Biochar for Copper Removal from Aqueous Solutions: A Comprehensive Review

Authors:

Dilton Ashwin Mascarenhas [1], Gautham P. Jeppu [1], S.V.S.R Krishna Bandaru [1*]

Affiliation:

Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education (MAHE), Manipal, Karnataka, India.

Corresponding Authors:

- Dr. S.V.S.R Krishna Bandaru

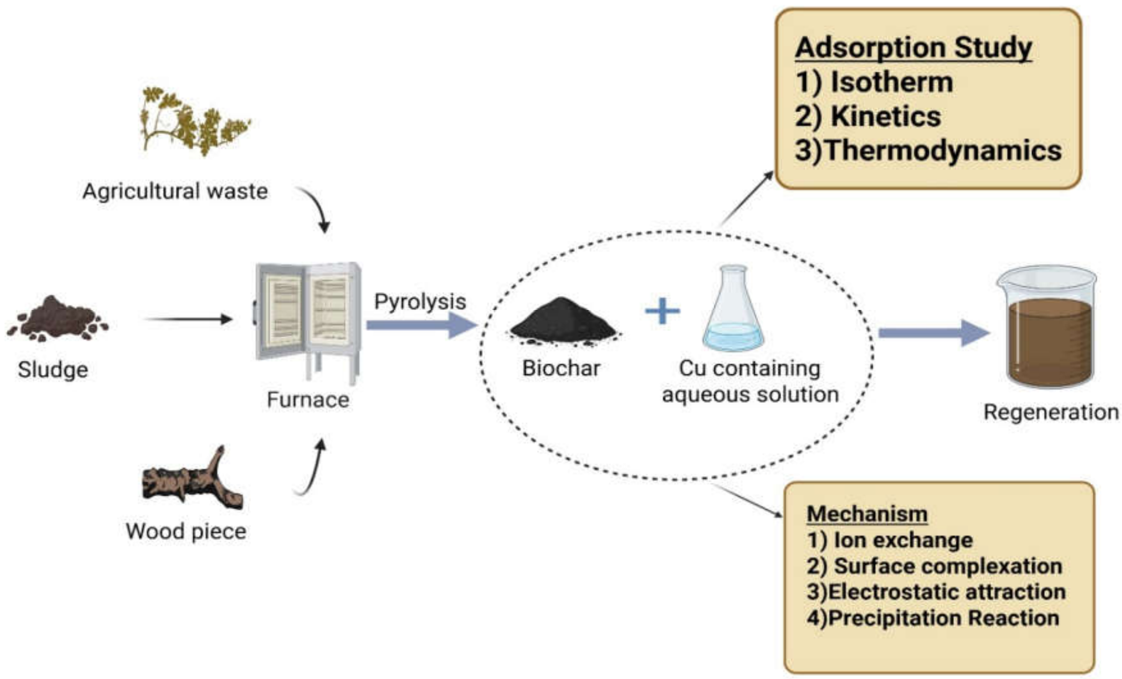
Abstract

Water contamination by heavy metals remains a pressing global concern due to its serious environmental and public health implications. Among these pollutants, copper is particularly noteworthy owing to its extensive industrial application and potential toxicity at elevated concentrations. Traditional treatment methods such as chemical precipitation, ion exchange, and membrane filtration often face limitations including high operational costs, poor efficiency at trace concentrations, and the generation of secondary waste. In recent years, biochar—a carbon-rich, porous material derived from the pyrolysis of diverse biomass sources—has gained attention as a cost-effective and sustainable alternative for copper removal from aqueous environments. This review presents a comprehensive overview of the current advancements in copper adsorption using biochar. Key aspects such as biochar production methods, physicochemical properties, and various characterization techniques are discussed in detail. The influence of parameters like surface area, pore structure, surface functionality, and charge on adsorption efficiency is critically analysed. Mechanistic insights into copper uptake—including ion exchange, surface complexation, electrostatic interactions, and precipitation—are thoroughly examined. The review further investigates how operational factors such as pH, initial copper concentration, contact time, temperature, and biochar dosage affect adsorption performance. In addition, adsorption kinetics, isotherm models, and thermodynamic analyses are evaluated to better understand the interaction between copper ions and biochar surfaces. Emphasis is also placed on biochar regeneration and reusability, comparative performance across different feedstocks, and its effectiveness relative to conventional adsorbents. Finally, the review identifies existing challenges and knowledge gaps while underscoring the need for standardised protocols, field-scale validation, and advancement toward commercial-scale applications to fully harness the potential of biochar in sustainable copper remediation technologies.

Key Words

Biochar, Copper adsorption, Aqueous solutions, Heavy metals removal, Wastewater treatment, Regeneration and reusability.

Graphical Abstract



1. Introduction

Water contamination is a worldwide issue that endangers public health as well as the sustainability of the environment. Heavy metals like copper are among the plenty potentially dangerous substances that have contaminated water bodies due to mining, industrial operations, and agricultural practices. These pollutants can accumulate in food chains, remain in aquatic environments, and eventually impact ecosystems as well as human populations worldwide (1).

Even though copper is a necessary micronutrient, copper becomes dangerous at high concentrations. Streams, groundwater, and sediments can become contaminated by excessive copper in water due to mining, smelting, and industrial discharges (2,3). Aquatic life faces moderate or severe ecological threats due to copper's ability to disrupt biological processes and harm biota (1). The important cause of human health hazards is drinking tainted water, which can have both non-cancer and cancerous effects, particularly in areas close to industrial or mining sites (4). Children are especially at risk, as some studies show that in some places, hazard index values are greater than acceptable limits (3). Long-term exposure to water tainted with copper may lead to digestive problems and, in extreme situations, liver or kidney damage (5). The necessity of routine monitoring and efficient remediation is highlighted by the persistence of copper in sediments and its potential to surpass established safety guidelines (6).

Chemical precipitation, ion exchange, membrane filtration (including ultrafiltration, nanofiltration, and reverse osmosis), and electrochemical techniques are examples of conventional methods for extracting copper from water (2). Although these methods can be effective, they frequently have serious drawbacks. Disadvantages include high operating costs, inefficiency at low copper concentrations, and the production of secondary pollutants, such as toxic sludge (6). Such challenges emphasise the need for more economical, efficient, and sustainable copper removal technology, especially as regulatory requirements tighten and the demand for clean water rises internationally (7).

Biochar is a carbon-rich substance. The pyrolysis of biomass, which entails heating organic waste products without oxygen, yields biochar. Through this method, agricultural and other organic wastes are converted into a stable, porous carbon structure that can be used in environmental applications, especially as a heavy metal adsorbent (8,9).

Biochar is very effective at adsorption because of a number of important physicochemical characteristics. These consist of substantial porosity, a high specific surface area, and a large number of surface functional groups (such carboxyl, hydroxyl, and aromatic rings) (9–12). By introducing more functional groups and increasing its surface area, biochar can be modified chemically or physically to improve its adsorption capacity (11,13). Through processes like physical adsorption, ion exchange, surface complexation, and electrostatic interactions, these characteristics improve its capacity to interact with and immobilise heavy metal ions (11,13).

Biochar is made from renewable biomass sources and can be made from industrial or agricultural waste. Biochar is regarded as an environmentally friendly material that lessens the burden on the environment (8,14). When compared to traditional adsorbents, its manufacturing and use are typically less expensive, making it suitable for extensive soil and water remediation operations (8,15). Furthermore, the usage of biochar can aid in carbon sequestration, enhancing its environmental advantages (15,16).

Biochar's special chemistry and structure are responsible for efficiently adsorbing a variety of heavy metals from contaminated soils and water, such as lead, cadmium, arsenic, mercury, copper, and zinc (8–10,12,13,15,17). By using modification techniques like impregnation with metal oxides or combining with other materials, its adsorption performance can be further improved (10,11,13,17).

This review's objective is to provide an overview and critical assessment of recent studies on the application of biochar for copper adsorption from aqueous solutions. The review will cover the regeneration and reusability of biochar, which are essential for realistic and sustainable water treatment applications, as well as the mechanisms behind copper removal by biochar, the variables affecting adsorption efficiency, the different types of biochar and its modifications, and biochar's comparison with other adsorbents. Key aspects like adsorption mechanisms, such as cation exchange, surface complexation, electrostatic interactions, and precipitation which are considered as primary pathways will be explored. The review will go over how copper adsorption capacity and efficiency are affected by variables such as feedstock, pyrolysis temperature, pH, adsorbent dosage, and the presence of competing ions. Various types of biochar as well as modification and composite will be explored. The regeneration and reusability of biochar will also be checked. Future research paths and real-world uses of biochar in the cleanup of copper-contaminated water will be addressed by this review article investigation.

