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Advances in biochar-based absorbents: Sustainable solutions for heavy metal removal from contaminated water

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Heavy metal contamination in water poses serious environmental and health risks, necessitating cost-effective and sustainable remediation methods. Biochar, a carbon-rich material produced through the pyrolysis of organic waste such as agricultural residues, sewage sludge, and marine algae, has emerged as an efficient adsorbent for removing heavy metals. This review examines recent advancements in biochar-based adsorption, focusing on key factors influencing its efficiency, including feedstock type, pyrolysis conditions, surface functionality, and porosity. The study explores the role of modified biochars, such as magnetic biochar, in enhancing metal recovery while maintaining high adsorption capacity. The adsorption mechanisms like cation exchange, electrostatic interactions, complexation, and precipitation are analysed to explain the effectiveness of biochar in capturing heavy metals such as Pb(II), Cd(II), Cu(II), and Zn(II). Additionally, the impact of parameters such as pH, contact time, and initial metal concentration on adsorption performance is discussed. While biochar presents a scalable and eco-friendly wastewater treatment solution, challenges such as competitive adsorption in multi-metal systems, regeneration efficiency, and production costs remain there. Future research should focus on optimising biochar modifications, integrating it with existing treatment technologies, and enhancing its selectivity for specific contaminants.

Keywords: Biochar, Contaminated water treatment, Heavy metal adsorption, Magnetic biochar, Metal ion removal, Water remediation

Introduction

Background on heavy metal contamination in water

Heavy metal contamination in water is a pressing environmental and public health issue due to the persistence, bioaccumulation, and toxicity of these pollutants. Significant sources of heavy metal contaminants include industrial discharge, mining activities, agricultural runoff, and municipal waste. Industries such as electroplating, textiles, battery manufacturing, and electronics produce wastewater containing metals like Cadmium (Cd), lead (Pb), Copper (Cu), and Zinc (Zn). When untreated, this wastewater can contaminate local water systems, introducing toxic metals into the environment. Similarly, mining and smelting operations release metals during ore extraction and processing, which can infiltrate water systems through surface runoff or groundwater seepage. The toxic effects of heavy metals, including Cd, Pb, Cu, and Zn, are profound, impacting both human health and ecosystems even at low concentrations. Cadmium exposure can lead to severe health issues, such as kidney damage, skeletal demineralisation, and respiratory problems.

Chronic exposure has also been linked to carcinogenicity and bone disorders. In aquatic ecosystems, cadmium accumulates in species, disrupting food webs and posing a threat to biodiversity. Lead, especially harmful to children, interferes with neurological development, cognitive functions, and behaviour, while in adults, it is associated with cardiovascular, renal, and reproductive complications. Ecologically, lead harms soil health, reduces fertility, and negatively impacts aquatic life, leading to decreased species diversity. Copper, though essential in trace amounts, becomes toxic when over-accumulated, causing gastrointestinal, hepatic, and neurological symptoms in humans[1].

In contrast, in aquatic environments, high copper concentrations disrupt fish respiration, leading to mortality. Zinc, essential at low levels, can cause toxicity when elevated, resulting in gastrointestinal and neurological issues in humans and stunting growth and reproductive capacity in aquatic species. The persistence of heavy metals in the environment, coupled with their tendency to bioaccumulate and biomagnify, means that contamination can have long-lasting effects on both

ecosystems and human health[2]. These metals accumulate in soils, waters, and organisms, moving up the food chain and posing risks to top predators, including humans. The environmental and ecological risks posed by heavy metals highlight the need for effective remediation methods to manage contaminated water bodies. Among potential solutions, biosorption using materials like biochar has gained attention as a low-cost and environmentally friendly approach for removing heavy metals. Biochar's ability to adsorb heavy metals offers promise in mitigating contamination, thereby protecting public health and promoting ecological stability.[3]

Importance of biochar in environmental remediation

Biochar is a porous, carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions. In recent years, biochar has garnered significant interest due to its unique characteristics, including low cost, environmental sustainability, diverse feedstock availability, and stability in both mechanical and thermal conditions. These qualities make biochar an attractive option for various environmental applications, particularly in wastewater treatment for removing heavy metals[4]. Numerous studies have demonstrated the potential of biochar in adsorbing heavy metals from wastewater, attributed to its highly porous structure and abundance of functional groups[5]. Moreover, recent investigations have shown that biochar's sorption performance can be significantly enhanced through physical and chemical modifications. Surface activation using acids (HNO_3, H_3PO_4), bases (KOH, NaOH), or metal doping with iron, manganese, and magnesium has been found to increase the surface area, introduce new functional groups, and create active sites for complexation with metal ions[6]. These modifications promote mechanisms such as ion exchange, electrostatic interaction, surface precipitation, and chelation, which collectively improve removal efficiencies for metals like Pb^{2+}, Cd^{2+}, Cr^{6+}, and Cu^{+2} Ref. [2]. Various types of biochar derived from feedstocks, such as sawdust[4], peanut shell, and energy cane[7] have shown effectiveness as sorbents for heavy metal removal. Common biochar feedstocks include agricultural wastes like wood, rice straw, and fruit peels, as well as non-traditional materials such as dairy manure and wastewater sludge[8], microalgae, and marine macroalgae[9]. Marine macroalgae-derived biochar, in particular, has demonstrated enhanced heavy metal uptake attributed to its higher ash content, elevated pH, and presence of oxygenated surface functional groups that facilitate cationic metal sorption. Beyond standalone adsorption, biochar is increasingly being integrated into composite and hybrid systems—such as biochar-supported nanomaterials, membranes, and bio-electrochemical reactors—for synergistic pollutant removal[1]. These novel configurations offer higher selectivity, faster kinetics, and improved regeneration capabilities. However, despite these advancements, a systematic understanding of how modification techniques influence performance across different wastewater matrices remains fragmented in the literature. This review aims to consolidate these findings and highlight emerging design strategies for biochar-based systems in real-world remediation scenarios[3].

Aim of the review

This review aims to explore recent advancements in the use of biochar-based adsorbents for removing heavy metals from contaminated water sources. This review also includes a comprehensive overview of current research developments, focusing on the properties of biochar that make it a promising solution for heavy metal adsorption, including its porous structure, surface functionality, and adaptability to a wide range of feedstocks. Unlike previous reviews, which often focus broadly on general adsorption trends or conventional feedstocks, this review uniquely emphasises emerging trends in feedstock innovation (e.g., marine macroalgae, industrial sludge), novel surface modification strategies (e.g., metal doping, nanocomposite integration), and adsorption mechanisms under variable environmental conditions. It also aims to bridge a gap in the literature by comparing biochar performance across real wastewater systems versus laboratory simulations—an area that remains underreported and poorly understood[3]. By examining recent findings, this review aims to elucidate the mechanistic pathways through which biochar interacts with various heavy metals, including ion exchange, electrostatic attraction, surface complexation, and redox interactions. Furthermore, it assesses the efficiency of biochar across diverse treatment scenarios, including industrial effluents, mine drainage, and synthetic wastewater, and evaluates its regeneration potential and field applicability. In doing so, this review introduces a novel classification framework for biochar adsorbents based on feedstock type, modification level, and performance in real-world matrices. This is intended to guide future research toward designing targeted, application-specific biochar materials for optimised heavy metal remediation.

Novelty and scope of this review

In recent years, several review articles have investigated the role of biochar in heavy metal remediation; however, most of these studies have focused on conventional feedstocks, generalised adsorption performance, or isolated aspects of modification techniques. This review diverges from earlier literature in three significant ways. First, it synthesises and evaluates findings related to emerging biochar feedstocks, including marine macroalgae, industrial sludge, and invasive plant biomass, which are underexplored in previous reviews yet possess distinctive chemical and structural properties favourable for heavy metal sorption[9]. Second, it emphasises a mechanistic and comparative analysis of different surface functionalisation strategies (e.g., metal doping, oxidation, alkaline activation) by mapping how these modifications influence biochar-metal interactions under varying water chemistry conditions. This provides a clearer picture of how structure-function relationships govern performance.

Third, this review addresses the translation gap between lab-scale studies and field-scale applications of biochar in real wastewater systems in a unique manner. While many published works assess metal adsorption in controlled laboratory conditions, few critically compare these results with performance in complex, variable real-world effluents. This review compiles such comparative insights to reveal how biochar properties must be optimised based on the actual characteristics of wastewater, including pH, ionic strength, presence of competing ions, and organic matter content. Furthermore, this review proposes a novel classification framework that categorises biochar adsorbents based on feedstock type, level of surface engineering, and wastewater matrix compatibility. This approach could inform future material design and deployment strategies. By bridging overlooked themes in biochar-based remediation—particularly in the context of scalability, regeneration, hybrid systems, and feedstock valorisation—this review aims to serve as a forward-looking reference for both academic researchers and practitioners. It not only consolidates current knowledge but also outlines actionable insights for overcoming practical limitations, thereby enhancing the potential of biochar as a next-generation sorbent for sustainable water treatment applications.

