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BIOCHAR-BASED MATERIALS FOR WATER PURIFICATION: A COMPREHENSIVE REVIEW

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Abstract

With the rapid industrialization, urbanization and agricultural developments, water pollution has emerged as one of the most critical environmental issues of the world. The traditional water treatment technologies are also costly, inefficient and have secondary pollutants. Biochar is a carbon rich material generated by thermochemical conversion of biomass in the absence of oxygen and has shown promise as a sustainable, economical adsorbent for water purification. The porous structure, high specific surface area, and large number of functional groups on the surface and tunable physicochemical properties make biochar a material that has proven to have very high potential to remove a wide range of contaminants from an aqueous environment. This review summarizes the technologies of biochar production, physicochemical properties and modification methods to improve adsorption performance. The mechanisms involved in pollutant removal, such as electrostatic interaction, ion exchange, filling the pore volume, surface complexation, and π - π interaction are critically discussed. Moreover, the application of pristine and engineered materials of biochar for heavy metal, dye, pharmaceuticals, nutrients and emerging contaminant remediation is systematically reviewed. Current problems with the large scale implementation, regeneration, environmental safety and economic feasibility are also discussed. Finally, future research directions are suggested to help the development of high-performance biochar based materials in sustainable water treatment technologies.

1. Introduction

Industrial effluents, agricultural run-off, pharmaceutical wastes and municipal wastes from cities are causing fresh water contamination, which has become a serious environmental problem worldwide. Heavy metals, dyes, pharmaceutical drugs, pesticides and emerging contaminants are introduced continuously into aquatic systems exposing the water, biodiversity, and humans to threats to the water quality (Ali et al., 2012; Mohan et al., 2014). There is no denying that water scarcity has become more dire around the world and water treatment technologies that are efficient, sustainable, and cost-effective are growing in importance.

In the existing treatment technologies, adsorption is considered one of the most promising methods for removing mercury because of its simplicity, high efficiency, flexibility and cost-effectiveness (Tan et al., 2015). Although it is the standard adsorbent material used in water purification, the high production and regeneration cost of activated carbon is an incentive for researchers to find materials for use as adsorptive agents that do not cost so much (Ali et al., 2012).

Biochar has been found to be a promising carbonaceous material for use in environmental remediation and water treatment. Biochar is a thermochemical process product of biomass combustion under oxygen deficient conditions, and has a porous structure, high specific surface area, and rich functional groups to adsorb contaminants (Ahmad et al., 2014; Wang & Wang, 2019). Moreover, biochar production can make use of renewable biomass materials, including agricultural residues, forestry wastes, animal manure, sewage sludge, food wastes, and so on, which can be helpful for implementing the concept of waste valorization and circular economy (Zhao et al., 2018).

Many studies have revealed that biochar can effectively remove a wide range of contaminants such as heavy metals, organic pollutants, dyes, pharmaceuticals, endocrine-disrupting compounds and other emerging contaminants (Inyang et al., 2016; Dong et al., 2023). In addition, in the past few years, biochar has been engineered to produce modified and composite biochars that have greatly improved adsorption properties and specific pollutant selectivity (Rajapaksha et al., 2016; Mandal et al., 2021).

The growing scientific interest in biochar-based materials is demonstrated by the number of publications dealing with biochar production, modification, adsorption mechanism and environmental application. Although significant progress has been made, implementation issues at larger scales, regeneration, environmental safety, and standardization issues continue to be significant research priorities (Xiang et al., 2020; Lima et al., 2025).

The aim of this review is to give a comprehensive overview about biochar based materials for water purification, including production technologies, physicochemical properties, modification strategies, mechanisms of pollutants removal, industrial applications, material rejuvenation, key challenges and future research perspectives.

2. Literature Review

To be able to cover the latest developments in biochar water purification technologies, the literature was collected systematically from major scientific international databases. The review concentrated mainly on peer-reviewed journal articles published from 2011 to 2025, and a few studies cited a lot, which were published before 2011, were included due to their important role in the development of the research of biochar (Ahmad et al., 2014; Mohan et al., 2014).

The search strategy used was the use of combinations of keywords such as “Biochar”, “Engineered Biochar”, “Modified Biochar”, “Water Purification”, “Wastewater Treatment”, “Adsorption”, “Heavy Metal Removal”, “Organic Pollutant Removal”, “Pharmaceutical Contaminants”, “Emerging Pollutants”, and “Biochar Composites”. Searches were repeated with various combinations of these terms to find studies on production technologies, surface modification, adsorption mechanisms, regeneration and environmental applications.

Articles, review papers, and highly cited studies, directly related to biochar applications in water treatment, were only included. Only articles containing original and sound information on methodology were included, as well as conference papers and duplicate publications. Studies published in languages other than English and articles lacking methodological information were not included. Studies with detailed experimental data, mechanistic interpretations and practical aspects of water purification were given preference.

The retrieved literature was grouped into thematic sections such as basic information about biochar, production methods, physicochemical properties, modification technologies, adsorption mechanisms, contaminant removal possibilities, biochar reusability and regeneration, challenges and future perspectives. The thematic organization allowed for a critical review of the existing knowledge and for the identification of the research trends, technological advances and gaps in knowledge of the field (Wang & Wang, 2019; Liang et al., 2021; Yu et al., 2022).