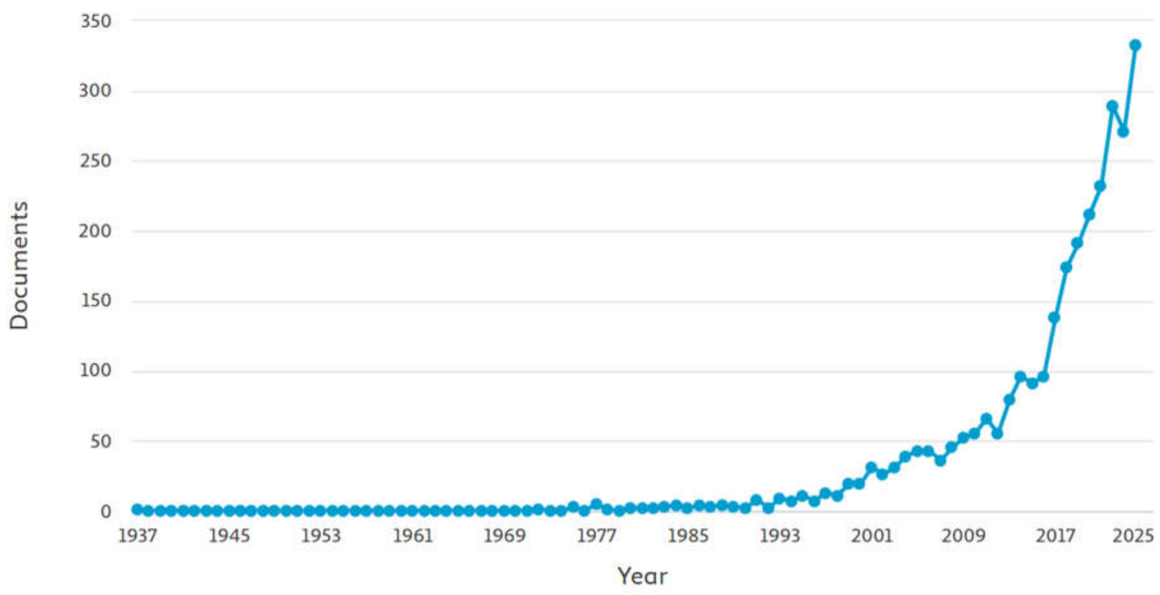


Figure 1. Number of documents published per year on copper adsorption using biochar.

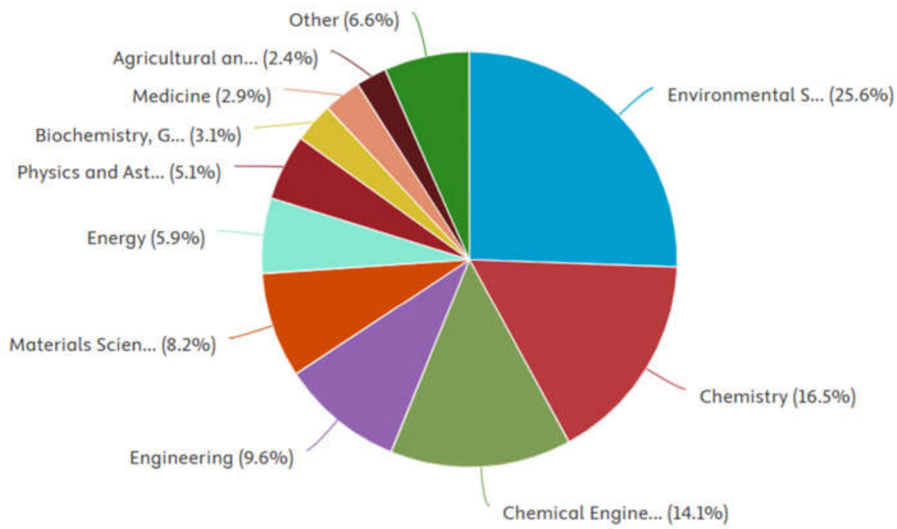


Figure 2. Field of research on copper adsorption using biochar

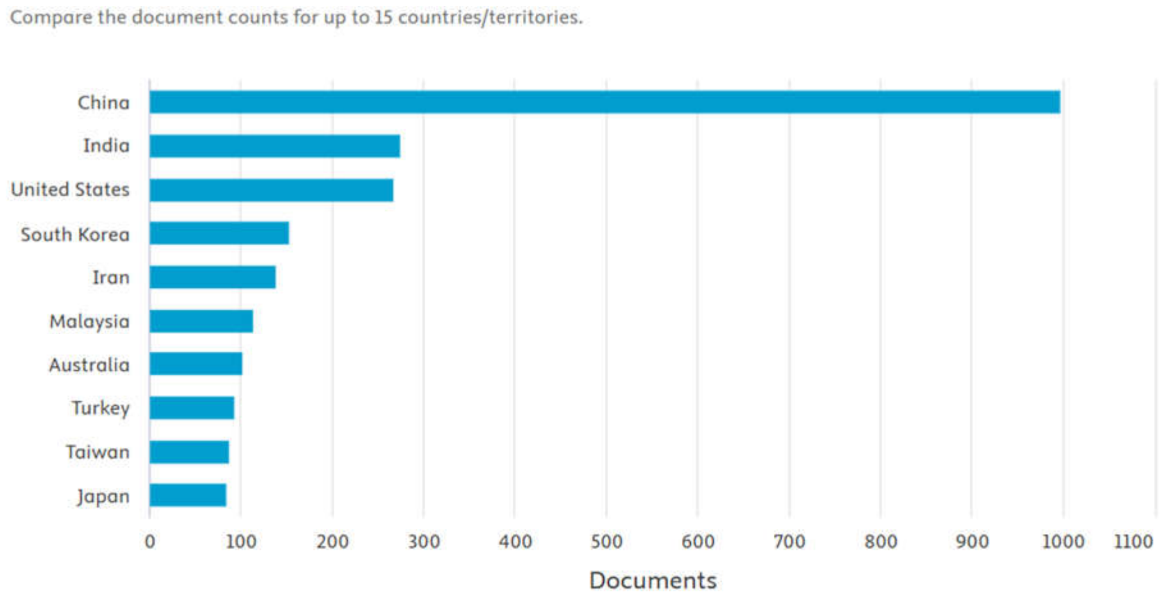


Figure 3. Number of documents published in various countries on copper adsorption using biochar.

A Scopus database search was conducted using the key words “copper “ AND “Adsorption” and “biochar” or activated carbon” . The Figures 1, 2 and 3 shows the results. As shown in figures above the research output on copper adsorption using biochar has grown significantly during the past 30 years. Although there were almost no studies on this topic before 2000, the number of publications has grown exponentially since 2010, particularly after 2015. By 2025, over 300 papers are published annually, which indicates that biochar is a sustainable and an environmentally friendly adsorbent for cleaning up heavy metals such as copper. Most of the publications were under the field of Environmental science (25.6%), followed by chemistry (14.1%), and chemical engineering (14.1%).b China has the most publications in over 1000 publications, whereas United states and India had around 300 publications followed by South Korea and Iran which have around 150 publications. This indicates that there is worldwide interest in use of biochar as an adsorbent for removal for copper.

The purpose of this review is to give readers a thorough understanding of biochar's use as an adsorbent in the removal of copper from aqueous environments. Copper adsorption mechanisms, affecting variables (temperature, pH, and biochar modification), comparison of the effectiveness of various biochars, obstacles, gaps in information, and potential paths will be addressed.

2. Biochar production and sources

A carbon-rich material called biochar is created by thermochemically transforming several kinds of biomass. The selection of the precursors and the particular production conditions—particularly the pyrolysis process—have a significant impact on its characteristics and efficacy. It is possible to create biochar from a variety of biomass sources, such as wood, manure, crop residues, and from other kinds of organic wastes. Lignocellulosic biomass, which is made up of cellulose, hemicellulose, and lignin, is frequently utilised because of its quantity and advantageous qualities for the creation of biochar (18–22). The physicochemical characteristics of the final biochar, including its carbon content, surface area, and ability to retain nutrients, are greatly influenced by the type of feedstock used. Choosing the right feedstock is essential to customising biochar for a given use (19,21,23,24). The three primary processes for producing biochar are hydrothermal carbonisation, gasification, and pyrolysis. The most popular method is pyrolysis, or heat breakdown without oxygen (18,20,24). Temperature, heating rate, and residence duration are important variables influencing the yield and quality of biochar. While lower temperatures favour higher yields with distinct structural features, higher temperatures often result in biochar with increased surface area and porosity but lower yield (19,24). The characteristics of biochar can be further altered by different reactor designs and physical or chemical activation techniques, increasing its suitability for uses such as energy storage, soil amendment, and pollutant adsorption (18,25). A variety of organic resources can be used to make biochar, but common sources include wood, dung, and agricultural waste. Both the feedstock and the particular pyrolysis conditions utilised during production have a significant impact on the characteristics of biochar, enabling customisation to satisfy various industrial and environmental requirements.