Properties and Characteristics of Biochar

Biochar is a carbon-rich solid material produced through the pyrolysis of biomass in an oxygen-limited environment. This process involves the thermal decomposition of organic materials, such as agricultural residues, wood, and other biomass sources, at temperatures typically ranging from 300°C to 700°C. The resulting biochar exhibits a high carbon content and stability, making it suitable for various environmental applications, particularly in the remediation of contaminated soils and water[10]. The characteristics of biochar, including its physicochemical properties, can vary significantly depending on the feedstock used and the conditions of the pyrolysis process[11]. Depending on the type of feedstock and pyrolysis parameters, such as temperature, residence time, and heating rate, the physicochemical characteristics of biochar can vary significantly. This tunability enables the optimisation of biochar for targeted applications, especially for the adsorption of heavy metals, where surface chemistry and porosity play critical roles. Consequently, biochar can be tailored to enhance its adsorption capabilities for specific contaminants, such as heavy metals in wastewater. The summary of key properties of biochar is given in Table 1.

Key properties of biochar for adsorption

The effectiveness of biochar as an adsorbent for heavy metal removal is primarily attributed to its unique properties, which include high porosity, a large surface area, and the presence of various functional groups. These characteristics facilitate the adsorption processes that are essential for capturing and immobilising contaminants in wastewater. The porous structure of biochar provides a large surface area for adsorption, while its chemical composition enables interactions with dissolved metal ions[12].

Table 1 — Summary of key properties of biochar

Property	Description	Influence on Adsorption	References
Surface Area	Typically ranges from 100 to 1000 m^2/g	Higher surface area increases the adsorption capacity	[13]
Porosity	Micropores and mesopores facilitate the transport	Enhances accessibility to adsorbate	[19]
Functional Groups	Includes carboxyl, hydroxyl, and carbonyl groups	Promotes ion exchange and complexation	[18]
Thermal Stability	High stability under varying temperatures	Reduces degradation of Biochar	[12]
Chemical Stability	Resistance to leaching of adsorbed contaminants	Ensures long-term efficacy	[14]

Furthermore, the modification of biochar, whether through physical activation or chemical treatments, can enhance its adsorption efficiency, making it a versatile material for environmental remediation[13]. Advanced modification methods—including acid/base activation, metal ion impregnation (e.g., Fe^{3+}, Mn^{2+}), and oxidative treatment—can significantly increase the density and variety of active sites on biochar surfaces. These tailored properties make biochar adaptable for treating a broad spectrum of heavy metals, including both cationic and anionic species.

Porosity and surface area

The porosity and surface area of biochar play crucial roles in its efficacy as an adsorbent for heavy metals. The high surface area, typically ranging from 100 to 1000 m^2/g, allows for extensive interaction with contaminants, while the porous structure facilitates the transport of metal ions to the internal surfaces of the biochar [14]. For instance, slow pyrolysis at moderate temperatures (400–600°C) often results in biochars with well-developed mesoporosity, which is particularly effective for adsorbing larger metal complexes[15]. Conversely, high-temperature biochars tend to have reduced surface functional groups but increased surface area, making them suitable for physical adsorption-based mechanisms. Therefore, feedstock selection and pyrolysis control are critical in designing biochar with optimal adsorption potential for specific contaminants.

Functional Groups

The presence of functional groups on the surface of biochar is critical for its interaction with heavy metals. Functional groups such as carboxyl, hydroxyl, and carbonyl groups can enhance the adsorption capacity through various mechanisms, including ion exchange and complexation[16]. The type and abundance of these functional groups depend on the feedstock and the pyrolytic conditions employed during biochar production. For instance, biochars produced at higher temperatures tend to have few functional groups but increased carbon content, which may influence their affinity for different heavy metals. Modifying Biochar through chemical treatments can introduce or enhance these functional groups, thereby improving its overall adsorption performance[17]. Moreover, surface functionalisation using oxidising agents (e.g., HNO_3, H_2O_2) or metal salts (e.g., $FeCl_3$, $KMnO_4$) has been widely applied to introduce new functional moieties or enhance metal-binding sites. These treatments enhance specific interactions with metal ions, such as inner-sphere complexation and redox-driven adsorption[3].

Thermal and chemical stability

Biochar is renowned for its thermal and chemical stability, which significantly influences its application as an adsorbent in wastewater treatment. The stability of biochar is primarily due to its refractory nature, which enables it to withstand degradation under various environmental conditions [12]. This stability is beneficial not only for ensuring the longevity of biochar in adsorption applications but also for minimising the leaching of adsorbed heavy metals back into the environment. Long-term column studies have demonstrated that biochar can retain over 80% of its metal adsorption capacity after multiple adsorption-desorption cycles, highlighting its reusability and sustainability in real-world systems.Its chemical inertness also allows for integration with other technologies, such as membranes or microbial systems, without structural breakdown [18].

Factors affecting biochar properties

Pyrolysis temperature

The pyrolysis temperature is a crucial factor influencing the properties of biochar. Studies have shown that as the pyrolysis temperature increases, the surface area and porosity of biochar significantly increase. For instance, Mohan *et al.*[7] conducted experiments to evaluate the impact of pyrolysis temperature on biochar derived from sugarcane bagasse. They observed a significant increase in surface area from 50 m^2/g at 300°C to over 300 m^2/g at 600°C. Similarly, Lu *et al.*[12] highlighted that biochars produced at higher temperatures (>500°C) not only exhibited large pore sizes but also a high carbon content, contributing to improved stability and adsorption performance. However, Vijayaraghavan *et al.* [20] noted that excessive temperatures (>700°C) may lead to the degradation of functional groups essential for metal ion interactions. Their study on pinewood-derived biochar indicated a 50% reduction in surface oxygenated groups at temperatures exceeding 700°C, leading to diminished adsorption capacities for lead ions. Furthermore, high pyrolysis temperatures typically increase the aromaticity and graphitic nature of biochar, which enhances long-term stability in soil and aqueous systems but may reduce the availability of polar functional groups crucial for chemisorption processes. This introduces a trade-off

between surface area and chemical reactivity, emphasising the importance of optimising pyrolysis conditions based on the target contaminant and treatment context.[21]

Feedstock Types

The selection of biomass feedstock has profound implications for the physicochemical properties of the resulting biochar. For instance, Hopkins et al.[22] conducted a comparative study of biochar derived from various feedstocks, including straw, wood chips, and animal manure. They found that biochar produced from wood chips exhibited the highest surface area (over 500 m^2/g) and the most remarkable adsorption capacity for cadmium ions, while straw-derived biochar showed significantly lower adsorption capacity due to its higher ash content and lower surface area (around 250 m^2/g). Furthermore, Xing *et al.*[23] reported that biochar from lignocellulosic sources contained a higher concentration of oxygen-containing functional groups, which are pivotal for binding heavy metals. In addition to common lignocellulosic biomass, recent studies have explored marine biomass, invasive plant species, and sewage sludge as alternative sources of feedstock. These sources can introduce nitrogen-, sulphur-, or phosphorus-containing functionalities into the biochar matrix, potentially improving its affinity for both cationic and anionic contaminants[3]. However, the variability in elemental composition and ash content also demands careful preprocessing and performance evaluation to ensure suitability for specific applications.

Surface Modification Techniques

Surface modification techniques are employed to enhance the adsorption properties of biochar, allowing for more effective removal of heavy metals from contaminated water. Ahmad et al.[13] reviewed various modification methods and demonstrated that chemical treatments significantly increased the adsorption capacity of biochar. For example, a study by Wang *et al.* [18] investigated the effects of sulfuric acid treatment on corn stalk-derived biochar. The treated biochar exhibited a 150% increase in Pb^{2+} adsorption capacity compared to untreated biochar due to the introduction of carboxylic functional groups that promote ion exchange. Similarly, Zhang *et al.*[8] highlighted that steam activation of pinewood biochar resulted in increased surface area and a significant improvement in its capacity to adsorb cadmium, confirming the importance of surface modification in optimising biochar's performance in wastewater treatment applications. Recent advancements include the use of iron, manganese, and zero-valent metal impregnation to introduce redox-active sites that enhance the removal of chromium and arsenic through redox-adsorption synergy[21]. Additionally, nanostructured biochar–metal oxide composites have shown promising results for selective adsorption under competitive multi-metal conditions. These approaches are paving the way for multi-functional adsorbents with tailored surface chemistry.