3. Fundamentals of Biochar

Biochar is a porous carbon-rich material that is created by thermochemically converting biomass in an oxygen limited or oxygen free environment. Biochar is specially engineered for environmental use, such as soil improvement, carbon sequestration, pollution reduction and water purification, in contrast with its conventional use for energy production (Ahmad et al. 2014; Wang & Wang 2019).

Biochar has its roots in the very fertile soils of the Amazon Basin (terra preta) that are rich in stable carbon from partially burned biomass. The soils have continued to be very fertile for centuries and have motivated researchers to explore the potential of biochar as a multifunctional soil amendment for solving environmental problems (Beesley et al., 2011).

Biochar can be produced from a variety of different biomass sources, such as food waste, animal manure, sewage sludge, forestry wastes, and agricultural residues. The physicochemical properties of biochar depend greatly on the composition of the feedstock used. In general, biochars from

lignocellulosic materials tend to possess high carbon content and well-developed porosity, while biochars derived from manure generally have higher mineral contents and improved ion-exchange capacities (Tan et al., 2015; Yin et al., 2021).

Biochar properties are significantly influenced by its porosity, surface chemistry and carbon content. Biochar usually has micropores, mesopores, and macropores all of which give rise to a large surface area and a high number of adsorption sites for contaminants (Inyang et al., 2016). Moreover, it also has functional groups of hydroxyl, carboxyl, carbonyl, phenolic, nitrogen-containing and sulfur-containing groups on its surface, which can interact with pollutants in the dissolved organic matter by a variety of adsorption mechanisms (Li et al., 2017).

One of the most crucial advantages of biochar is its environmental sustainability. Biochar helps to manage waste and recover resources, and sequesters carbon for long-term storage, since it is derived from renewable biomass resources (Zhao et al., 2018). Thus, the synergies make biochar one of the most promising materials for sustainable water purification technologies and environmental remediation applications.

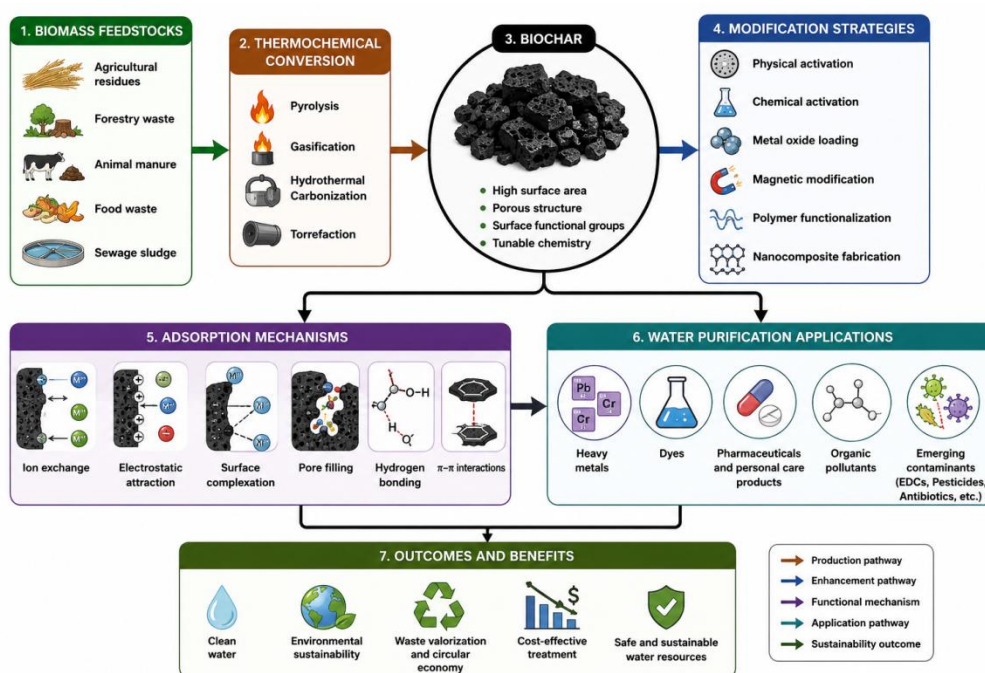


Figure 1. Schematic overview of biochar production and water purification applications

4. Biochar Production Technologies

Important production technology used for biochar synthesis is a key factor influencing its physicochemical properties, adsorption capacity and environmental performance. The biochar properties, including carbon content, pore structure, surface area and distribution of functional groups, are significantly affected by the parameters of the pyrolysis process such as temperature, heating rate, residence time, pressure and feedstock composition (Wang & Wang, 2019; Qiu et al., 2021). Therefore, to maximize the effectiveness of biochar on water purification, it is necessary to choose the right method for producing biochar.

Pyrolysis is the most common technology for biochar production and is a process of decomposing biomass in the absence of oxygen. Pyrolysis can be either slow pyrolysis, fast pyrolysis or flash pyrolysis depending on the operating conditions. Slow pyrolysis is usually used to produce biochar and tends to produce carbonaceous products that are very stable and have good porosity and adsorption capacity (Ahmad et al., 2014; Tan et al., 2015). Fast pyrolysis is aimed at producing bio-oil, while flash pyrolysis is aimed at producing bio-oil at an even more rapid heating rate which further decreases biochar yield.