3. Notable properties of biochar and suitability

The efficiency of biochar in agricultural and environmental applications is directly related to its pH of zero-point charge (pHpzc), surface area, porosity, surface functional groups, and surface charge. These qualities are highly modifiable by feedstock selection as shown in table 1, pyrolysis temperatures, and post-treatment procedures, directly influencing biochar’s adsorption and remediation capacities. For adsorption applications, a high surface area and well-developed porosity are essential. The pyrolysis temperature and the kind of biomass feedstock have the most effects on these characteristics; biochars with lignocellulosic materials and moderate-to-high temperatures (400–900°C) have more developed pore structures and bigger surface areas (26–28). Additional treatments such as chemical activation, ball milling, and templating can further enhance surface area and porosity, exposing more adsorption sites. Chemical activation, ball milling, and templating are a few more processes that can increase surface area and porosity and reveal more adsorption sites (26,28,29). FTIR and XPS investigations can identify the different functional groups (such as carboxylic, phenolic, lactonic, and phosphate) present on the surfaces of biochar (4-7,9,10). The feedstock and pyrolysis temperature affect the number and kind of these groups. Higher temperatures decrease these but may add new functionalities, whereas lower temperatures favour oxygen-containing groups (carboxyl, hydroxyl) (30,31). In order to facilitate hydrogen bonding, electrostatic interactions, and surface complexation with pollutants, surface functional groups are essential for adsorption processes (30,32,33). The amount of ash and the presence of functional groups determine surface charge, which varies with pyrolysis temperature. Because there are more oxygen-containing groups at lower temperatures, there is a greater negative surface charge; at higher temperatures, this charge decreases (34). The pHpzc indicates the pH at which the biochar surface has zero net charge (27). For the adsorption of cationic pollutants, biochars with a high cation exchange capacity (CEC) and negative surface charge are ideal, whereas biochars with a greater pHpzc and positive charge are preferable for anionic contaminants. Through feedstock selection, pyrolysis conditions, and post-treatments, the surface area, porosity, functional groups, surface charge, and pHpzc of biochar can be tailored (27). The combination of these characteristics establishes whether biochar is appropriate for a certain adsorption and remediation activity.

Table: 1 Influence of feedstock composition on porosity and surface functionality

Feedstock Component	Effect on Porosity/Surface Area	Effect on Surface Functionality	Reference
High Lignin/Cellulose (Woody)	Greater surface area and porosity, especially at moderate/high pyrolysis temperature	Functional groups are fewer but more stable and aromatic.	(35–37)

High Ash (Manure, Sludge)	Eliminating ash can increase porosity; too much ash can obstruct pores.	Surface functional groups are abundant and beneficial for cationic adsorption.	(35,36,38)
Agricultural Waste (Straw, Husk)	Moderate porosity that can be enhanced through activation or modification	Surface functional groups are abundant and beneficial for cationic adsorption.	(35,39,40)
Pyrolysis Temperature	Higher temperatures reduce functional groups and increase porosity.	Lower porosity and functional groups are preserved at lower temperatures.	(36,37,39)

Table 2: Comparison of low-temperature vs. high-temperature biochars for cu removal from aqueous solution.

Outcome	Low-Temperature Biochar(≤500°C)	High-Temperature Biochar (≥700°C)	Reference
Surface Functional Groups	Higher (carboxyl, hydroxyl)	Lower (depleted by pyrolysis)	(41,42)
Main Removal Mechanism	Complexation with surface groups, ion exchange	Mineral precipitation, some complexation	(44,45)
Surface Area	Moderate	Higher	(44,45)
Effect of DOM	Enhances Cu binding	Less pronounced	(41)

4. Main mechanisms of copper adsorption

As shown in Figure 4, several important mechanisms are involved in copper adsorption onto different adsorbents, and each one adds to the total removal efficiency and selectivity.

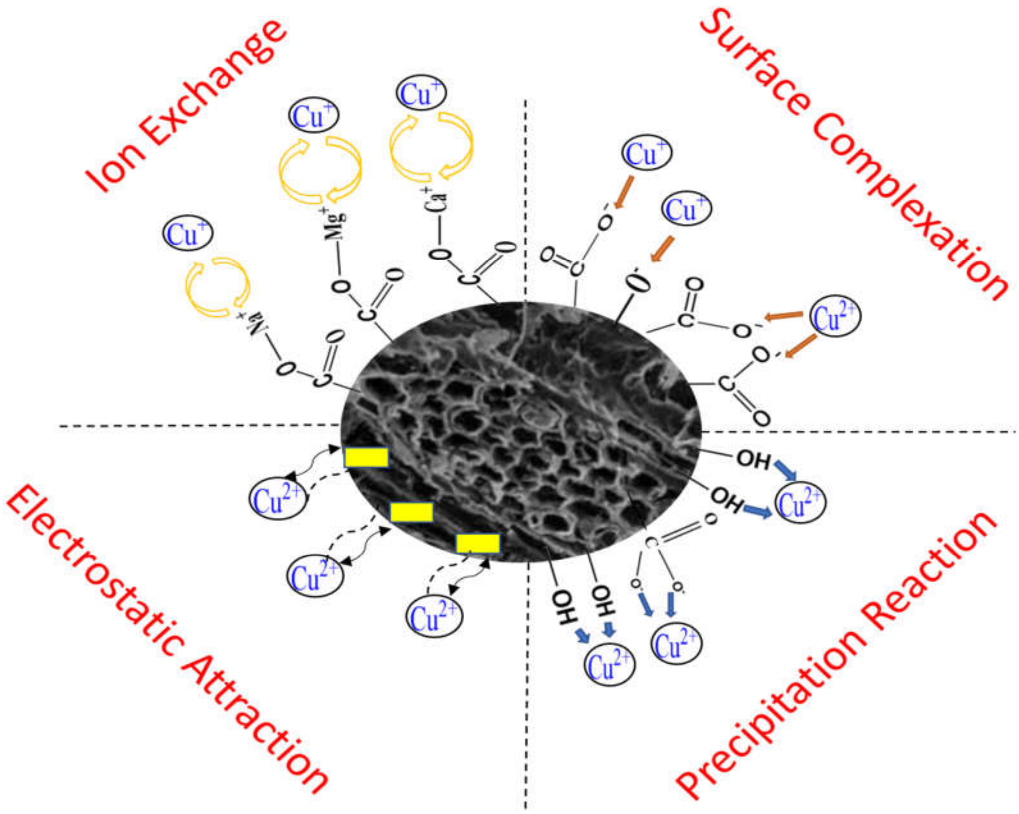


Figure 4. Types of adsorption mechanisms for copper adsorption on biochar

4.1 Ion Exchange

Ion exchange plays a crucial role in the adsorption of copper onto biochar, especially at lower copper concentrations. During this interaction, copper ions (Cu^{2+}) present in the solution displace other positively charged ions—such as calcium (Ca^{2+}), potassium (K^{+}), or magnesium (Mg^{2+})—that are loosely attached to the negatively charged sites on the surface of the biochar. These negatively charged sites arise primarily from oxygen-containing functional groups, such as carboxyl (-COOH) and hydroxyl (-OH) groups, as well as mineral constituents embedded within the biochar structure. This exchange mechanism enables effective binding of copper ions onto the biochar, contributing significantly to its capacity for copper removal from` aqueous environments (46–49). When biochar is added to copper-contaminated water, copper ions (Cu^{2+}) are drawn to the negatively charged sites on the biochar surface through electrostatic attraction. As these copper ions attach to the biochar, the original positively charged ions—such as calcium, potassium, or magnesium—that were previously bound to these sites are released back into the solution, effectively exchanging places with the copper. This ion exchange process is not only swift but also reversible, making it an efficient and dynamic mechanism for the removal of copper from aqueous environments (46,48,49).

Biochars enriched with higher levels of readily exchangeable cations—either originating from the source biomass or introduced through modification—offer an increased number of available sites for copper uptake. For instance, sludge biochar modified with hydroxyapatite provides an abundant supply of calcium ions (Ca^{2+}), which significantly enhances copper adsorption capacity via cation exchange. This enrichment facilitates more efficient displacement of copper ions onto the biochar surface, thereby improving its performance in copper-contaminated aqueous systems (48). Activation techniques, such as steam treatment or doping with minerals like magnesium or iron, can increase the availability of exchangeable cations and enhance the negative charge on the biochar surface, thereby improving copper adsorption (47). Additionally, the porosity and surface area of biochar play a significant role in facilitating access of copper ions to these exchange sites. Biochars possessing well-developed pore structures enable more efficient ion exchange by providing greater accessibility for copper ions to interact with the functional sites (46,49).

Ion exchange reaction is given by,

$$\textbf{Biochar-M}^{2+} + \textbf{Cu}^{2+}\textbf{(aq)} \longrightarrow \textbf{Biochar-Cu}^{2+} + \textbf{M}^{2+}\textbf{(aq)}$$

Where M^{2+} represents an exchangeable cation on the biochar surface, such as Ca^{2+}, K^{+}, or Mg^{2+}.