Mechanisms of Heavy Metal Adsorption

Electrostatic Interaction

Electrostatic interactions are a primary mechanism by which biochar adsorbs heavy metals. These interactions occur when oppositely charged ions attract each other, facilitating the binding of metal cations to the negatively charged sites on the biochar surface. For example, Znad *et al.* [24] investigated the electrostatic interactions between lead ions and biochar produced from rice husk-derived biochar and found that the adsorption capacity was significantly influenced by pH. Maximum lead uptake occurred near pH 5, where the biochar surfaces were sufficiently negatively charged, allowing Pb^{2+} to remain in its cationic form, thereby optimising attraction. The magnitude of electrostatic attraction is influenced by solution chemistry, including pH, ionic strength, and the point of zero charge (pHpzc) of the biochar. At pH values above the pHpzc, the surface becomes negatively charged, favouring the adsorption of positively charged metal ions. However, at lower pH, competition with H^+ ions may suppress this mechanism, particularly for divalent metals such as Zn^{2+} or Ni^{2+}. As shown in Fig. 1, the electrostatic attraction facilitates the binding of lead ions to the negatively charged sites on biochar.

Ion Exchange

Ion exchange is another crucial mechanism that facilitates the adsorption of heavy metals by biochar. In this process, metal ions in the solution are exchanged for cations present on the surface of the biochar. A study by Bak *et al.*[25] on biochar produced from coconut coir demonstrated that sodium ions in the biochar could be replaced by cadmium ions from the solution, thereby enhancing cadmium removal efficiency. The authors found that the ion exchange capacity of the biochar was strongly correlated with its cation exchange capacity (CEC), further supporting the role of ion exchange in the adsorption

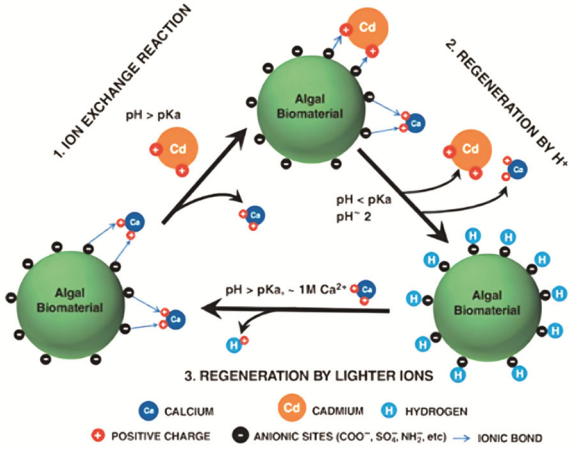

Fig. 1 — Electrostatic interactions between lead ions and biochar (source: [24])

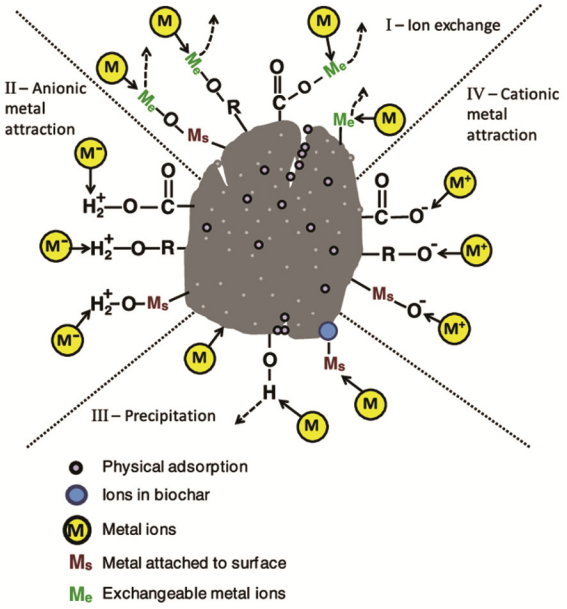

Fig. 2 — Ion exchange mechanism between sodium and cadmium ions (source: [24])

of heavy metals. In highly porous and functionally rich biochars, cation exchange may proceed through outer-sphere or inner-sphere complexation pathways, depending on the dynamics of the hydration shell. The biochar matrix can be pre-loaded with low-affinity cations (e.g., Na^+, K^+) to increase exchange selectivity toward higher-valent or toxic metals like Cd^{2+} and Cr^{3+}. The competitive nature of ion exchange means it is sensitive to the presence of background electrolytes such as Ca^{2+} or Mg^{2+} in real wastewater matrices, which may inhibit exchange unless selectivity is engineered through surface modification This exchange contributes not only to higher removal efficiencies but also to the biochar's selectivity for specific metal ions, depending on its initial ionic composition and treatment conditions. The ion exchange mechanism between sodium and cadmium ions is shown in Fig. 2.

Complexation with functional groups

Biochar contains various functional groups, such as carboxyl, hydroxyl, and carbonyl groups, which can interact with heavy metal ions through complexation. This mechanism enables the formation of stable complexes between metal ions and functional groups, thereby significantly enhancing the adsorption capacity. Wang et al.[18] examined the complexation ability of bamboo-derived biochar and reported that carboxyl and phenolic groups were primarily responsible for Pb^{2+} binding, forming inner-sphere surface complexes. Complexation is highly dependent on pH, as deprotonation of surface functional groups (–COOH → $–COO^-$) enhances ligand availability for metal coordination. Advanced spectroscopic studies

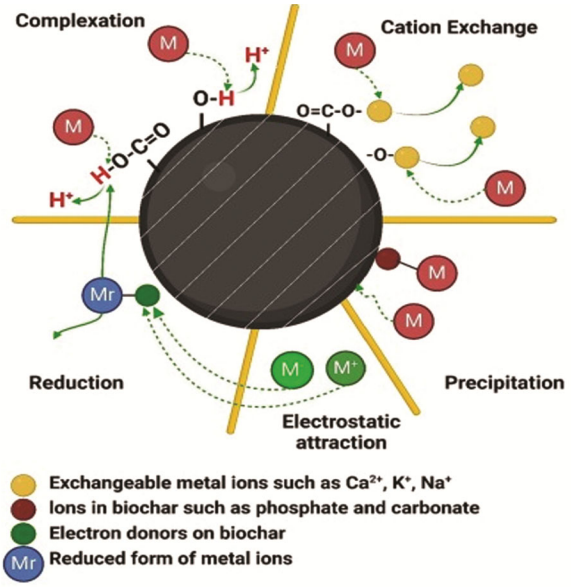

Fig. 3 — Complexation between lead ions and functional groups on biochar (source: [26].)

such as FTIR, XPS, and NEXAFS have confirmed the formation of surface complexes, including –COO–Pb and –OH–Cu bonds[17]. These interactions often dominate at mid to neutral pH, particularly for metals with strong affinities for oxygen- or nitrogen-containing ligands. As shown in Fig. 3, the complexation process illustrates how lead ions interact with functional groups on biochar, thereby increasing adsorption efficiency.

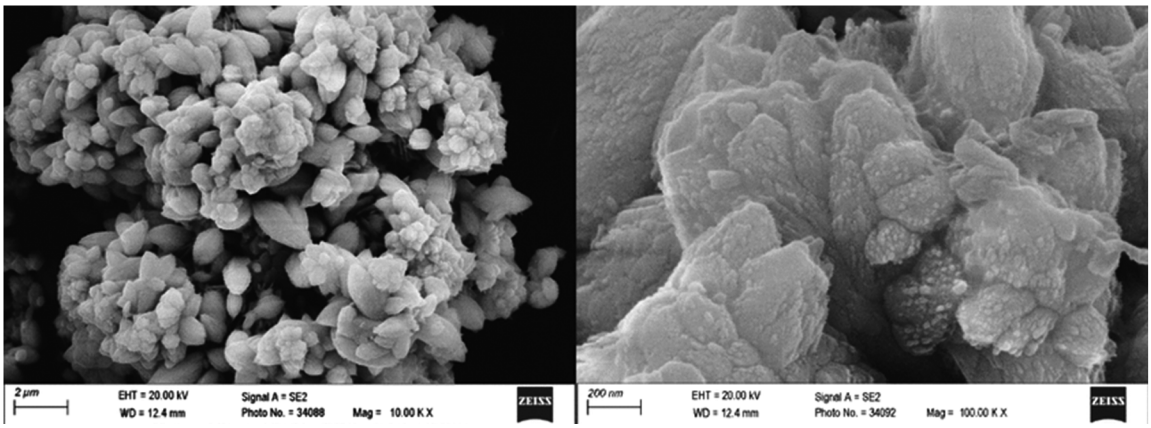

Fig. 4 — SEM images of lead ions precipitated as lead carbonate by biochar derived from wood chips (source: [27])

Precipitation and metal reduction

In addition to adsorption mechanisms, biochar can also facilitate the precipitation of heavy metals and their reduction to less toxic forms. Cheng *et al*.[27] demonstrated that woodchip-derived biochar promoted Pb^{2+} precipitation as $PbCO_3$ due to the release of carbonate ions during pyrolysis. Additionally, sulfur-containing biochars can form insoluble metal sulphides under reducing conditions. Metal reduction is particularly relevant for redox-sensitive contaminants like Cr(VI), which can be reduced to Cr(III) by electron-donating groups or redox-active moieties on the biochar surface (e.g., quinones, phenols). This not only immobilises the metal but also reduces its toxicity[21]. Precipitation and redox reactions are especially useful in complex wastewater where multiple forms of metals co-exist. However, these mechanisms require precise control of pH, redox potential, and competing anions, such as phosphate and sulphate. As depicted in Fig. 4, the precipitation of lead ions illustrates the conversion of soluble lead into insoluble forms, enhancing removal from wastewater.