Another thermochemical conversion method is gasification, where the biomass is partially oxidized at high temperature, typically in the range of 700–1200 °C. While the main goal of gasification is to create syngas, biochar is produced as a by-product. However, the mineral content

and aromaticity of gasification biochars are typically higher as a result of their high operating temperature, which can be beneficial to removing certain inorganic contaminants (Wang & Wang, 2019).

Hydrothermal carbonization (HTC) is a promising process for treating wet biomass. The reaction conditions for HTC are relatively low-temperature, at 180-250 °C, and take place in hot compressed water, in contrast to pyrolysis. The process avoids the need for energy intensive drying and yields a product that is a hydrochar with high oxygen functional groups which can enhance the adsorption of metal ions and polar organic contaminants (Liang et al., 2021).

Torrefaction is a mild thermal treatment at the temperature range of 200-300 °C under oxygen deficient conditions. The adsorption capacities of torrefied biochars are usually lower than those of biochars produced by pyrolysis processes, but they can be used as good precursors for activation and surface modification processes (Wang & Wang, 2019).

Overall, the production conditions have a significant impact on the biochar properties. Generally speaking, higher temperatures lead to more surface area, aromaticity, and structural stability, while lower temperatures tend to keep oxygen-bearing functional groups that lead to ion exchange and surface complexation. Thus, the production technologies must be carefully controlled to produce biochar with desired characteristics for the specific use in water treatment (Qiu et al., 2021; Xiang et al., 2020).

Table 1. Comparison of Major Biochar Production Technologies and Their Characteristics

Production Technology	Typical Temperature (°C)	Main Product	Key Characteristics	Advantages	Limitations
Slow Pyrolysis	300–700	Biochar	High carbon content, well-developed porosity, high stability	High biochar yield, suitable for adsorption applications	Longer processing time
Fast Pyrolysis	400–700	Bio-oil	Rapid heating and short residence time	High liquid fuel production	Lower biochar yield
Flash Pyrolysis	500–1000	Bio-oil and gases	Extremely rapid heating	High energy conversion efficiency	Very low biochar production
Gasification	700–1200	Syngas	High ash content and aromatic carbon structures	Energy generation and pollutant immobilization	Lower biochar yield
Hydrothermal Carbonization (HTC)	180–250	Hydrochar	Rich in oxygen-containing functional groups	Suitable for wet biomass, no drying required	Lower surface area than pyrolysis biochar
Torrefaction	200–300	Torrefied Biochar	Partial carbonization and moderate porosity	Low energy consumption and improved biomass handling	Lower adsorption capacity
Activated Biochar Production	500–900	Activated Biochar	Very high surface area and pore volume	Enhanced adsorption performance	Additional processing cost

HTC = Hydrothermal Carbonization.

5. Physicochemical Properties of Biochar

Biochar's physicochemical properties play a crucial role in determining the interactions between biochar and contaminants, and affect adsorption capacity, selectivity, reactivity, and environmental stability and thus the effectiveness of biochar as an adsorbent. The properties are highly dependent on the type of the raw material, production technology, pyrolysis conditions and post-treatment modifications (Ahmad et al., 2014; Wang & Wang, 2019).

The surface area and pore structure of biochar is one of its most crucial properties. Biochar is usually structured as a hierarchical porous network with the presence of micropores, mesopores and macropores. Micropores are responsible for a significant part of the adsorption capacity due to the extremely large internal surface area, while mesopores and macropores promote the transfer and accessibility of contaminants to the active sites (Inyang et al., 2016). In general, biochars produced at higher temperatures have larger surface areas because they have more pores and volatile compounds are removed.

The surface functional groups can also have significant roles in adsorption processes. Most commonly, biochar surfaces are hydroxyl, carboxyl, carbonyl, phenolic, nitrogen containing and sulfur containing, which can be involved in ion exchange, electrostatic attraction, and surface complexation reactions, respectively (Li et al., 2017). The latter are especially relevant to the adsorption of polar organic contaminants and heavy metals.

The elemental composition of biochar can provide useful information on the degree of carbonization and stability of biochar. As the pyrolysis temperature increases, the content of carbon increases, and the content of hydrogen and oxygen decreases, which makes the aromaticity and environmental stability of the pyrolysate increase (Tan et al., 2015). Aromatic carbon structures are useful for hydrophobic interaction and π - π electron donor-acceptor interactions, two of the most significant interactions that mediate the removal of dyes, pharmaceuticals, and other organic pollutants.

The surface charge and pH characteristics also have an impact on the adsorption performance. Biochar can have a range of pH values based on the feedstock and the process of its creation. Under certain conditions, the surface charge of biochar will be positive or negative, depending on the point of zero charge (pHPZC), which influences electrostatic interactions with contaminants (Li et al., 2017).

The ability to exchange positively charged ions with pollutants in solution, known as cation exchange capacity (CEC), is another key characteristic of biochar. This property is especially useful for the removal of heavy metals like lead, cadmium, copper and zinc (Inyang et al., 2016).

All these physicochemical properties altogether control the adsorption behavior of biochar. It is crucial to optimize the balance of the properties of biochar, including porosity, surface functionality, stability and chemical reactivity, to make it a high-performance material for use in more advanced water purification applications (Qiu et al., 2021; Yu et al., 2022).