4.2 Surface Complexation

Surface complexation serves as a vital mechanism through which biochar adsorbs copper ions from aqueous solutions, particularly at moderate to high copper concentrations. In this mechanism, various functional groups on the biochar surface—such as carboxyl (-COOH), hydroxyl (-OH), amine ($-NH_2$), imine (-NH), and phosphate groups—interact directly with copper ions to form stable, often covalent, inner-sphere complexes. This chemisorption process is notably stronger and more selective than simple electrostatic attraction, as it involves electron sharing or transfer between the copper ions and these surface groups, resulting in robust and specific bonding (50–54).

The adsorption mechanism initiates as copper ions in solution approach the biochar surface and interact with reactive functional groups present on it. For instance, carboxyl and hydroxyl groups are capable of donating electron pairs to copper ions, leading to the formation of coordinate (or dative) bonds. Similarly, biochars that have been chemically modified to contain amino or imine groups exhibit enhanced copper binding due to the strong affinity of nitrogen-containing groups for copper ions (50,53,54). This enhanced interaction has been confirmed through analytical techniques such as X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR). Furthermore, phosphate and other phosphorus-containing functional groups introduced via chemical modifications also play a significant role in complex formation, thereby further increasing the copper adsorption capacity of biochar (51,54). The evidence for these complexation interactions is typically observed as shifts in characteristic peaks corresponding to these functional groups in FTIR spectra, along with detectable changes in the copper's chemical state in XPS measurements following adsorption.

Surface complexation reaction is given by,

$$\textbf{Biochar-COO}^{-} + \textbf{Cu}^{2+}\textbf{(aq)} \longrightarrow \textbf{Biochar-COO-Cu}^{+}$$

Where COO^{-} is a carboxylate group, similar reactions occur with –OH, $–NH_2$, and phosphate groups.

4.3 Electrostatic Attraction

Electrostatic attraction is a key mechanism driving the adsorption of copper ions (Cu^{2+}) onto biochar, particularly when the solution pH exceeds the biochar's point of zero charge, causing the surface to carry an overall negative charge. Under these conditions, the positively charged copper ions in the solution are naturally drawn to and retained by the negatively charged sites on the biochar surface. These sites are commonly formed by oxygen-containing functional groups such as carboxyl (-COOH) and hydroxyl (-OH) groups (55–58). The density and availability of these negatively charged functional groups can be increased through chemical modification or by incorporating additional components like chitosan or iron oxide particles. Such enhancements boost the surface's negative charge, thereby strengthening its attraction and affinity toward copper ions in the aqueous environment (58,59). The adsorption process begins as copper ions in the aqueous solution are attracted to the negatively charged surface of biochar, forming an outer-sphere association. This interaction does not involve direct chemical bonding but is driven primarily by electrostatic forces. Electrostatic attraction plays a vital role at lower copper concentrations and during the initial phase of adsorption, as it helps to concentrate copper ions near the biochar surface, thereby enhancing their availability for subsequent mechanisms such as ion exchange or surface complexation (55,58). The effectiveness of this electrostatic interaction can be further enhanced by increasing the overall negative charge density on the biochar surface, which can be achieved by introducing additional functional groups or by adjusting the solution pH to optimize the surface charge (60,61).

For example, research has demonstrated that biochar materials—especially those enhanced with amino (-NH_2) or hydroxyl (-OH) groups, or those coated with iron or magnesium oxides—show improved ability to capture copper ions from water (58,61). This improved copper uptake is largely due to stronger attractions between the charged copper ions and the modified surfaces of the biochar. Additionally, the presence of other charged particles in the water can affect how well copper is removed: if there are many competing positively charged ions, they might block or compete for the same adsorption sites, reducing the efficiency of copper capture (55,56). Overall, electrostatic attraction—where opposite charges pull each other together—allows for quick and reversible removal of copper ions. This process works alongside other methods like swapping ions or forming surface bonds and becomes particularly effective when biochar is specifically designed to have more surface charge and a higher density of functional groups that can interact with copper (55–60,62).

Electrostatic attraction reaction is given by,

Cu^{2+}(aq) + Biochar-(negatively charged site) $\longrightarrow$ [Biochar-Cu^{2+}] (adsorbed by electrostatic attraction.

This process relies on the physical attraction between the copper ion and the negatively charged surface, without the formation of a direct chemical bond.

4.4 Precipitation Reactions

Precipitation reactions represent one of the most commonly used and highly efficient strategies for removing copper from contaminated water, particularly under alkaline conditions or when specific chemical groups or additives are present. In these methods, dissolved copper ions interact with added substances such as alkaline agents (like lime or sodium hydroxide), carbonate salts (such as sodium carbonate or calcium carbonate), or sulfur-based reagents (e.g., sodium sulfide). Through these reactions, the copper ions are transformed into solid forms—such as copper hydroxide, copper carbonate, or copper sulfide—that are much less soluble in water (57,59,62). Once formed, these solid copper compounds separate out of the water as particles, often referred to as sludge, which can then be physically removed. Advanced approaches may facilitate the recovery of copper by generating magnetic particles that can be extracted more easily. The effectiveness of this removal process is highly sensitive to the water's pH; for example, copper hydroxide is most efficiently formed and removed when the pH is maintained between 8 and 10, where removal rates often exceed 90%—a result that meets or surpasses most regulatory standards for industrial wastewater discharge (59,62).

Once the solid copper compounds form, they can be separated from the treated water using methods such as settling, filtration, or—in cases where magnetic properties are imparted—by magnetic extraction. The specific removal technique depends on the design and requirements of the treatment system. The type of chemical reagent chosen for precipitation, as well as the process conditions, plays a significant role in determining both the amount and the physical characteristics of the resulting sludge (57,59,62). For instance, using sodium carbonate (soda ash) often generates settled solids that are bulkier and easier to handle than those produced with some other chemicals. Precipitation-based treatment not only efficiently extracts copper from wastewater, but it also offers the possibility of recovering the copper for reuse, which supports resource conservation and environmental sustainability. As such, these processes are increasingly recognized as practical and responsible solutions for managing industrial effluents containing copper (57,59,62).

Precipitation reaction is given by,

$$\mathbf{Cu^{2+}(aq) + 2OH^{-} \longrightarrow Cu(OH)_2 \downarrow}$$

Similarly, Sulphide and carbonate ions react with copper ions to form copper sulphide and copper carbonate precipitate.

5. The factors affecting adsorption

5.1 The most important Factors Affecting Adsorption

The adsorption capacity in aqueous systems is influenced by several key factors. Solution pH significantly affects adsorption by altering the charge and solubility of both the adsorbent and adsorbate; depending on the specific system, metal adsorption may increase or decrease with pH (63–66). Higher initial concentrations of pollutants generally enhance adsorption capacity, as more molecules are available to interact with the adsorbent surface (63–65). Contact time also plays a crucial role, with adsorption typically occurring in phases—initial rapid uptake followed by a slower process until equilibrium is reached—depending on the system and adsorbent characteristics (67,68). Temperature can influence adsorption as well; in some systems, increased temperature improves adsorption capacity by enhancing molecular mobility and potentially causing structural changes in the adsorbent (63,64,69). While increasing the dosage of adsorbent like biochar often raises the total contaminant removal, it may lead to a decrease in adsorption capacity per unit mass due to site saturation (70). Lastly, surface modification techniques—such as chemical or thermal treatments—can enhance the surface area, porosity, and functional groups of adsorbents, thereby improving their adsorption efficiency and selectivity (66,70,71).

5.2 The Additional Factors Influencing Adsorption

Adsorption in aqueous systems is further influenced by factors such as ionic strength, particle characteristics, and surface chemistry. The presence and concentration of other ions in the solution can alter electrostatic interactions or compete for active sites, thereby affecting the overall adsorption (63–65,68). Smaller particle sizes and larger surface areas generally enhance adsorption capacity due to the increased number of available active sites (64,67,69). Additionally, the surface chemistry of adsorbents plays a crucial role in the adsorption mechanism. Functional groups and surface charge, often modified through chemical treatments, facilitate processes such as ion exchange, hydrogen bonding, and van der Waals interactions (64,66,69).

6. Adsorption isotherm, kinetics and thermodynamics

To comprehend how pollutants interact with adsorbents in water treatment and environmental remediation, adsorption isotherms, kinetics and thermodynamics are crucial. The distribution of molecules between liquid and solid phases is described by the Langmuir and Freundlich isotherms, and the rate of adsorption is modelled by pseudo-first and pseudo-second-order kinetics. Studies of thermodynamics shed light on the characteristics and viability of the adsorption process.

6.1 Isotherm Models: Langmuir and Freundlich

The Langmuir and Freundlich isotherms are widely used models to describe adsorption behaviour. The Langmuir isotherm typically represents monolayer adsorption on a homogeneous surface with a finite number of identical sites and is often the best fit for adsorption data, as indicated by high correlation coefficients ($R^2 > 0.99$). This model has shown superior applicability in cases such as methylene blue adsorption on activated hydrochar, glyphosate on resin, and malachite green on biochar (72–75). In contrast, the Freundlich isotherm describes adsorption on heterogeneous surfaces and is sometimes more suitable for complex or multicomponent systems. It has been effectively applied to scenarios such as the adsorption of antibiotics on chitosan-carbon nanotube beads and organochlorine insecticides on various adsorbents (76–78).