Adsorption isotherms

The adsorption isotherm is a critical tool for evaluating the interaction between adsorbate molecules and the adsorbent surface. In this study, three classical models like Langmuir, Freundlich, and Dubinin–Radushkevich (D–R) were used to fit the isotherm data of ACE and AMX adsorption onto both unmodified (B7) and $ZnCl_2$-activated Biochar (BZn7). The Langmuir isotherm, which assumes monolayer adsorption on a homogeneous surface, provided the best fit for ACE adsorption onto BZn7 (R^2 = 0.9981), indicating a high degree of surface uniformity and strong adsorbate–adsorbent affinity. On the other hand, the Freundlich model fit AMX adsorption more accurately (R^2 = 0.9931), suggesting a multilayer adsorption behaviour on heterogeneous surfaces, likely due to the varied interaction sites on biochar. The maximum adsorption capacities (Q_{max}) obtained from the Langmuir model were significantly higher for BZn7 than for B7, at 332.08 mg/g for ACE and 175.86 mg/g for AMX, compared to 64.99 and 26.62 mg/g, respectively, for B7. This difference is attributed to the enhanced porosity, higher surface area, and abundance of functional groups in BZn7, which result from $ZnCl_2$ activation[28]. These values not only surpass those of many other adsorbents reported in literature, such as orange-peel biochar (118 mg/g for ACE) and peanut husk activated carbon (168 mg/g for AMX), but also highlight BZn7's potential as a highly competitive adsorbent for wastewater treatment. The D–R isotherm model was employed to determine the nature of the adsorption mechanisms. The calculated mean adsorption energies (E) for both ACE and AMX were below one kJ/mol (0.31 kJ/mol for ACE, 0.04 kJ/mol for AMX), indicating that physisorption is the dominant mechanism for both compounds. However, the relatively higher E value for ACE suggests a slightly stronger interaction, possibly due to its smaller molecular size and ability to penetrate micropores more effectively. These results align well with FTIR and pore analysis studies, which revealed that micropore filling and n–π interactions are key contributors to ACE adsorption. In contrast, AMX adsorption is governed more by surface functional group interactions (hydrogen bonding and zwitterionic charge balancing).

Comparative analysis of mechanisms for different heavy metals

Lead

Lead (Pb), a toxic heavy metal often found in industrial wastewater, is effectively removed by

biochar primarily through ion exchange and complexation mechanisms. Due to its relatively large ionic radius and high affinity for negatively charged surfaces, lead ions (Pb^{2+}) interact well with biochar that contains oxygenated functional groups, such as carboxyl and hydroxyl. As reported by Bandara *et al*.[28], biochar derived from agricultural residues such as rice husk, corncob, and wheat straw exhibited excellent Pb^{2+} removal performance, primarily driven by ion exchange between lead and exchangeable surface cations (e.g., Na^{+}, Ca^{2+}), and surface complexation with oxygen-containing moieties. These mechanisms operate synergistically: ion exchange initiates rapid adsorption, while complexation provides potent and selective binding. Notably, lead adsorption remains high over a broad pH range (5–7), as Pb^{2+} maintains its cationic form and readily interacts with deprotonated functional groups. Additionally, higher pyrolysis temperatures (above 500°C) enhance the aromatic carbon content and surface functionalisation of biochar, thereby increasing the density of available complexation sites and improving adsorption stability[29].This suggests that selecting high-cellulose feedstocks and controlling pyrolysis conditions are key to optimising Pb^{2+} adsorption performance[30].

Cadmium

Biochar effectively removes Cadmium (Cd) through a combination of electrostatic interactions and ion exchange. However, the efficiency of each mechanism depends on specific properties such as biochar surface charge and cation exchange capacity (CEC). Smaller in ionic radius than lead, Cd^{2+} ions benefit from high-porosity and mesoporous structures in biochar, which increase contact surface area and diffusion pathways[22]. Bandara *et al*.[28] reported that rice husk biochar, with its high CEC and micropore volume, outperformed wheat straw-derived biochar in cadmium adsorption, particularly at near-neutral pH where Cd^{2+} competes less with protons for binding sites. Cadmium adsorption is also enhanced by the presence of surface hydroxyl and phenolic groups that promote both outer-sphere and inner-sphere complexation[30]. These interactions become dominant at pH 6–8, where surface deprotonation increases the number of negatively charged adsorption sites. Furthermore, thermally treated biochars (500–600°C) exhibit improved stability and greater surface reactivity, confirming the importance of pyrolysis temperature in Cd^{2+} remediation.

Copper

Copper adsorption by biochar is typically governed by complexation with functional groups and ion exchange, making it effective when biochar is rich in oxygenated functional groups. Copper ions (Cu^{2+}) exhibit a high affinity for functional groups such as carboxyl, hydroxyl, and carbonyl, which form stable complexes with the metal ions. Alfei *et al*.[26] found that wood-derived biochar, rich in these functional groups, efficiently removed Copper primarily through complexation. This study concluded that complexation mechanisms significantly enhance the stability of copper adsorption, making it less susceptible to environmental conditions such as pH fluctuations. Unlike Cd^{2+} or Zn^{2+}, Copper is also more redox-reactive in the presence of modified or doped biochars. Some studies have noted a partial reduction of Cu^{2+} to Cu^{+} or precipitation as $Cu(OH)_2$ at elevated pH levels (>7), thereby enhancing immobilisation[30]. This dual mechanism—adsorption and partial redox conversion—offers added stability, especially in systems with fluctuating pH and ionic strength.

Zinc

Zinc adsorption by biochar primarily relies on electrostatic interactions and cation exchange, particularly under alkaline conditions. Zn^{2+}, due to its relatively small hydrated radius and high charge density, is efficiently attracted to negatively charged surfaces, especially those with high pHpzc values. Xu *et al*.[31] demonstrated that coconut shell-derived biochar exhibited enhanced Zn^{2+} removal via surface ion exchange, supported by its high surface area and well-developed microporosity. Electrostatic attraction increases as solution pH exceeds the biochar's point of zero charge, typically between pH 6 and 8. Zinc also interacts with surface silanol and carboxyl groups, although less strongly than Cu^{2+} or Pb^{2+}. This makes pH optimisation and pre-treatment of biochar crucial for enhancing Zn^{2+} uptake[14]. Moreover, Zn^{2+} is more susceptible to competitive inhibition in multi-metal systems, necessitating the design of tailored adsorbents when co-contaminants are present[29].

Biochar Feedstocks

The type of feedstock used for biochar production plays a significant role in determining its properties, which in turn affect its adsorption efficiency for heavy metals. Each feedstock contributes a different elemental composition, functional group, and mineral content, which impacts the biochar's performance in

removing contaminants from wastewater. This section explores four primary types of biochar feedstocks, emphasising the influence of their unique properties on adsorption efficiency.

Agricultural waste-based biochar

Agricultural wastes such as rice husks, wheat straw, and corn stover are widely utilised as biochar feedstocks. These materials typically yield biochars with a high surface area and rich in functional groups, thereby enhancing their adsorption capacity for heavy metals such as cadmium, lead, and Copper. In particular, biochars derived from rice husks exhibit excellent adsorption performance due to their high CEC and oxygenated functional groups, as evidenced by Bandara *et al*.[28].This study found that rice husk biochar effectively removed cadmium and lead from the solution, attributed to ion exchange and complexation mechanisms. Additionally, biochar derived from agricultural residues can be a cost-effective and sustainable option for large-scale wastewater treatment. Recent studies have shown that the silica-rich ash content in rice husk biochar also contributes to the immobilisation of metal ions like Cr(VI) and As(V) through surface precipitation and ligand exchange[32]. This makes rice-based biochars not only efficient in terms of physical adsorption but also chemically reactive across a wide range of pH values.

Forestry waste and wood-based biochar

Forestry waste, including sawdust and wood chips, produces biochar with high stability and porosity, making it an ideal material for adsorbing heavy metals. Biochars derived from wood-based feedstocks, such as pinewood, are effective in removing lead and Copper, primarily due to their large surface area and abundant surface functional groups. The research by Tan *et al*.[33] highlights the influence of pyrolysis temperature on the properties of pinewood biochar. They demonstrated that higher temperatures increase the surface area, thereby enhancing the adsorption of metals like lead. This indicates that optimising pyrolysis conditions can significantly boost the adsorption capacity of wood-based biochars. Wood-derived biochars also exhibit high thermal stability and consistent elemental composition, which is beneficial in maintaining performance under variable field conditions. For example, Boni *et al*.[34] observed that pinewood biochar retained over 80% of its initial arsenic adsorption capacity after multiple column cycles, indicating excellent long-term applicability in fixed-bed systems.