6. Biochar Modification Strategies

Pristine biochar has great adsorption capacity, but the adsorption capacity is often limited by relatively low surface area, limited active functional groups, low adsorption selectivity and low regeneration ability. In order to address these issues, several modifications have been developed to improve the physicochemical properties of biochar and make it more effective in water purification applications (Wang & Wang, 2019; Rajapaksha et al., 2016).

One of the most common strategies to enhance the properties of biochar is physical activation. In this method, heat typically is applied to a high-temperature steam or carbon dioxide to expand the porosity and surface area by eliminating volatile components from the carbon matrix. The adsorption ability of biochars is usually much higher for both organic and inorganic pollutants as they have more adsorption sites available (Tan et al., 2015).

Another successful approach is chemical activation and is typically done with activating agents like potassium hydroxide (KOH), sodium hydroxide (NaOH), phosphoric acid (H_3PO_4), and zinc chloride ($ZnCl_2$). These chemicals create pores and add other functional groups to the surface, which significantly enhance the adsorption capacity (Wang & Wang, 2019; Qiu et al., 2021).

Acid and alkali modifications are often used to modify the functional group content of the surface chemistry. Acid treatments involve addition of oxygen-containing groups (e.g. carboxyl and hydroxyl) which increases the ability of the metal ions to adsorb to the surface by surface complexation and ion exchange. On the other hand, alkali treatments result in an increase in pore accessibility and in a higher basicity (Li et al., 2017).

Since metal oxide modification provides the introduction of extra catalytic properties and reactive sites, this has been a matter of great concern. Biochar structures are often modified with iron oxides, manganese oxides, titanium oxide, magnesium oxide and zinc oxide to improve adsorption capacity and aid the removal of contaminants by precipitation, redox reactions and surface complexation (Gao et al., 2011; Rajapaksha et al., 2016).

The iron-containing nanoparticles (e.g., Fe_3O_4) are indispensable to the preparation of magnetic biochar composites, as they enable easy recovery of spent adsorbents by applying an external

magnetic field. The properties of these materials include high adsorption capacity, efficient separation and regeneration properties (Chen et al., 2011; Mohan et al., 2014).

The recent developments have also resulted in chitosan, graphene derivatives, carbon nanotubes, and metal-organic framework containing polymer modified and nanocomposite biochars. These man-made biochars can have properties that are better than the ones of conventional adsorption processes, such as adsorption capacity, the ability to be selectively regenerated, and multifunctional properties, in addition to adsorption capacity (Mandal et al., 2021; Han et al., 2024). This has made modification strategies an important aspect of the development and application of biochar-based technologies for sustainable water purification.

Table 2. Comparison of Biochar Modification Strategies for Water Purification Applications

Modification Strategy	Typical Modifying Agents	Main Improvements	Target Contaminants	Advantages	Limitations
Physical Activation	Steam, CO ₂	Increased surface area and porosity	Heavy metals, dyes, organic pollutants	Environmentally friendly and simple process	High energy consumption
Chemical Activation	KOH, NaOH, H ₃ PO ₄ , ZnCl ₂	Enhanced pore development and surface functionality	Heavy metals, pharmaceuticals, dyes	Very high adsorption capacity	Chemical consumption and post-treatment requirements
Acid Modification	HNO ₃ , HCl, H ₂ SO ₄	Increased oxygen-containing functional groups	Heavy metals and cationic pollutants	Improved surface complexation	Possible structural damage
Alkali Modification	NaOH, KOH	Increased basicity and pore accessibility	Organic pollutants and dyes	Enhanced adsorption efficiency	Additional processing costs
Metal Oxide Modification	Fe ₃ O ₄ , Fe ₂ O ₃ , MnO ₂ , TiO ₂ , ZnO	Increased reactive sites and catalytic activity	Heavy metals, phosphate, arsenic	High selectivity and multifunctionality	Higher production complexity
Magnetic Modification	Magnetite, Maghemite, Zero-Valent Iron	Easy separation and regeneration	Heavy metals and organic contaminants	Rapid recovery using magnetic field	Potential nanoparticle release
Polymer Functionalization	Chitosan, Polyaniline, Polyethyleneimine	Additional functional groups and selectivity	Pharmaceuticals, heavy metals	Improved adsorption and stability	Increased material cost
Nanocomposite Modification	Graphene, Carbon Nanotubes, MOFs	Enhanced adsorption kinetics and multifunctionality	Emerging contaminants and mixed pollutants	Superior performance	Expensive production and scalability challenges

MOFs = Metal-Organic Frameworks.

7. Adsorption Mechanisms

The highly effective adsorption properties of biochar can be attributed to the multi-chemical-physical mechanism. Biochar's surface chemistry and porous structure is heterogeneous, which facilitates multiple interactions with contaminants under different environmental conditions (Li et al., 2017; Inyang et al., 2016).

Electrostatic attraction is a very significant adsorption mechanism. Electrostatic forces can either attract or repel positively or negatively charged contaminants, depending on the pH of the solution and the point of zero charge (p_{znc}) of the biochar surface. This mechanism is especially significant in the early stages of adsorption and plays a significant role in the quick adsorption of dissolved pollutants (Li et al., 2017).