6.2 Kinetic Models: Pseudo-First and Pseudo-Second Order

Adsorption kinetics are commonly described using pseudo-first-order and pseudo-second-order models. Pseudo-second-order kinetics often provides the best fit for experimental data involving dyes, glyphosate, and various other pollutants, indicating that chemisorption is likely the rate-limiting step (72–75). However, in certain cases—particularly for some antibiotics—the pseudo-first-order model may offer a better fit, suggesting that physical adsorption mechanisms could play a more dominant role in those systems (77).

6.3 Thermodynamic Studies

Thermodynamic parameters such as $\Delta H°$, $\Delta G°$, and $\Delta S°$ are essential for understanding the nature of adsorption processes, indicating whether the adsorption is spontaneous, endothermic, or exothermic, and helping to identify the underlying mechanism. For example, glyphosate adsorption was found to be endothermic with a high activation energy, pointing toward a chemisorption mechanism (73,77). Adsorption can occur through either physical or chemical interactions, with the dominant mechanism depending on factors such as the nature of the adsorbent, the adsorbate, and the specific environmental conditions of the system (77). The adsorbent, adsorbate, and system complexity all influence the choice of isotherm and kinetic model. The optimal model is found using non-linear fitting techniques and statistical characteristics (such as R^2) (75,79). Understanding these models aids in designing efficient adsorption systems for water treatment and pollution control (74,77,79).

7. Comparison of different biochar sources: agricultural (agri) biochars vs. woody biochars

The capacity of biochar, which is made from a variety of woody and agricultural sources, to adsorb copper from water has been extensively researched. The removal efficiency (%) and adsorption capacity (mg/g) are commonly used metrics to assess the performance of various biochars. When tailored for pyrolysis conditions, agricultural biochars often exhibit greater copper adsorption capacities and removal efficiencies than woody biochars.

7.1 Adsorption Capacity (mg/g)

Depending on the feedstock and pyrolysis temperature, agricultural biochars (such as maize straw, potato stems, pineapple leaves, and sugarcane bagasse) frequently have greater maximum adsorption capabilities for copper, ranging from roughly 12.5 mg/g to 60.7 mg/g (80–83).The adsorption capabilities of woody biochars, such as sawdust, hardwood, and softwood, are generally lower; values of 6.8 mg/g for hardwood and 1.5–4.4 mg/g for softwood and hardwood biochars have been observed (80,84,85), as shown in table 3. Even higher capacities, up to 371.5 mg/g, can be achieved by modified or magnetically enhanced biochars (often derived from agricultural sources), however these are not directly comparable to unmodified woody or agricultural biochar (83,86).

Table 3: Different biochar sources and their adsorption capacity

Biochar Source	Adsorption Capacity (mg/g)	Reference
Corn straw (agri)	12.5	(80)
Potato stem (agri)	61.8	(81)
Pineapple leaf (agri)	60.7	(82)
Hardwood (woody)	6.8	(80)
Softwood (woody)	1.5	(84)
Jarrah (woody)	4.4	(84)

7.2 Removal Efficiency (%)

Agricultural biochars have demonstrated high adsorption performance, with removal efficiencies exceeding 60%, and certain optimized materials achieving up to 87% even after multiple use cycles (81,82). In contrast, woody biochars generally show lower removal efficiencies under similar conditions, often falling below 50% (84,85).

Both agricultural and woody biochars benefit from higher pyrolysis temperatures (500–600°C) in terms of surface area and adsorption efficiency; however, under comparable circumstances, agricultural sources continue to perform better than woody ones (80–82,84,87). For copper adsorption, surface functional groups and porosity are essential, and agricultural biochars frequently have better qualities (81,82,87). In terms of both adsorption capacity and removal efficiency, agricultural biochars routinely exceed woody biochars in copper adsorption from water, particularly when generated at higher pyrolysis temperatures. They are therefore a viable and affordable choice for applications involving water cleanup.

8. Regeneration and reusability

The capacity of biochar, a carbon-rich substance made from biomass, to adsorb copper ions from water is being investigated more and more. Whether biochar can be efficiently regenerated and reused while retaining good performance across several adsorption-desorption cycles is a crucial factor for practical application, which are shown in figure 5.

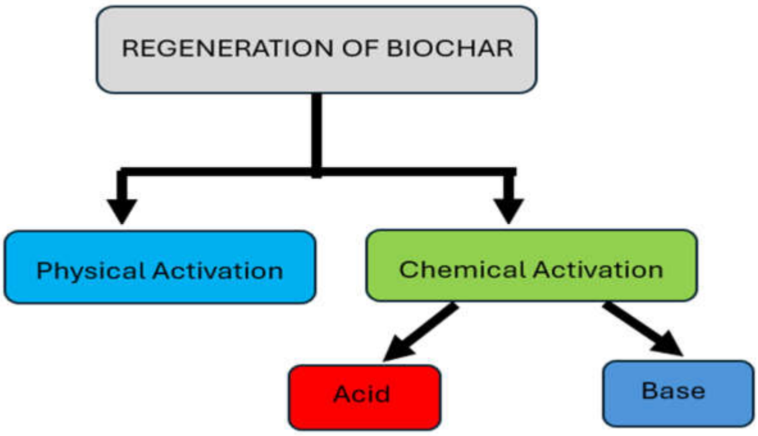


Figure 5: Types of regeneration of Biochar

Desorption methods play a crucial role in the regeneration and reuse of copper-laden biochar, with NaOH and HCl being commonly used agents due to their effectiveness in releasing adsorbed copper ions, thereby enabling future reuse of the adsorbent (88). Optimized biochars, such as those derived from pineapple leaves, demonstrated sustained performance by maintaining a high copper removal efficiency of 87% even after five consecutive adsorption-desorption cycles using pressure cooker regeneration (10). Similarly, magnetic-biochar/alginate beads exhibited strong reusability across multiple cycles, with minimal loss in adsorption capacity following desorption with HCl or NaOH (88).

Table 4: Regeneration methods of biochar

Biochar Type/Modification	Max Cu(II) Adsorption (mg/g)	Reusability/Regeneration Method	Performance After Cycles	Reference
Pineapple leaf biochar (PLB)	60.7	Pressure cooker regeneration	87% efficiency after 5 cycles	(89)
Magnetic-biochar/alginate bead	234.1	NaOH or HCl desorption	Reusable over several cycles	(88)

8.1 Factors Affecting Reusability

Biochars adsorption and reusability performance can be significantly enhanced by optimizing its source and modification processes, particularly by increasing surface area, pore volume, and the content of functional groups such as amino or oxygen-containing groups (88–90). Additionally, the efficiency of copper desorption and the retention of adsorption capacity over successive cycles are influenced by the choice of desorption agent and technique, further emphasizing the importance of tailored regeneration strategies for sustained biochar performance (88,89). A right regeneration method, like pressure cooker treatment or chemical desorption, biochar can sustain high adsorption effectiveness for several cycles.

9. Comparison with other adsorbents

Different adsorbents can be seen in figure 6, adsorption capacities of up to 265 mg/g can be achieved by optimised or modified biochars (such as those with ammonium phosphate or hierarchical pore structures), surpassing the majority of clay and zeolites (91–97). Standard adsorbents like activated carbon have been shown to outperform biochar in certain investigations, but often has fewer functional groups (93,96,98). In general, zeolite is less effective than the best-performing biochars, but it exhibits good adsorption and capacities comparable to some biochar's (97,98). Although clay and other natural materials are less expensive than charcoal and zeolite, they have lesser adsorption capabilities (98), as seen in table 5.