Manure and sewage sludge-based biochar

Biochar derived from manure and sewage sludge exhibits a unique composition, characterised by a high mineral content, alkaline nature, and specific functional groups. This composition enhances its ability to adsorb heavy metals, often via precipitation and electrostatic interactions. For instance, a study by Wystalska *et al*.[19] showed that sewage sludge biochar exhibited high adsorption capacities for metals like Copper and nickel due to its ash content and basic pH, which facilitate metal precipitation reactions. Such biochars are particularly advantageous in treating industrial wastewater with high metal concentrations, as the mineral-rich composition contributes to more robust adsorption mechanisms. However, these biochars may also contain potentially harmful trace contaminants (e.g., PAHs, heavy metals), depending on the sludge origin. Han et al.[35] recommend that sewage-derived biochars be thermally treated at temperatures above 600°C to reduce organic pollutants and enhance their stability for environmental applications.

Algal biochar

Algal Biochar, derived from macroalgae and microalgae, is gaining attention due to its unique nitrogen, sulphur, and phosphorus content, which introduces additional functional groups beneficial for heavy metal adsorption. Tan *et al*.[21] found that algal biochar exhibited high adsorption capacities for metals such as lead and Zinc, facilitated by nitrogen-rich functional groups that enable complexation and electrostatic interactions. Algal biochar's versatility and nutrient content make it promising for specific applications where enhanced adsorption of diverse metal ions is required. Moreover, Jung *et al*.[9] demonstrated that marine macroalgae biochar showed high phosphate and heavy metal removal efficiency, attributed to its elevated pH, high mineral content, and structural uniformity. Algal biochars also degrade more rapidly under field conditions, which may enhance nutrient release but require optimisation of their performance for reuse scenarios.

Biochar Modification Techniques

Physical modification methods

Physical modification methods are essential for enhancing the adsorptive capacity of biochar. Thermal

treatment and activation (using steam or CO_2) are widely employed to increase surface area and pore volume and improve surface functionality. Such modifications often yield biochar with enhanced porosity and higher surface area, which are favourable characteristics for adsorbing heavy metal ions from wastewater.

Thermal Treatment

Thermal treatment of biochar typically involves heating biomass at elevated temperatures in an inert or limited oxygen environment. This pyrolysis process alters the structural and chemical properties of the biomass, increasing its stability, carbon content, and porosity. Research has shown that the temperature and duration of pyrolysis significantly impact the surface area, pore structure, and functional groups present in biochar, which, in turn, affect its adsorption performance for heavy metals. For example, Leng *et al*. [36] observed that increasing the pyrolysis temperature from 400°C to 700°C resulted in a biochar with a higher surface area and microporosity, thereby enhancing its effectiveness in adsorbing lead (Pb^{2+}) and Cadmium (Cd^{2+}) from aqueous solutions. This improvement is attributed to the increased presence of oxygen-containing functional groups at higher pyrolysis temperatures, which facilitates the formation of heavy metal binding sites on the biochar surface. Another study by Hu *et al*. [37] highlighted that biochar prepared at high temperatures (600°C-800°C) showed increased pore size and volume, enhancing its adsorption performance. However, excessively high temperatures can lead to a decrease in surface functional groups, especially oxygenated species, which are essential for metal ion complexation, indicating the need to optimise pyrolysis conditions rather than maximise them indefinitely[11].

Activation by steam or CO_2

Activation is another physical modification technique used to enhance the porosity and surface area of biochar. Unlike thermal treatment, which involves heating in an inert atmosphere, activation is achieved by exposing biochar to steam or carbon dioxide at elevated temperatures. This process creates additional micro- and mesopores, thereby increasing the number of available adsorption sites for metal ions. Activation by steam or CO_2 has been shown to significantly improve the adsorption capacity of biochar. For instance, Bushra *et al*.[32] conducted a study where biochar activated with steam at 800°C exhibited a 40% increase in surface area and a 35% higher adsorption capacity for zinc ions (Zn^{2+}) compared to non-activated biochar. This enhancement was attributed to the formation of a highly porous structure, which provides more binding sites for heavy metal ions, as shown in Fig. 5. Activation using CO_2, on the other hand, also proves to be effective in enhancing the adsorption properties of biochar. In a study by Cha et al.[38], CO_2-activated Biochar demonstrated a higher adsorption capacity for arsenic (As^{5+}) ions due to its increased surface area and favourable surface charge characteristics, making it an effective adsorbent for negatively charged metal ions in aqueous solutions. Furthermore, steam and CO_2 activation techniques are environmentally preferable alternatives to chemical activation, as they do not introduce secondary pollutants or corrosive residues [35]. They are particularly advantageous in designing reusable adsorbents for large-scale or column-based applications. However, the effectiveness of physical activation is also feedstock-dependent: biomass with high lignin or ash content tends to respond better to steam activation than cellulose-rich feedstock

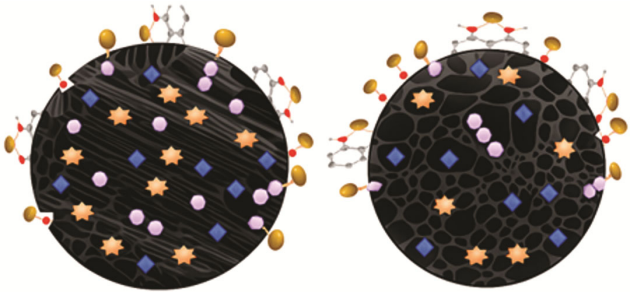

Fig. 5 — Microporous structure of (a) unactivated biochar and (b) steam/CO_2 activated biochar (Source: [32])

Chemical Modification Techniques

Acidic Treatment

Acid treatment of biochar typically involves exposing it to strong acids, such as hydrochloric acid (HCl), sulfuric acid (H_2SO_4), or nitric acid (HNO_3). This process removes impurities, increases the surface area, and introduces oxygen-containing functional groups, such as carboxyl, hydroxyl, and carbonyl groups, which serve as effective binding sites for heavy metal ions[5]. Acid-treated biochar has demonstrated enhanced adsorption of heavy metals such as Cadmium (Cd) and lead (Pb) due to the increased surface polarity and availability of these functional groups, which promote electrostatic

interactions and inner-sphere complexation with metal ions[18]. For example, nitric acid modification significantly enhanced the lead adsorption capacity of biochar, as demonstrated by Wang *et al*.[30] where the adsorption increased by over 50% after treatment, due to an increase in CEC and oxygenated surface sites. However, overexposure to strong acids can also reduce biochar stability by degrading its carbon matrix and releasing trace acidic by-products into the treated water, thereby affecting surface activation and structural integrity[35].

Alkaline treatment

In contrast to acid treatment, alkaline treatment uses bases such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) to increase the surface basicity and introduce more negative charge on the biochar surface. This modification enhances CEC and facilitates the removal of metal cations, such as Copper (Cu^{2+}) and Zinc (Zn^{2+}), through electrostatic attraction. The base-modified biochar surface has been shown to facilitate the removal of acidic metal cations from aqueous solutions through enhanced electrostatic interactions, particularly in systems with multiple metal contaminants[33]. Comparative studies have revealed that base-treated biochar exhibits significantly higher adsorption capacities than unmodified biochars. However, the extent varies based on feedstock composition and metal speciation. While alkaline treatment enhances performance, it can also leach excess Na^+ or K^+ into solution, potentially altering ionic competition and reducing selectivity. Moreover, high alkalinity may cause the pH to shift beyond optimal adsorption ranges in real wastewater [22]

Metal oxide impregnation

Impregnation of biochar with metal oxides, such as iron oxide (Fe_2O_3), manganese oxide (MnO_2), and titanium dioxide (TiO_2), is a widely explored modification technique. Metal oxide impregnation enhances both the redox and complexation capabilities of biochar, improving its adsorption efficiency for metals such as arsenic (As^{5+}), chromium (Cr^{6+}), and mercury (Hg^{2+}). These oxides introduce surface hydroxyl groups and electron donors that can promote reduction reactions, surface precipitation, or direct complexation. For instance, iron oxide-modified biochar has been demonstrated to improve the removal efficiency of Cr(VI) by reducing Cr(VI) to Cr(III), which is less toxic and more readily adsorbed on the biochar surface[39]. While metal-doped biochars offer superior reactivity, achieving uniform dispersion and long-term structural stability of the impregnated particles remains a challenge, especially under high ionic strength or variable pH conditions[38].