Removal of contaminated materials is also a significant aspect of ion exchange. Biochar surfaces have exchangeable ions like calcium, magnesium, potassium and sodium ions which can be exchanged with the ion contaminant in solution. This is particularly important for the immobilization of toxic heavy metals like lead, cadmium, copper and zinc (Inyang et al., 2016; Qiu et al., 2021).

It is believed that surface complexation is one of the main mechanisms for the adsorption of heavy metal ions. Hydroxyl, carboxyl, carbonyl and phenolic groups form stable complexes with metal ions, which leads to adsorption (Li et al., 2017) that can be strong and irreversible.

The porous structure of biochar can also help remove contaminants by filling the pores. Organic molecules enter micropores and mesopores as it becomes physically adsorbed in the internal structure of the adsorbent. This mechanism plays a crucial role in the case of dyes, pharmaceuticals and other low molecular weight organic contaminants (Tan et al., 2015).

The adsorption performance is further improved due to hydrogen bonding and π - π electron donor-acceptor interactions. Hydrogen bonding occurs between the functional groups on biochar surface and contaminant molecules, while π - π interaction between aromatic structures on biochar and aromatic organic pollutants like phenols, dyes, pharmaceuticals and pesticides (Mohan et al., 2014; Sun et al., 2011).

Hydrophobic interactions also play important role in removal of nonpolar organic compounds. The high-temperature pyrolysis makes the biochar more aromatic, thus enhancing the hydrophobic effect that causes the hydrophobic contaminants to partition on the biochar surface from the water (Tan et al., 2015).

Precipitation and redox reactions can also play a large role in the removal of contaminants, in some cases. Biochars could also facilitate the production of insoluble metal precipitates and engineered biochars with iron and/or manganese oxides could promote oxidation-reduction reactions that may transform contaminants into less toxic forms (Zhou et al., 2013; Rajapaksha et al., 2016).

These mechanisms generally do not take place independently from each other in practical water treatment systems. On the contrary, removal of contaminants is usually the result of synergic interactions of several processes. To achieve this, it is crucial to understand these mechanisms, which are fundamental for designing more advanced biochar materials that can have better adsorption efficiency, selectivity and long-term performance (Li et al., 2017; Yu et al., 2022). Summarizes

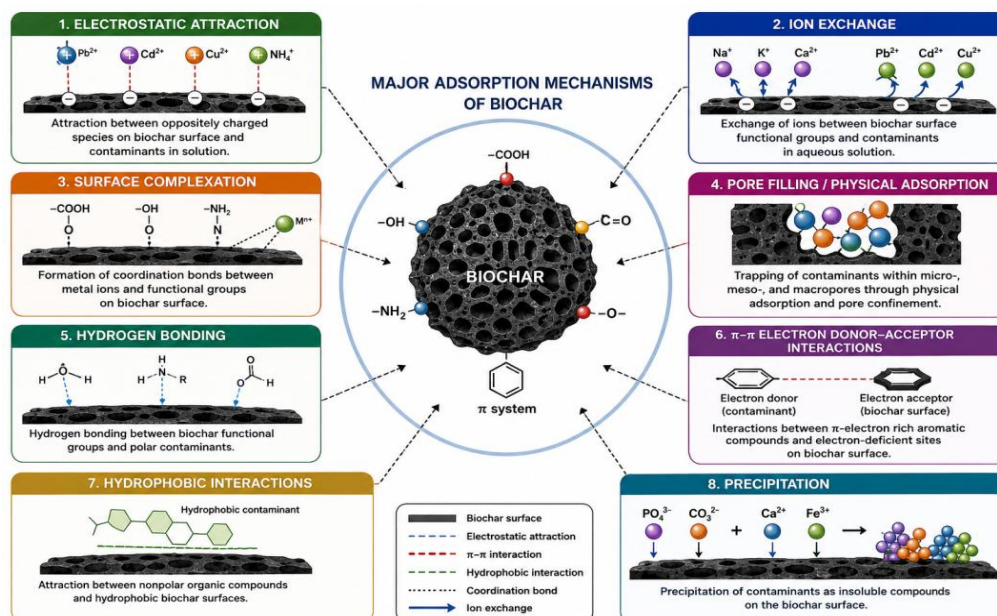


Figure 2. Major adsorption mechanisms of biochar.

8. Removal of Heavy Metals

Metals (e.g., lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), copper (Cu), zinc (Zn) and nickel (Ni)) are toxic, persistent, non-biodegradable and bioaccumulating, and are regarded as one of the most serious environmental problems. These contaminants are from different industrial processes such as mining, electroplating, battery production, metalworking, textiles, farming, and so on (Inyang et al., 2016; Yin et al., 2021). Heavy metals, even at low concentrations, can be a major problem for human health and aquatic ecosystems.

Heavy metal removal is one of the most effective applications of biochar based materials due to its porous structure, large surface area, minerals and its functional groups (Ahmad et al., 2014; Qiu et al., 2021). The metal removal process can occur through several mechanisms of adsorption, such as ion exchange, electrostatic attraction, surface complexation, precipitation and redox reactions (Li et al., 2017). The presence of oxygen functional groups, like hydroxyl, carboxyl, and carbonyl groups, increases the number of active binding sites, which improves the adsorption efficiency.