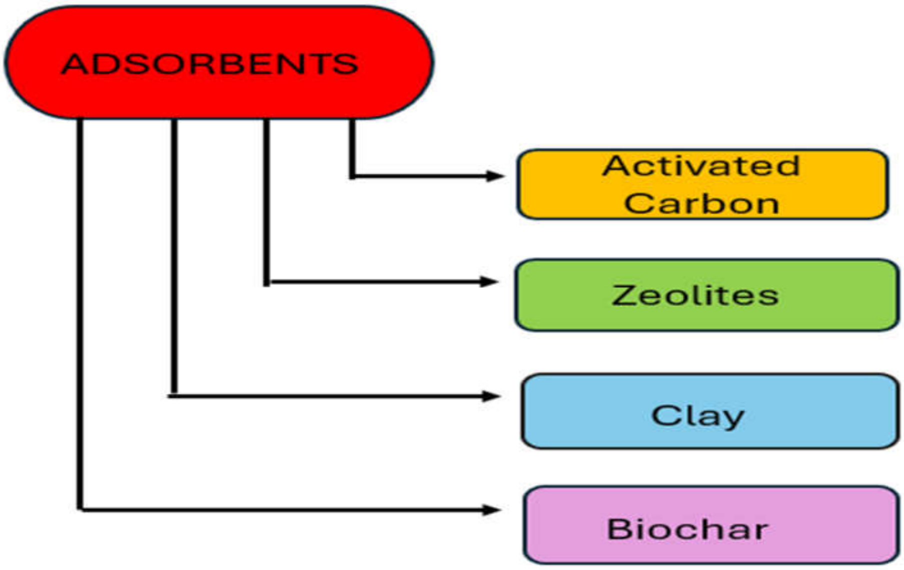


Figure 6: Types of adsorbents used for copper adsorption

Table 5: Adsorption performance comparison table

Adsorbents	Typical Cu(II) Adsorption Capacity (mg/g)	Key Findings	Reference
Activated Carbon	4-898	Good performance, but less functional groups than biochar.	(93,96)
Zeolite	163	Effective, but slightly less than high-performing biochar	(97,98)
Clay	Lower than Biochar/Zeolite	Used for Cu(II) removal, but generally lower capacity	(98)
Biochar	35-265	High Capacity, especially when optimized or modified; rapid kinetics	(8,91,92,94–97)

9.1 Economic and Sustainability Considerations

Biochar is inexpensive, sustainable, and widely accessible because it is made from waste biomass. By using industrial or agricultural byproducts in its manufacture, waste and environmental effect can be decreased (8,92,93,98,99). The production of activated carbon is more costly and frequently involves energy-intensive procedures and non-renewable precursors, despite its effectiveness (93,96). Although zeolite and clay are cheap and plentiful by nature, they may need to be modified to work better, which raises the price (97,98).

10. Limitations and challenges using biochar

Depending on the type of feedstock, pyrolysis temperature, and modification techniques, biochar's characteristics can vary substantially, resulting in varying adsorption capacities and performance between studies and batches (100–104). For instance, a broad variety of copper adsorption capabilities (from 4–223 mg/g) are demonstrated by biochar derived from various sources (hardwood, corn straw, seaweed, municipal trash, and pine residue) and at various pyrolysis temperatures (100–102,104). Performance can be enhanced by modifications (such as chemical, magnetic, or mineral additives), but they also increase complexity and variability (104–107). It is challenging to compare findings or create general suggestions because experimental parameters including pH, initial copper content, contact time, and temperature vary greatly between investigations (100–102,105). Copper adsorption can be greatly impacted by the presence of competing ions or mixed waste streams, however these variables are not always assessed (100,108). Most studies are conducted at laboratory scale using batch systems, which may not reflect real wastewater conditions or continuous flow systems (103,104). Although biochar exhibits promise in the removal of copper from water, issues with scale-up, uneven material characteristics, and a lack of standardised testing must be resolved before it can be effectively applied in actual water.

11. Future perspectives of biochar

Enhancing adsorption efficiency, selectivity, and practical use at bigger sizes are the main goals of future views. Copper adsorption capability and selectivity are greatly increased when magnetic nanoparticles or functional groups (such as amino groups) are added to biochar. Because of their high adsorption capabilities (up to 234.1 mg/g and 85.93 mg/g, respectively), ease of separation, and reusability, magnetic-biochar/alginate beads and activated magnetic biochars are appropriate for real-world water treatment applications (109,110). Adding functional groups to biochar (such as amino modification) can improve stability and selectivity at different pH levels and boost adsorption capacity by up to five times (111). To reach its full potential in environmental remediation, field-scale validation and commercialisation should be the top priorities of future research.

12. Conclusion

Biochar exhibits great promise as an efficient, reasonably priced, and ecologically benign adsorbent for the extraction of copper from aqueous solutions. Its adsorption capacity, selectivity, and stability are continuously improved by a variety of modifications, including activation, amino functionalisation, and metal doping. Some modified biochars have been shown to achieve copper adsorption capacities of over 150 mg/g and removal efficiencies of up to 100%. Cation exchange, surface complexation, and electrostatic interactions are the mechanisms that underlie copper adsorption, and pseudo-second-order kinetic models and Langmuir isotherms are frequently used to characterise the process. More comparison studies that explicitly assess the effectiveness of various biochar types and changes under standardised settings are obviously needed, notwithstanding these encouraging results. Furthermore, long-term research is necessary to evaluate the biochar's resilience, regeneration, and practicality for copper remediation, particularly in intricate or mixed-contaminant systems. To completely realise and maximise the use of biochar for sustainable copper adsorption in environmental remediation, more research in these areas will be essential.

Reference

1. Hadjipanagiotou C, Christou A, Zissimos AM, Chatzitheodoridis E, Varnavas SP. Contamination of stream waters, sediments, and agricultural soil in the surroundings of an abandoned copper mine by potentially toxic elements and associated environmental and potential human health–derived risks: a case study from Agrokipia, Cyprus. Environmental Science and Pollution Research. 2020;27(33):41279–98.

2. Fitzgerald DJ. Safety guidelines for copper in water. American Journal of Clinical Nutrition [Internet]. 1998;67(5 SUPPL.):1098S-1102S. Available from: https://doi.org/10.1093/ajcn/67.5.1098S

3. Georgopoulos PG, Roy A, Yonone-Lioy MJ, Opiekun RE, Lioy PJ. Environmental copper: Its dynamics and human exposure issues. J Toxicol Environ Health B Crit Rev. 2001;4(4):341–94.

4. Ugwu CE, Igbokwe AM, Suru SM, Dike CC, Mbachu AN, Maduka HCC. Evaluating the human health risks of heavy metal contamination in copper and steel factory

effluents in Nnewi, Anambra State, Nigeria. Toxicol Rep [Internet]. 2024;12(January):614–21. Available from: https://doi.org/10.1016/j.toxrep.2024.05.009

5. Alkhanjaf AAM, Sharma S, Sharma M, Kumar R, Arora NK, Kumar B, et al. Microbial strategies for copper pollution remediation: Mechanistic insights and recent advances. Environmental Pollution [Internet]. 2024;346(September 2023):123588. Available from: https://doi.org/10.1016/j.envpol.2024.123588

6. Liu Y, Wang H, Cui Y, Chen N. Removal of Copper Ions from Wastewater: A Review. Int J Environ Res Public Health. 2023;20(5).

7. Vesković J, Bulatović S, Miletić A, Tadić T, Marković B, Nastasović A, et al. Source-specific probabilistic health risk assessment of potentially toxic elements in groundwater of a copper mining and smelter area. Stochastic Environmental Research and Risk Assessment [Internet]. 2024;38(4):1597–612. Available from: https://doi.org/10.1007/s00477-023-02643-6

8. Bayar J, Ali N, Dong Y, Ahmad U, Anjum MM, Khan GR, et al. Biochar-based adsorption for heavy metal removal in water: a sustainable and cost-effective approach. Environ Geochem Health [Internet]. 2024;46(11):1–25. Available from: https://doi.org/10.1007/s10653-024-02214-w

9. Qiu B, Tao X, Wang H, Li W, Ding X, Chu H. Biochar as a low-cost adsorbent for aqueous heavy metal removal: A review. J Anal Appl Pyrolysis [Internet]. 2021;155(December 2020):105081. Available from: https://doi.org/10.1016/j.jaap.2021.105081

10. Lee HS, Shin HS. Competitive adsorption of heavy metals onto modified biochars: Comparison of biochar properties and modification methods. J Environ Manage [Internet]. 2021;299(August):113651. Available from: https://doi.org/10.1016/j.jenvman.2021.113651

11. Xiao J, Hu R, Chen G. Micro-nano-engineered nitrogenous bone biochar developed with a ball-milling technique for high-efficiency removal of aquatic Cd(II), Cu(II) and Pb(II). J Hazard Mater [Internet]. 2020;387(December 2019):121980. Available from: https://doi.org/10.1016/j.jhazmat.2019.121980

12. Liu Z, Xu Z, Xu L, Buyong F, Chay TC, Li Z, et al. Modified biochar: synthesis and mechanism for removal of environmental heavy metals. Carbon Research [Internet]. 2022;1(1):1–21. Available from: https://doi.org/10.1007/s44246-022-00007-3

13. Li Y, Yu H, Liu L, Yu H. Application of co-pyrolysis biochar for the adsorption and immobilization of heavy metals in contaminated environmental substrates. J Hazard Mater [Internet]. 2021;420(July):126655. Available from: https://doi.org/10.1016/j.jhazmat.2021.126655

14. Pal DB, Singh A, Jha JM, Srivastava N, Hashem A, Alakeel MA, et al. Low-cost biochar adsorbents prepared from date and delonix regia seeds for heavy metal sorption. Bioresour Technol [Internet]. 2021;339(July):125606. Available from: https://doi.org/10.1016/j.biortech.2021.125606

15. Hussain A, Maitra J, Khan KA. Development of biochar and chitosan blend for heavy metals uptake from synthetic and industrial wastewater. Appl Water Sci. 2017;7(8):4525–37.