Nanoparticle impregnation

In addition to metal oxides, biochar can be modified with nanoparticles, such as silver (Ag), iron (Fe), and Zinc (Zn), which provide enhanced adsorption sites and, in some cases, antimicrobial properties. Nanoparticle-impregnated biochar demonstrated high efficiency in adsorbing heavy metals due to the increased surface area and reactive sites introduced by the nanoparticles[3] Silver nanoparticles, for example, not only enhance adsorption efficiency but also impart antimicrobial activity, making biochar suitable for both heavy metal removal and pathogen control in contaminated water. However, the environmental impact and cost of nanoparticle-modified biochar must be carefully considered, as these factors can limit its scalability and sustainable use in large-scale applications[40]. Recent efforts are exploring the green synthesis of nanoparticles using plant extracts or bio templates to reduce environmental impact while retaining performance[29], offering a pathway toward safer, scalable nanoparticle-biochar hybrids.

Comparison of different modification methods

Comparison of different modification methods is shown in Table 2. Modification techniques for biochar, including both physical and chemical methods, offer distinct advantages depending on the target application, feedstock, and operational constraints. Physical modifications, such as thermal treatment and gas activation, are relatively cost-effective and straightforward to scale, primarily enhancing surface area, porosity, and structural stability. These approaches are particularly suitable for large-scale or low-cost operations where the baseline adsorption capacity is sufficient. However, chemical modifications often provide superior performance in terms of heavy metal adsorption capacity due to the introduction of functional groups or the impregnation of metal oxides or nanoparticles. These chemically enhanced biochars demonstrate higher efficiency in removing a wide range of metals, particularly in complex wastewater with multiple metal contaminants, where specific interactions with functional groups and metal oxides improve selectivity and adsorption capacity [1316] In practice, the choice between physical and chemical modification depends on the particular requirements of the

Table 2 — Comparison of different modification methods

Modification method	Characteristics	Advantages	Limitations	Effective heavy metals	References
Physical Modification	Increases surface area and porosity without altering chemical structure	Cost-effective, easy to implement, suitable for large-scale use	Limited functional groups for specific metal binding	Pb, Cd, Zn	Xing *et al* [41]
Thermal Activation	High-temperature heating in an inert atmosphere creates pores	Enhances Porosity and surface area	Requires energy input; minimal effect on surface chemistry	Cu, Ni	Hu *et al*. [37]
Steam/CO_2 Activation	Introduces micro- and mesopores through high-temperature steam or CO_2 treatment	Improves adsorption capacity by creating fine pores	Increased energy demand; minimal functional group enhancement	Pb, Cd, Zn	Bushra *et al*. [32]
Chemical Modification	Alters surface chemistry with acids, bases, or metal oxides/nanoparticles	High adsorption efficiency; effective for multiple metal types	Higher cost; may require additional handling for safe application	Cr, Hg, Cu, [repeated entry deleted]	Lee *et al*. [42]
Acid Treatment	Uses acids (e.g., HCl, H_2SO_4) to remove impurities and add oxygen-containing functional groups	Increases affinity for cationic heavy metals	Risk of residual acidity; environmental disposal considerations	Cd, Pb	Wang *et al*. [30]
Base Treatment	Uses alkaline solutions (e.g., NaOH, KOH) to enhance surface alkalinity	Increases cation exchange capacity and surface reactivity	May produce waste requiring neutralisation	Cu, Zn	Tan *et al*. [33]
Metal Oxide Impregnation	Incorporates metal oxides (e.g., Fe_2O_3, MnO_2) on the biochar surface	High reactivity with specific metals; good for multi-metal systems	High production cost; potential leaching of metal oxides	As, Cr, Hg	Viotti *et al*. [39]
Nanoparticle Impregnation	Uses nanoparticles (e.g., Ag, Fe) to introduce reactive sites and antimicrobial properties	Enhanced adsorption and antimicrobial effect	Higher cost, environmental impact of nanoparticles	Pb, Cu, Cd	Almutairi *et al*. [40]

wastewater treatment application. Physical methods may be sufficient in scenarios where low to moderate concentrations of heavy metals are present. At the same time, chemical modifications are preferable for high-contamination or multi-metal systems that demand higher adsorption efficiency. Hybrid approaches that combine both physical and chemical modifications are also gaining attention, as they can balance cost and performance by leveraging the advantages of both methods[14]. For instance, biochars thermally treated at high temperatures and subsequently functionalised with Fe- or Mn-based oxides have shown remarkable performance in removing both cationic and anionic metals, including Pb^{2+}, Cr(VI), and As(V)[39]. These synergetic systems offer tailored surface properties, combining physical robustness with chemical specificity. Recent studies also emphasise the potential of biochars derived from inherently functional biomass, such as marine macroalgae, sewage sludge, or agricultural residues, which naturally contain nitrogen, sulfur, or mineral-rich components. When combined with targeted chemical treatments, these feedstocks yield biochars with an enhanced affinity for specific heavy metals, thereby minimising the need for excessive modification steps[32]. These biochars offer an environmentally sustainable solution, as they utilise renewable feedstocks while reducing the need for extensive chemical treatment. In addition to conventional methods, emerging technologies such as plasma-assisted activation, electrochemical modification, and green synthesis approaches, including the use of plant extracts for nanoparticle formation, are being explored for their ability to impart high functionality with a minimal environmental footprint[40]. These innovations also align with circular economy principles by reducing secondary pollution and energy input. Ultimately, the advancement of scalable, economically viable, and environmentally sound modification strategies—whether physical, chemical, or hybrid will play a key role in optimising biochar for diverse wastewater treatment needs. These approaches hold immense promise in delivering efficient, selective, and sustainable solutions for removing heavy metals under varying contamination conditions.

Applications of Biochar for Heavy Metal Removal

The role of biochar in removing heavy metals is well-documented across various types of wastewaters, including industrial effluents and contaminated groundwater. However, its effectiveness and behaviour in single-metal versus multi-metal systems underscore both the potential and limitations of biochar-based

treatment solutions. This section explores the distinctions in adsorption mechanisms, efficiency, and competitive dynamics between single-metal and multi-metal systems, drawing on experimental findings to provide a comparative analysis.

Single metal systems

In single-metal adsorption studies, biochar exhibits a high affinity and efficiency for individual metal ions due to the presence of specific functional groups and surface sites that remain unoccupied by competing ions. Single-metal systems are characterised by streamlined interactions where metals, such as cadmium, lead, and nickel, engage directly with biochar's functional groups, including hydroxyl, carboxyl, and carbonyl groups, through mechanisms like ion exchange, surface complexation, and precipitation. For example, Bandara et al.[28] reported high adsorption efficiencies for cadmium on rice husk-derived biochar, driven by effective binding with oxygen-containing functional groups. Without interference from other ions, the binding follows a predictable pattern, allowing precise estimations of adsorption capacity and kinetics. In single-metal settings, biochar's adsorption capacity for metals such as lead and cadmium can achieve up to 90% removal efficiency in controlled laboratory studies. This high capacity is attributed to enhanced electrostatic attraction, which is unchallenged by competing ions. The primary advantage of these systems is that biochar's active sites are utilised fully and selectively, optimising removal rates and providing insight into the optimal surface characteristics of biochar for specific metals. However, single-metal batch studies may overestimate the real-world performance of biochar, where wastewater typically contains multiple co-existing ions that compete for adsorption sites. These studies nonetheless provide essential baseline data for evaluating surface reactivity, which can inform the rational design of modified biochars with targeted affinity for priority metals[29].

Multi-metal systems

In multi-metal systems, where multiple heavy metal ions are present, biochar faces competition among ions for limited binding sites. The dynamic adsorption mechanisms in such systems make it challenging to maintain high removal efficiencies for all metals simultaneously. Studies indicate that biochar's adsorption efficiency for individual metals often decreases due to competition, as certain metals may dominate the available adsorption sites based on ionic radius, charge, or affinity for specific functional groups on biochar. Lee et al.[42] examined the competitive adsorption behaviour of biochar in a system containing lead, Copper, and Zinc. The study found that lead ions displayed the highest affinity for the biochar surface, followed by Copper and Zinc, attributed to lead's larger atomic radius and higher polarizability, which enhanced its interactions with biochar's oxygenated groups. The presence of Copper and Zinc, however, led to a 15-20% reduction in the adsorption capacity of lead compared to its uptake in a single-metal system. Such competition can be partially mitigated through surface modification strategies that increase selectivity or introduce functional groups targeting specific ions. Another study by Tan *et al*.[21] explored biochar derived from algal biomass in multi-metal systems, showing how the sulphur- and nitrogen-rich functional groups on algal biochar offered selectivity towards specific metals, such as Zinc over Copper. This suggests that the chemical composition, as well as the types of functional groups present on biochar, significantly influence adsorption in multi-metal contexts. Biochars with higher surface area and microporous structure tend to offer more adsorption sites, which can partially offset the competitive adsorption limitations seen in multi-metal systems. Recent work by Boni *et al*. [34] and Viotti *et al*. [39] suggests that column-mode systems using metal oxide-modified biochars can reduce competitive interference by enabling sequential adsorption or redox transformation pathways. Furthermore, hybrid adsorbents combining biochar with ion-imprinted polymers or nanoclaysare being investigated for their ability to selectively remove metals even in complex effluents [27].

