 6 (SDG 6) – ensuring access to safe and clean water for all (Neogi et al., 2022). Biochar, a versatile carbon-rich material, offers a multifaceted solution to water-related challenges. Its unique porous structure and exceptional adsorption capabilities make it a potent tool for water quality improvement. Integrating biochar into water treatment processes can effectively remove contaminants, pollutants, and impurities, thus advancing the goal of providing safe drinking water and sustainable sanitation. Furthermore, when applied to agricultural practices, biochar enhances soil water retention, mitigates runoff, and reduces the need for excessive irrigation, thereby conserving this precious resource. Biochar is a carbon-negative material that stores carbon and helps mitigate climate change by sequestering carbon from the atmosphere. This indirectly supports efforts to combat climate change, interconnected with various SDGs, including SDG 6. Embracing biochar and its composites represents a holistic and sustainable approach toward achieving SDG 6, safeguarding water resources, and fostering a healthier, more resilient planet for future generations.

7 Conclusion

In conclusion, the chapter underscores the growing importance of biochar and its composite materials in addressing water pollution challenges. While these materials hold significant potential for removing pollutants from water, it is evident that several critical issues must be addressed in future research. The biochar composites' stability, biotoxicity, environmental interactions, and potential ecotoxicity warrant thorough investigation. Moreover, the shift from simulated to actual wastewater treatment is imperative, considering the complexity of contaminants in real-world scenarios. Researchers must explore techniques for effectively and simultaneously removing multiple pollutants from genuine wastewater.

Furthermore, understanding the multifaceted factors influencing biochar preparation, material properties, and adsorption capacities is essential for optimizing their performance in wastewater treatment. While the promise of biochar-based composites is evident, practical applications for real wastewater treatment remain limited. Additionally, the environmental impact of (modified) biochar on its surroundings demands further clarification.

This chapter sheds light on the evolving landscape of biochar-based composites in wastewater treatment, highlighting the need for continued research and practical applications. As we navigate the path toward environmentally sustainable water treatment solutions, addressing these challenges will be pivotal in realizing the full potential of biochar and its composites.

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