16. Liu C, Zhang HX. Modified-biochar adsorbents (MBAs) for heavy-metal ions adsorption: A critical review. J Environ Chem Eng [Internet]. 2022;10(2):107393. Available from: https://doi.org/10.1016/j.jece.2022.107393

17. Maneechakr P, Mongkollertlop S. Investigation on adsorption behaviors of heavy metal ions (Cd2+, Cr3+, Hg2+and Pb2+) through low-cost/active manganese dioxide-modified magnetic biochar derived from palm kernel cake residue. J Environ Chem Eng. 2020;8(6).

18. Sakhiya AK, Anand A, Kaushal P. Production, activation, and applications of biochar in recent times. Vol. 2, Biochar. Springer Science and Business Media B.V.; 2020. p. 253–85.

19. Li Y, Xing B, Ding Y, Han X, Wang S. A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass. Bioresour Technol [Internet]. 2020;312(June):123614. Available from: https://doi.org/10.1016/j.biortech.2020.123614

20. Zhou Y, Qin S, Verma S, Sar T, Sarsaiya S, Ravindran B, et al. Production and beneficial impact of biochar for environmental application: A comprehensive review. Bioresour

Technol [Internet]. 2021;337(June):125451. Available from: https://doi.org/10.1016/j.biortech.2021.125451

21. Yaashikaa PR, Senthil Kumar P, Varjani SJ, Saravanan A. Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants. Bioresour Technol [Internet]. 2019;292(July):122030. Available from: https://doi.org/10.1016/j.biortech.2019.122030

22. Amalina F, Syukor Abd Razak A, Krishnan S, Sulaiman H, Zularisam AW, Nasrullah M. Advanced techniques in the production of biochar from lignocellulosic biomass and environmental applications. Cleaner Materials [Internet]. 2022;6(March):100137. Available from: https://doi.org/10.1016/j.clema.2022.100137

23. Zhang Z, Zhu Z, Shen B, Liu L. Insights into biochar and hydrochar production and applications: A review. Energy [Internet]. 2019;171:581–98. Available from: https://doi.org/10.1016/j.energy.2019.01.035

24. Amalina F, Razak ASA, Krishnan S, Sulaiman H, Zularisam AW, Nasrullah M. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review. Journal of Hazardous Materials Advances [Internet]. 2022;7(July):100134. Available from: https://doi.org/10.1016/j.hazadv.2022.100134

25. Cha JS, Park SH, Jung SC, Ryu C, Jeon JK, Shin MC, et al. Production and utilization of biochar: A review. Journal of Industrial and Engineering Chemistry [Internet]. 2016;40:1–15. Available from: http://dx.doi.org/10.1016/j.jiec.2016.06.002

26. Leng L, Xiong Q, Yang L, Li H, Zhou Y, Zhang W, et al. An overview on engineering the surface area and porosity of biochar. Science of the Total Environment [Internet]. 2021;763:144204. Available from: https://doi.org/10.1016/j.scitotenv.2020.144204

27. Remmani R, Yılmaz M, Benaoune S, Di Palma L. Optimized pyrolytic synthesis and physicochemical characterization of date palm seed biochar: unveiling a sustainable adsorbent for environmental remediation applications. Environmental Science and Pollution Research [Internet]. 2024;31(50):60065–79. Available from: https://doi.org/10.1007/s11356-024-35218-1

28. Hu R, Xiao J, Wang T, Chen G, Chen L, Tian X. Engineering of phosphate-functionalized biochars with highly developed surface area and porosity for efficient and

selective extraction of uranium. Chemical Engineering Journal [Internet]. 2020;379(May 2019):122388. Available from: https://doi.org/10.1016/j.cej.2019.122388

29. Lopez-Tenllado FJ, Motta IL, Hill JM. Modification of biochar with high-energy ball milling: Development of porosity and surface acid functional groups. Bioresour Technol Rep [Internet]. 2021;15(February):100704. Available from: https://doi.org/10.1016/j.biteb.2021.100704

30. Li H, Dong X, da Silva EB, de Oliveira LM, Chen Y, Ma LQ. Mechanisms of metal sorption by biochars: Biochar characteristics and modifications. Chemosphere [Internet]. 2017;178:466–78. Available from: http://dx.doi.org/10.1016/j.chemosphere.2017.03.072

31. Suliman W, Harsh JB, Abu-Lail NI, Fortuna AM, Dallmeyer I, Garcia-Pérez M. The role of biochar porosity and surface functionality in augmenting hydrologic properties of a sandy soil. Science of the Total Environment [Internet]. 2017;574:139–47. Available from: http://dx.doi.org/10.1016/j.scitotenv.2016.09.025

32. Tan XF, Zhu SS, Wang RP, Chen Y Di, Show PL, Zhang FF, et al. Role of biochar surface characteristics in the adsorption of aromatic compounds: Pore structure and functional groups. Chinese Chemical Letters [Internet]. 2021;32(10):2939–46. Available from: https://doi.org/10.1016/j.cclet.2021.04.059

33. Saghir S, Pu C, Fu E, Wang Y, Xiao Z. Synthesis of high surface area porous biochar obtained from pistachio shells for the efficient adsorption of organic dyes from polluted water. Surfaces and Interfaces [Internet]. 2022;34(September):102357. Available from: https://doi.org/10.1016/j.surfin.2022.102357

34. Tan Z, Yuan S, Hong M, Zhang L, Huang Q. Mechanism of negative surface charge formation on biochar and its effect on the fixation of soil Cd. J Hazard Mater. 2020;384(February 2019).

35. Hassan M, Liu Y, Naidu R, Parikh SJ, Du J, Qi F, et al. Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: A meta-analysis. Science of the Total Environment [Internet]. 2020;744:140714. Available from: https://doi.org/10.1016/j.scitotenv.2020.140714

36. Leng L, Xiong Q, Yang L, Li H, Zhou Y, Zhang W, et al. An overview on engineering the surface area and porosity of biochar. Science of the Total Environment [Internet]. 2021;763:144204. Available from: https://doi.org/10.1016/j.scitotenv.2020.144204

37. Ferraro G, Pecori G, Rosi L, Bettucci L, Fratini E, Casini D, et al. Biochar from lab-scale pyrolysis: influence of feedstock and operational temperature. Biomass Convers Biorefin. 2024;14(5):5901–11.

38. Islam MS, Kwak JH, Nzediegwu C, Wang S, Palansuriya K, Kwon EE, et al. Biochar heavy metal removal in aqueous solution depends on feedstock type and pyrolysis purging gas. Environmental Pollution [Internet]. 2021;281:117094. Available from: https://doi.org/10.1016/j.envpol.2021.117094

39. Arán D, Antelo J, Fiol S, Macías F. Influence of feedstock on the copper removal capacity of waste-derived biochars. Bioresour Technol. 2016;212:199–206.

40. Tomczyk A, Sokołowska Z, Boguta P. Biomass type effect on biochar surface characteristic and adsorption capacity relative to silver and copper. Fuel. 2020;278(October 2019).

41. Michael-Kordatou I, Michael C, Duan X, He X, Dionysiou DD, Mills MA, et al. Dissolved effluent organic matter: Characteristics and potential implications in wastewater treatment and reuse applications. Water Res. 2015;77:213–48.

42. Robert I, Perla G, Natalie J. Article (refereed) - postprint. 2019;

43. Gmach MR, Cherubin MR, Kaiser K, Cerri CEP. Sci Agric. 2020;77(3).

44. McDowell WH. Dissolved organic matter in soils - Future directions and unanswered questions. Geoderma. 2003;113(3–4):179–86.

45. Zhang H, Zheng Y, Wang XC, Wang Y, Dzakpasu M. Characterization and biogeochemical implications of dissolved organic matter in aquatic environments. J Environ Manage [Internet]. 2021;294(13):113041. Available from: https://doi.org/10.1016/j.jenvman.2021.113041

46. Ma J, Huang W, Zhang X, Li Y, Wang N. The utilization of lobster shell to prepare low-cost biochar for high-efficient removal of copper and cadmium from aqueous: Sorption properties and mechanisms. J Environ Chem Eng [Internet]. 2021;9(1):104703. Available from: https://doi.org/10.1016/j.jece.2020.104703

47. Zhou S, Yang YX, Cao JJ, Meng LL, Cao JN, Zhang C, et al. Monitoring of copper adsorption on biochar using spectral induced polarization method. Environ Res [Internet]. 2024;251(P2):118778. Available from: https://doi.org/10.1016/j.envres.2024.118778

48. Chen Y, Li M, Li Y, Liu Y, Chen Y, Li H, et al. Hydroxyapatite modified sludge-based biochar for the adsorption of Cu2+ and Cd2+: Adsorption behavior and mechanisms. Bioresour Technol [Internet]. 2021;321(November 2020):124413. Available from: https://doi.org/10.1016/j.biortech.2020.124413

49. Yang GX, Jiang H. Amino modification of biochar for enhanced adsorption of copper ions from synthetic wastewater. Water Res [Internet]. 2014;48(1):396–405. Available from: http://dx.doi.org/10.1016/j.watres.2013.09.050