Case studies and field applications

Industrial Wastewater

Industrial wastewater is a significant source of heavy metal contamination, primarily due to the discharge of effluents from manufacturing processes, particularly in sectors such as electroplating, textiles, and electronics. A pivotal case study conducted by Boni *et al*.[34] demonstrated the efficacy of wood chip-derived biochar in treating electroplating wastewater using a fixed-bed column system. Operational parameters such as influent concentration, flow rate, and contact time were optimised to assess performance under near-field conditions. The results indicated a remarkable reduction

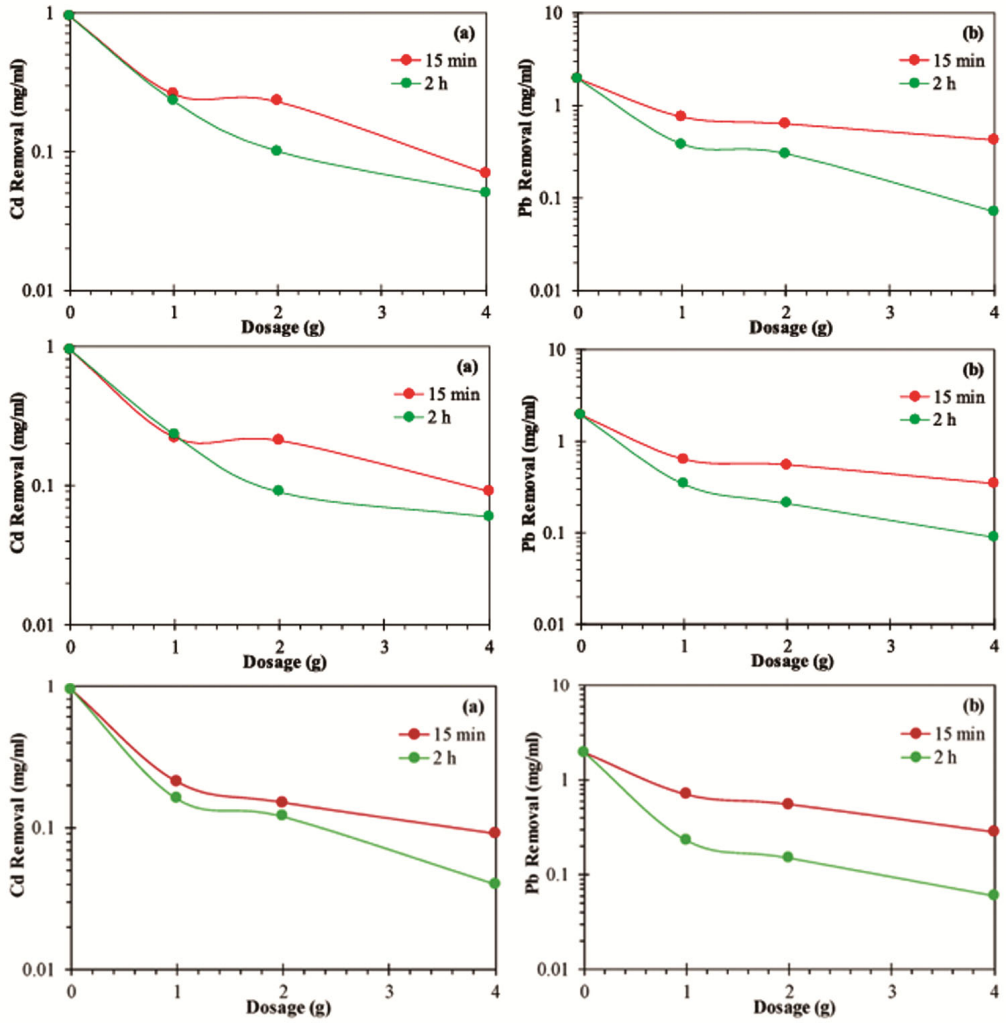

Fig. 6 — Heavy metal removal performance by biochar derived from corncob, rice husk and wheat straw (a) cadmium removal and (b) lead removal (source:[28])

of heavy metals, specifically chromium (Cr), nickel (Ni), and lead (Pb), achieving overall removal efficiencies exceeding 85%. (Fig. 6). This was attributed to the high surface area and porosity of the biochar, coupled with the presence of functional groups that facilitated ion exchange and complexation. The complexation and ion exchange of biochar with industrial wastewater are shown in Fig. 7. The regeneration potential of the biochar was also evaluated, revealing that even after three cycles of adsorption-desorption, the material retained approximately 75% of its initial adsorption capacity after three adsorption–desorption cycles, indicating its practical viability for repeated use This case also underscores the importance of column-mode studies, which simulate continuous treatment conditions more realistically than batch experiments, offering valuable insights into breakthrough behaviour, regeneration frequency, and operational scaling.

Mining effluents

Mining operations frequently lead to the leaching of heavy metals, such as arsenic (As), Cadmium (Cd), and mercury (Hg), into surrounding water bodies. A field-simulated batch study using biochar from lignocellulosic biomass investigated its potential to treat mining runoff contaminated with multiple metals. Removal efficiencies reached 85% for As and 78% for Cd, driven by adsorption to oxygenated functional groups and mineral components within the biochar matrix. The study utilised a batch adsorption method to determine the biochar's capacity to remove various metals under different environmental conditions. The results demonstrated that the biochar effectively reduced heavy metal concentrations, with

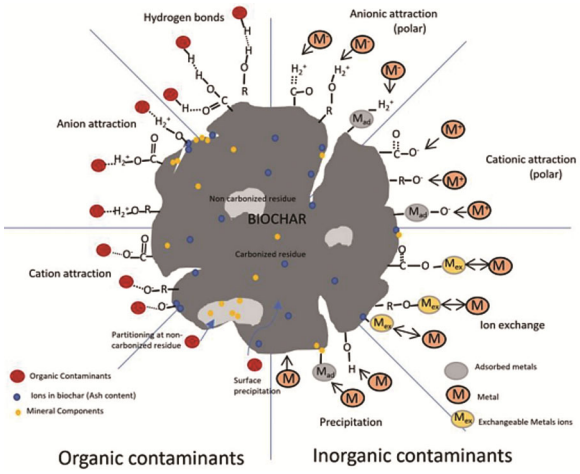

Fig. 7 — Complexation and ion exchange of biochar with industrial wastewater (source:[28]) [11].

up to 85% removal for As and 78% for Cd, primarily due to the adsorption mechanisms facilitated by the biochar's high surface area and the presence of reactive functional groups. The study also noted the potential for biochar to immobilise heavy metals, thereby reducing their bioavailability and toxicity in aquatic environments. These findings underscore the importance of optimising biochar characteristics to enhance its effectiveness in specific contamination scenarios[15]. Additionally, co-application of biochar with passive mine drainage systems (e.g., constructed wetlands or permeable reactive barriers) is being explored to extend treatment lifespan while minimising maintenance demands[22].

Municipal wastewater treatment

Municipal wastewater treatment facilities are increasingly recognising biochar as a viable option for enhancing the removal of heavy metals from influent streams. A study by Hu *et al.* [37]evaluated the integration of sewage sludge-derived biochar into conventional treatment processes. Both batch and continuous flow trials were conducted to assess the contribution to heavy metal removal within municipal effluent treatment trains. Results demonstrated that the addition of biochar improved the removal rates of metals such as Zinc (Zn) and Copper (Cu) by 40% compared to conventional treatment methods alone. The synergistic effects were attributed to enhanced adsorption facilitated by the biochar's unique microstructure and the presence of anionic functional groups, which favoured metal binding through electrostatic attraction and surface complexation. The study concluded that the implementation of biochar not only increased heavy metal removal efficiencies but also contributed to the stabilisation of organic matter within the treatment system, offering a dual benefit in municipal wastewater management. Beyond metal adsorption, the application of biochar was also associated with enhanced stabilisation of organic matter, suggesting its potential as a dual-function additive in wastewater treatment. These findings support the feasibility of retrofitting existing municipal infrastructure with biochar filters or biochar-amended media, offering a low-cost, low-disruption enhancement that aligns with sustainable urban water management goals [19].