A great number of studies have reported considerable removal efficiency for lead, cadmium, chromium and copper with both unmodified and modified biochars. Magnetic biochars and metal oxide modified biochars, for instance, have higher adsorption capacity due to their higher surface reactivity and higher number of adsorption sites (Mohan et al., 2014; Wang et al., 2015). Some other studies also have found that removal of arsenic and chromium from contaminated water can be achieved by both adsorption and redox reactions with iron-modified biochars (Zhou et al., 2013).

The type of feedstock, pyrolysis temperature, the solution pH and the concentration of contaminants are significant factors that affect the adsorption performance of heavy metals. Overall, higher mineral content and cation exchange capacity of biochars are associated with higher metal removal efficiencies (Tan et al., 2016; Park et al., 2011). Therefore, biochar-based material is gaining considerable interest as sustainable and cost effective material for the remediation of heavy metal-contaminated water systems.

9. The removal of organic pollutants and dyes

Organic pollutants are a significant group of water pollutants and include synthetic dyes, pesticides, phenolic compounds, hydrocarbons, industrial chemicals and other persistent organic pollutants. Due to their high toxicity, resistance to biodegradation and persistence in the environment, removal of many of these substances from wastewater is an important environmental concern (Ali et al., 2012; Mohan et al., 2014).

The porous structures and aromatically structured carbon of biochar render it as an effective adsorbent for the removal of organic pollutants, making it a subject of great interest for removing contaminants (Tan et al., 2015). There are multiple adsorption mechanisms, such as pore-filling, hydrogen-bonding, hydrophobic interactions, van der Waals forces, and π - π electron donor-acceptor interactions, that govern the adsorption process between the aromatic contaminants and the carbonaceous surface of biochar (Sun et al., 2011; Li et al., 2017).

The removal of synthetic dyes from textile and industrial wastewater has been given special attention. The removal of dyes like methylene blue, Congo red, rhodamine B and malachite green by biochar-based adsorbents has been successful (Mohan et al., 2014). The dye structure, molecular size, solution pH, biochar chemistry, and biochar pore size distribution are among the factors that affect the adsorption efficiency. Enhanced surface functionality and porosity yield biochars that are often many times more efficient at adsorption than unmodified biochars (Rajapaksha et al., 2016).

Biochar has also demonstrated good adsorption capacity for pesticides, phenolics, EDCs and many industrial organic pollutants. Overall, high-temperature biochars tend to have a higher degree of hydrophobic organic compounds (HOCs) adsorption because they have higher aromaticity and surface area (Tan et al., 2015). Furthermore, biochars with magnetic particles, polymers or nanomaterials can enhance their selectivity and removal efficiency for certain classes of contaminants (Mandal et al., 2021).

In conclusion, the ability of biochar to effectively remove a wide range of organic contaminants suggests its potential as an environmentally friendly and sustainable adsorbent for wastewater treatment.

Table 3. Major Water Contaminants Removed by Biochar and Associated Adsorption Mechanisms

Contaminant Category	Representative Pollutants	Dominant Removal Mechanisms	Key Advantages of Biochar
Heavy Metals	Pb ²⁺ , Cd ²⁺ , Cr ⁶⁺ , Cu ²⁺ , Hg ²⁺ , As ³⁺	Ion exchange, surface complexation, electrostatic attraction, precipitation	High removal efficiency and strong metal immobilization
Synthetic Dyes	Methylene Blue, Congo Red, Rhodamine B, Malachite Green	π - π interactions, pore filling, electrostatic attraction, hydrogen bonding	Effective treatment of textile wastewater
Pesticides	Atrazine, Glyphosate, Chlorpyrifos	Hydrophobic interactions, pore filling, hydrogen bonding	Removal of persistent agricultural pollutants
Phenolic Compounds	Phenol, Bisphenol A, Cresols	π - π interactions, hydrophobic partitioning, hydrogen bonding	High affinity for aromatic compounds
Pharmaceuticals	Ibuprofen, Diclofenac, Carbamazepine, Acetaminophen	Pore filling, hydrogen bonding, π - π interactions, electrostatic attraction	Effective removal of trace organic contaminants
Antibiotics	Tetracycline, Ciprofloxacin, Sulfamethoxazole	Surface complexation, hydrogen bonding, electrostatic attraction	Reduction of antibiotic pollution risks
Endocrine-Disrupting Compounds (EDCs)	Bisphenol A, Nonylphenol, Phthalates	Hydrophobic interactions, π - π bonding	Effective removal of hormonally active compounds
Personal Care Products	Triclosan, Parabens, UV Filters	Hydrogen bonding, pore filling, hydrophobic interactions	Treatment of emerging contaminants
Microplastics and Nanoplastics	Polyethylene, Polystyrene Particles	Physical filtration, surface adsorption, aggregation	Potential application in plastic pollution control

EDCs = Endocrine-Disrupting Compounds.

10. Removal of Pharmaceuticals and Emerging Contaminants

Pharmaceuticals and personal care products are widely used, and therefore continuously released into aquatic environments all over the world. These contaminants have been reported in water systems around the world, including in the wastewater, surface and groundwater systems (Dong et al., 2023). The contaminants can be persistent in the environment and are not easily treatable by conventional treatment systems.