Challenges and Limitations

Competition among multiple heavy metals

In real wastewater systems, multiple heavy metal ions co-exist and compete for active adsorption sites on biochar. This competitive interaction can reduce the efficiency of biochar, particularly when it exhibits a preferential binding toward specific ions. This competition can reduce the adsorption efficiency of certain metals, mainly when biochar exhibits preferential binding toward specific ions. Studies have shown that ions with higher electro negativity or smaller hydrated radii often dominate adsorption, resulting in a reduced binding capacity for other metal ions. For instance, Zhou *et al.*[15] observed in multi-metal adsorption studies that lead (Pb) ions typically outcompete Cadmium (Cd) ions due to stronger electrostatic attractions and ion-exchange affinities, leading to lower removal rates for Cd in mixed-metal systems. Such selective affinity limits the effectiveness of biochar in industrial or mining effluents, where diverse metal ions must be removed simultaneously. This challenge can be partially addressed by tailoring surface chemistry through functional group enrichment or by using composite adsorbents that incorporate multiple active binding phases[16].

Longevity and regeneration of biochar adsorbents

The longevity and reusability of biochar are crucial factors for its practical application, particularly in industrial settings where continuous adsorption cycles are required. Although biochar can be regenerated through various methods, such as washing with acidic or alkaline solutions, repeated use often diminishes its adsorption capacity. Thermal regeneration, though effective, may alter the surface structure of biochar, reducing porosity and reactive functional groups. A study by Inyang *et al.*[43] demonstrated that after five

regeneration cycles, the adsorption efficiency of Biochar for Copper (Cu) and Zinc (Zn) was reduced by nearly 40%, highlighting the challenge of maintaining performance over extended usage. Furthermore, frequent regeneration may generate secondary liquid waste requiring separate treatment. The development of mild, non-destructive regeneration methods such as biochar reactivation using low-temperature ozone or microwave-assisted desorption is currently being explored [29].

Cost-effectiveness and scalability of biochar production

While biochar production from agricultural and forestry waste provides an inexpensive feedstock source, the scalability of biochar production for industrial applications poses logistical and economic challenges. Large-scale production requires energy-intensive pyrolysis processes, and the costs associated with temperature control, feedstock processing, and quality management can be prohibitive. Furthermore, biochar production at high temperatures enhances adsorption properties but increases operational costs, reducing its overall economic viability. Cha *et al*.[38] analysed the cost-efficiency of different feedstocks, revealing that high-temperature biochar derived from wood residues was more effective for heavy metal removal but entailed higher production costs than biochar from lower-temperature processes or mixed organic wastes. Therefore, achieving a practical trade-off between cost and performance is crucial for enabling the large-scale deployment of biochar-based treatment systems. Regional variability in biomass availability and energy infrastructure also influences scalability. Establishing decentralised pyrolysis units near biomass sources could reduce transportation costs and promote localised circular economy models[21].

Environmental concerns and by-products

Despite biochar's eco-friendly profile, certain environmental risks and by-products are associated with its use in removing heavy metals. When biochar binds heavy metals, it transforms them into less soluble forms; however, desorption and potential leaching remain concerns, particularly under acidic or saline conditions where metals may re-enter the water system. Additionally, biochar application can release secondary pollutants, such as polycyclic aromatic hydrocarbons (PAHs) or volatile organic compounds (VOCs), primarily if produced under suboptimal pyrolysis conditions. Han *et al*.[35] reported that biochar prepared at temperatures above 500°C contained trace amounts of PAHs, which could potentially leach harmful compounds during field applications. This underscores the necessity for careful optimisation of pyrolysis conditions and post-treatment screening to ensure environmental safety in field applications. Future regulatory frameworks may require pre-application certification of biochar quality, particularly for use in potable water systems or agricultural discharge zones. Incorporating life-cycle assessments (LCAs) can help assess the trade-offs between environmental risk and remediation benefit [37].

Future Perspectives and Research Directions

Innovations in biochar feedstock production

The effectiveness of heavy metal adsorption is closely tied to the physicochemical characteristics of biochar, such as its surface area, pore architecture, and surface functional groups, all of which are strongly influenced by feedstock type and pyrolysis parameters. To produce biochar with unique qualities, future studies should investigate a broader range of feedstocks, including unconventional sources such as marine algae, food waste, and industrial by-products. Recent research, for instance, indicates that biochar made from macroalgae has a greater specific surface area and iodine number, which improves its ability to remove Pb and Cd from wastewater. By encouraging more controlled thermal breakdown of feedstocks, novel technologies like hydrothermal carbonisation and microwave-assisted pyrolysis have the potential to lower energycosts while producing biochar with the desired characteristics. Furthermore, fine-tuning pyrolysis parameters, such as temperature, residence time, and heating rate, can allow for the selective tailoring of biochar properties to target specific heavy metal ions or to optimise performance in multi-metal environments. Co-pyrolysis of biomass with activating agents, such as phosphates or iron salts, is another avenue worth exploring, as it can create inherently functionalised biochars without post-synthesis treatment[29].

Development of multi-functional biochar

Another promising area is the development of multi-functional biochars with improved adsorption performance and broader applicability. The surface reactivity and metal-binding sites of biochar can be enhanced through functionalisation methods, including oxidation, metal impregnation (such as iron or manganese, for example), or acid/alkali modification. Functionalised biochar has demonstrated higher adsorption efficiencies due to increased ion exchange

capacity and electrostatic interactions, as seen with phosphate-impregnated biochar for arsenic (As) removal. Moreover, researchers are exploring biochar composites by integrating biochar with nanoparticles (such as Fe_3O_4 or TiO_2), polymers, or carbon-based materials like graphene. Additional features of these composites include pH-adjustable adsorption, magnetic separation, and photocatalytic degradation, all of which might improve adsorption capacity and operating flexibility. Studies indicate that Fe_3O_4-biochar composites, for example, facilitate easier separation of the adsorbent after treatment due to their magnetic properties, thereby promoting biochar regeneration and reducing potential metal leaching issues in aquatic environments. Future efforts may focus on green synthesis routes for these composites, such as utilising plant-based reducing agents to form nanoparticles in situ, which would align with sustainability goals and reduce production costs[15].

Integrating biochar with other treatment technologies

Integrating biochar with complementary treatment technologies is an emerging strategy for enhancing the removal of complex mixtures of contaminants from wastewater. Hybrid systems combining biochar adsorption with advanced oxidation processes (AOPs), membrane filtration, or electrocoagulation can maximise contaminant removal and address the limitations of individual methods. For instance, coupling Biochar with AOPs, such as Fenton oxidation or ozonation, has been shown to enhance the simultaneous immobilisation of heavy metals and degradation of organic pollutants, making it an attractive option for highly polluted industrial effluents. By combining the advantages of electrocoagulation's capacity to precipitate colloidal metals with biochar's high surface area for metal adsorption, electrocoagulation-biochar systems have also demonstrated promise in accomplishing substantial removal, even in complex multi-metal wastewater systems. Such integrated approaches not only improve overall treatment efficiency but also reduce biochar fouling and extend its functional lifespan. Future research should focus on optimising operating parameters such as contact time, pH, current density (for electrocoagulation), and biochar dosage to maximise synergies in these integrated systems. Moreover, real-world pilot studies are crucial for evaluating the long-term performance of such hybrid systems, particularly under variable influent compositions and flow regimes. Integration with intelligent monitoring tools and decision-support systems could further facilitate process control and scalability[6].

Conclusion

Biochar has emerged as a promising adsorbent for removing heavy metals from wastewater due to its adjustable surface properties, low production cost, and sustainable synthesis from diverse organic waste feedstocks. Its adsorption efficiency is primarily governed by factors such as feedstock type, pyrolysis parameters, surface modifications, and the underlying adsorption mechanisms, including electrostatic interactions, ion exchange, surface complexation, and precipitation. Biochar has demonstrated strong performance in both single-metal and multi-metal systems. However, competitive adsorption, reduced selectivity, and interference from co-existing ions present ongoing challenges in real-world industrial and mining effluents. Furthermore, the longevity and renewability of biochar, coupled with the need for cost-effective, scalable production, remain areas for improvement. Recent advances in the development of multi-functional biocharvia nanoparticle doping, surface oxidation, and composite formationalongside integration with complementary technologies such as electro-coagulation and AOPs, offer viable pathways for enhancing adsorption efficiency, selectivity, and reuse. This review distinguishes itself by synthesising comparative mechanistic insights across different metals, highlighting recent innovations in modification strategies, and critically evaluating field-level applications, thereby providing a more application-oriented perspective not extensively covered in existing reviews. Despite the progress, several gaps remain, including long-term field validation, environmental risk assessment (e.g., PAH leaching), and standardised regeneration protocols. Addressing these limitations will be essential for transitioning biochar from bench-scale studies to field-scale, regulatory-approved implementations. Future research should prioritise scalable synthesis routes, feedstock-specific customisation, and integration with existing treatment infrastructure. With sustained interdisciplinary collaboration and pilot-scale studies, biochar can evolve into a reliable, eco-friendly, and adaptable material for wastewater remediation in both urban and industrial settings.

Conflict of interest

The authors declare no conflict of interest.

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