Biochar-based materials have been found to have the ability to effectively remove these contaminants, high adsorption capacity, environmental friendliness, and modifiable surface chemistry (Yu et al., 2022). The effective removal of pharmaceutical compounds from aqueous solutions is achieved through different adsorption mechanisms such as pore filling, hydrogen bonding, electrostatic attraction, hydrophobic interaction and π - π interaction (Li et al., 2017).

The adsorption of pharmaceuticals, including tetracycline, ciprofloxacin, sulfamethoxazole, diclofenac, ibuprofen, carbamazepine and acetaminophen, have been successfully demonstrated by biochar-based adsorbents in several studies (Dong et al., 2023). The performance of contaminant adsorption is improved with surface modification of the biochars, as the additional functional groups and increased porosity offer more binding sites for the molecules of contaminants (Rajapaksha et al., 2016).

In addition, emerging contaminants (e.g., endocrine-disrupting compounds and personal care products) can be effectively removed by the hydrophobic interactions and the aromatic π - π bonding mechanisms (Sun et al., 2011). In addition, recent research indicates that biochar can play a role in the adsorption, aggregation, and filtering of microplastics (Dong et al., 2023).

The engineered biochar composites with metal oxides, magnetic nanoparticles, polymers, photocatalytic materials have been further developed, allowing biochar to be used in treating complex wastewater streams with multiple contaminant classes (Mandal et al., 2021). Thus, biochar materials are considered as key materials for future water treatment technologies to solve new water pollution problems.

11. Regeneration and Reusability

The use of biochar in water treatment will depend not only on the adsorption efficiency but also the ability to regenerate and reuse the biochar in several treatment cycles. Additionally, regenerated

spent adsorbents can be used in a large scale for treatment systems, but at a higher operational cost, which will increase the amount of waste. Therefore, the use of effective regeneration methods is crucial to increase the sustainability and economic feasibility of biochar-based treatment systems.

As the adsorption takes place, the contaminants bind to the surface of the biochar and to its pores, and the number of active adsorption sites decreases with time. The purpose of regeneration is to remove or modify the adsorbed contaminants so as to restore the adsorption capacity. Thermal treatment, chemical washing, solvent extraction, microwave irradiation, and electrochemical regeneration have been studied as various methods for regeneration. The effectiveness of thermal regeneration to remove organic pollutants means that it is widely used, while chemical regeneration is especially suited to desorption of heavy metals by acid or alkaline processes (Tan et al., 2015; Wang & Wang, 2019).

More recently microwave-assisted and electrochemical regeneration techniques have been shown to be effective and can be used to provide regeneration in shorter times and with lower energy consumption. With repeated cycles, however, the adsorption ability may be decreased over time due to pore blockage, damage to the structure, or loss of functional groups (Xiang et al., 2020; Liang et al., 2021).

A reusability of biochar is one of the influencing factors that play an important role in the long term applicability. Unmodified and modified biochars have demonstrated good adsorption performance with multiple regeneration cycles. The durability and regeneration efficiency of engineered biochars typically have improved structural stability (Mandal et al., 2021; Wang & Wang, 2019). Future studies should aim to develop environmentally friendly and cost-effective biochar regeneration methods that can effectively extend the lifespan of the adsorbent and reduce energy consumption and secondary waste, thus promoting sustainable biochar utilization for water purification applications.

12. Challenges and Limitations

Although significant advancements have been made over the last few years, there are still a number of scientific, technical, environmental and economic issues that inhibit the widespread use of biochar based materials in water treatment applications. Variability of biomass feedstocks is one of the main challenges, as it may introduce great variability in biochar characteristics like surface area, porosity, mineral composition, and distribution of functional groups (Ahmad et al., 2014; Wang & Wang, 2019). This variation can make the adsorption performance difficult to be reproduced and standardized.

Biochar properties are also largely affected by the production conditions. The pyrolysis temperature, pyrolytic heating rate, residence time and activation process can result in significantly different adsorption characteristics (Qiu et al., 2021). Because of this, it is difficult to commercialize because there are no accepted production protocols.

Another major drawback is the absence of large scale field validation. The vast majority of literature are laboratory studies with synthetic wastewater and controlled environments (Xiang et al., 2020). Wastewater in real applications is a mix of elements and can compete for adsorption sites, leading to decreased efficiency in treatment. Thus, the laboratory results may not always be representative of field performance.

The potential environmental risks should also be carefully considered. Depending on the quality of the feedstock and production conditions, biochar may contain very low levels of heavy metals, PAHs or other contaminants, which could be released during long-term use (Kumar et al., 2020). Additionally, the fate of engineered biochars in the environment with nanoparticles and metal additives is not well understood.

There is another challenge of economic feasibility. The production, modification, transport, regeneration, and disposal costs of biochar can impact the cost of treatment as a whole (Lima et al., 2025). The challenges mentioned above will have to be addressed by making the technology more standardized and by introducing technological innovations as well as long-term field studies, if biochar technologies are to be widely adopted.

13. Future Perspectives

The potential of using biochar-based materials in water purification is likely to be expanding in the future as a result of increasing demand for sustainable, efficient, and economically viable water purification technologies. Structural improvements and technological innovation in material science, environmental engineering and nanotechnology continue to offer the potential for better systems performance and greater utility of biochar-based systems (Lima et al., 2025).

A challenging and promising research line is the design of advanced engineered biochar materials with optimized physicochemical characteristics for specific contaminants. By carefully optimising feedstock selection, production parameters and surface modification methods, it is possible to produce highly selective adsorbents that are able to target specific classes of pollutants (Mandal et al., 2021). The use of metal oxides, graphene derivatives, carbon nanotubes, and photocatalytic materials with enhanced adsorption efficiency and addition of catalytic functions is expected to significantly contribute to this area in the future with the help of nanotechnology (Han et al., 2024).

Combination of biochar with advanced oxidation processes, photocatalytic system and electrochemical technologies provide further prospects for enhancing the efficiency of contaminant removal. Multifunctional biochar composites that can both adsorb and breakdown pollutants could be effective to treat complex wastewater streams with a combination of pollutants (Rajapaksha et al., 2016).

The use of AI, machine learning, and computational modeling is also anticipated to help speed up biochar production by enabling predictive optimization of feedstocks, production processes, and modifications. These methods can lower the expenses of experimental testing and help guide the development of efficient adsorbents (Lima et al., 2025).

Scales of pilot and field scale studies, life-cycle assessment, environmental risk analysis and techno-economic studies should also receive future research focus. These investigations will play a crucial role in making the transition from laboratory to field work and help ensure the environmental sustainability and commercial viability of biochar-based water treatment systems.

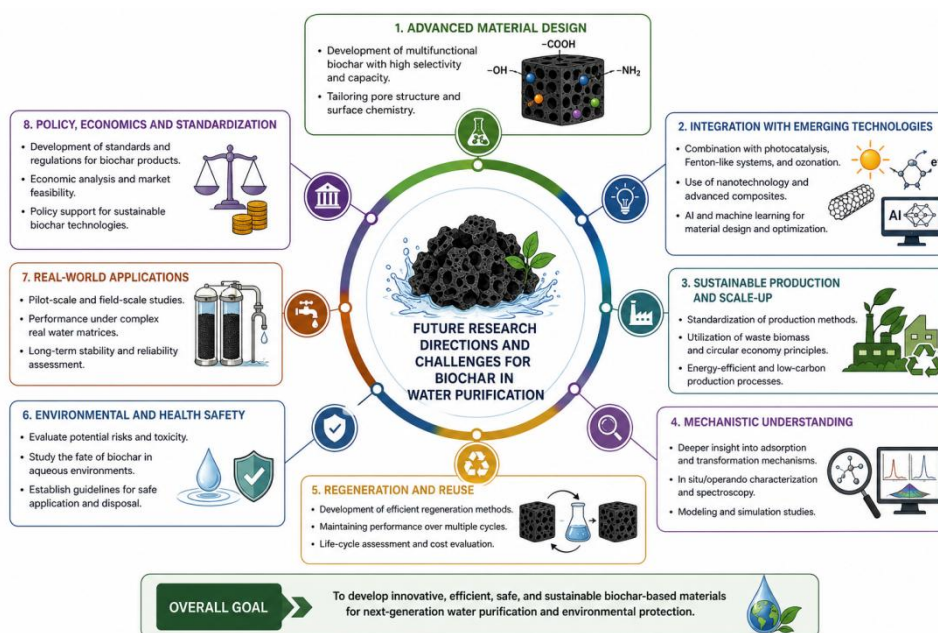


Figure 3. Future research directions and challenges.

14. Conclusion

With low cost, environmental compatibility and superior adsorption ability, the biochar-based materials have been proven to be high-potential and eco-friendly water purification adsorbents. Biochar, which is produced from renewable biomass resources, is one effective way to convert the wastes from agriculture and organic origin into value-added materials that can be used to tackle various challenges related to water pollution (Ahmad et al., 2014; Wang & Wang, 2019).

This review revealed that the effectiveness of biochar is directly linked to the characteristics of the feedstocks used, biochar production technologies, biochar physicochemical properties and modifications. The porous structure, huge specific surface area and rich functional groups allow it to have multiple adsorption mechanisms such as electrostatic attraction, ion exchange, surface complexation, pore filling, hydrogen bond, hydrophobic interaction, and π - π electron donor-acceptor interaction (Li et al., 2017; Tan et al., 2015). These mechanisms collectively make it possible to effectively remove the contaminants like heavy metals, dyes, pharmaceuticals, endocrine-disrupting compounds and other emerging contaminants from aquatic regions.

In recent years, efforts have been made to increase the adsorption capacity, adhesion and selectivity, the ability to regenerate and the operational flexibility of engineered biochars by the incorporation of metal oxides, magnetic particles, polymers, and nanomaterials, which have led to significant advances (Rajapaksha et al., 2016; Mandal et al., 2021). However, issues of variability of raw materials, standardisation of production, regeneration efficiency, environmental safety and scalability of implementation are major barriers to commercialization (Xiang et al., 2020; Lima et al., 2025).

In conclusion, biochar offers a sustainable and diverse solution for water purification, highlighting its potential to promote healthier environments and enhance water quality. The future promise of the material is that it will become even more effective with continued advances in material engineering, process optimization, environmental assessment, and field-scale validation, and will be able to be integrated into next-generation water treatment systems. These will make a heavy contribution to the world's quest to have water supplies that are safe, affordable and sustainable for future generations.

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