50. Yang GX, Jiang H. Amino modification of biochar for enhanced adsorption of copper ions from synthetic wastewater. Water Res [Internet]. 2014;48(1):396–405. Available from: http://dx.doi.org/10.1016/j.watres.2013.09.050

51. Gao Y, Zhu X, Yue Q, Gao B. Facile one-step synthesis of functionalized biochar from sustainable prolifera-green-tide source for enhanced adsorption of copper ions. J Environ Sci (China) [Internet]. 2018;73:185–94. Available from: https://doi.org/10.1016/j.jes.2018.02.012

52. Chen Y, Li M, Li Y, Liu Y, Chen Y, Li H, et al. Hydroxyapatite modified sludge-based biochar for the adsorption of Cu2+ and Cd2+: Adsorption behavior and mechanisms. Bioresour Technol [Internet]. 2021;321(November 2020):124413. Available from: https://doi.org/10.1016/j.biortech.2020.124413

53. Babeker TMA, Lv S, Khalil MN, Hao Z, Chen Q. Biochar modified by ammonium pyrrolidine dithiocarbamate for high selective adsorption of copper in wastewater. Sep Purif Technol [Internet]. 2025;354(P7):129436. Available from: https://doi.org/10.1016/j.seppur.2024.129436

54. Peng H, Gao P, Chu G, Pan B, Peng J, Xing B. Enhanced adsorption of Cu(II) and Cd(II) by phosphoric acid-modified biochars. Environmental Pollution [Internet]. 2017;229:846–53. Available from: http://dx.doi.org/10.1016/j.envpol.2017.07.004

55. Katiyar R, Patel AK, Nguyen TB, Singhania RR, Chen CW, Dong C Di. Adsorption of copper (II) in aqueous solution using biochars derived from Ascophyllum nodosum seaweed. Bioresour Technol [Internet]. 2021;328(January):124829. Available from: https://doi.org/10.1016/j.biortech.2021.124829

56. Su X, Chen Y, Li Y, Li J, Song W, Li X, et al. Enhanced adsorption of aqueous Pb(II) and Cu(II) by biochar loaded with layered double hydroxide: Crucial role of mineral precipitation. J Mol Liq [Internet]. 2022;357:119083. Available from: https://doi.org/10.1016/j.molliq.2022.119083

57. Hu H, Li X, Huang P, Zhang Q, Yuan W. Efficient removal of copper from wastewater by using mechanically activated calcium carbonate. J Environ Manage [Internet]. 2017;203:1–7. Available from: http://dx.doi.org/10.1016/j.jenvman.2017.07.066

58. Wang Y, Xu L, Li J, Ren Z, Liu W, Ai Y, et al. Synthesis of magnetic chitosan-composite biochar and its removal of copper ions (Cu2+) and methylene blue (MB) dye from aqueous solutions. Vol. 31, Environmental Science and Pollution Research. 2024. p. 59866–81.

59. Benalia MC, Youcef L, Bouaziz MG, Achour S, Menasra H. Removal of Heavy Metals from Industrial Wastewater by Chemical Precipitation: Mechanisms and Sludge Characterization. Arab J Sci Eng [Internet]. 2022;47(5):5587–99. Available from: https://doi.org/10.1007/s13369-021-05525-7

60. Wang H, Chen Q, Xia H, Liu R, Zhang Y. Enhanced complexation and electrostatic attraction through fabrication of amino- or hydroxyl-functionalized Fe/Ni-biochar composite for the adsorption of Pb(II) and Cd(II). Sep Purif Technol [Internet]. 2024;328(September 2023):125074. Available from: https://doi.org/10.1016/j.seppur.2023.125074

61. Yuan S, Tan Z. Effect and mechanism of changes in physical structure and chemical composition of new biochar on Cu(II) adsorption in an aqueous solution. Soil Ecology Letters. 2022;4(3):237–53.

62. Ren J, Shao E, Wu H, Guan Y. Highly selective and effective copper removal from wastewater by magnetic precipitation separation. Journal of Water Process Engineering [Internet]. 2025;69(30):106700. Available from: https://doi.org/10.1016/j.jwpe.2024.106700

63. Wang Q, Bian J, Ruan D, Zhang C. Adsorption of benzene on soils under different influential factors: an experimental investigation, importance order and prediction using artificial neural network. J Environ Manage [Internet]. 2022;306(January):114467. Available from: https://doi.org/10.1016/j.jenvman.2022.114467

64. Zhang J, Zhan S, Zhong L Bin, Wang X, Qiu Z, Zheng YM. Adsorption of typical natural organic matter on microplastics in aqueous solution: Kinetics, isotherm, influence factors and mechanism. J Hazard Mater [Internet]. 2023;443(PA):130130. Available from: https://doi.org/10.1016/j.jhazmat.2022.130130

65. Bilgiç C. Investigation of the factors affecting organic cation adsorption on some silicate minerals. J Colloid Interface Sci. 2005;281(1):33–8.

66. Gao Z, Bandosz TJ, Zhao Z, Han M, Qiu J. Investigation of factors affecting adsorption of transition metals on oxidized carbon nanotubes. J Hazard Mater. 2009;167(1–3):357–65.

67. Zhu S, Ye Z, Liu Z, Chen Z, Li J, Xiang Z. Polymers-13-01774.Pdf. 2021.

68. Li S, Yang M, Wang H, Jiang Y. Adsorption of microplastics on aquifer media: Effects of the action time, initial concentration, ionic strength, ionic types and dissolved organic matter. Environmental Pollution [Internet]. 2022;308(October 2021):119482. Available from: https://doi.org/10.1016/j.envpol.2022.119482

69. Fu L, Li J, Wang G, Luan Y, Dai W. Adsorption behavior of organic pollutants on microplastics. Ecotoxicol Environ Saf [Internet]. 2021;217(March):112207. Available from: https://doi.org/10.1016/j.ecoenv.2021.112207

70. Husien S, El-taweel RM, Salim AI, Fahim IS, Said LA, Radwan AG. Review of activated carbon adsorbent material for textile dyes removal: Preparation, and modelling. Current Research in Green and Sustainable Chemistry [Internet]. 2022;5(June):100325. Available from: https://doi.org/10.1016/j.crgsc.2022.100325

71. Natarajan R, Saikia K, Ponnusamy SK, Rathankumar AK, Rajendran DS, Venkataraman S, et al. Understanding the factors affecting adsorption of pharmaceuticals on different adsorbents – A critical literature update. Chemosphere [Internet]. 2022;287(P1):131958. Available from: https://doi.org/10.1016/j.chemosphere.2021.131958

72. Tran TH, Le AH, Pham TH, Nguyen DT, Chang SW, Chung WJ, et al. Adsorption isotherms and kinetic modeling of methylene blue dye onto a carbonaceous hydrochar adsorbent derived from coffee husk waste. Science of the Total Environment [Internet]. 2020;725:138325. Available from: https://doi.org/10.1016/j.scitotenv.2020.138325

73. Chen F xiong, Zhou C rong, Li G peng, Peng F fei. Thermodynamics and kinetics of glyphosate adsorption on resin D301. Arabian Journal of Chemistry [Internet]. 2016;9:S1665–9. Available from: http://dx.doi.org/10.1016/j.arabjc.2012.04.014

74. Saxena M, Sharma N, Saxena R. Highly efficient and rapid removal of a toxic dye: Adsorption kinetics, isotherm, and mechanism studies on functionalized multiwalled carbon nanotubes. Surfaces and Interfaces [Internet]. 2020;21(June):100639. Available from: https://doi.org/10.1016/j.surfin.2020.100639

75. Ganguly P, Sarkhel R, Das P. Synthesis of pyrolyzed biochar and its application for dye removal: Batch, kinetic and isotherm with linear and non-linear mathematical analysis. Surfaces and Interfaces [Internet]. 2020;20(July):100616. Available from: https://doi.org/10.1016/j.surfin.2020.100616

76. Li F, Fang X, Zhou Z, Liao X, Zou J, Yuan B, et al. Adsorption of perfluorinated acids onto soils: Kinetics, isotherms, and influences of soil properties. Science of the Total Environment. 2019;649:504–14.

77. Khumalo SM, Bakare BF, Rathilal S. Single and multicomponent adsorption of amoxicillin, ciprofloxacin, and sulfamethoxazole on chitosan-carbon nanotubes hydrogel beads from aqueous solutions: Kinetics, isotherms, and thermodynamic parameters. Journal of Hazardous Materials Advances [Internet]. 2024;13(October 2023):100404. Available from: https://doi.org/10.1016/j.hazadv.2024.100404

78. Amutova F, Jurjanz S, Akhmetsadykov N, Kazankapova M, Razafitianamaharavo A, Renard A, et al. Adsorption of organochlorinated pesticides: Adsorption kinetic and adsorption isotherm study. Results in Engineering. 2023;17(October 2022).

79. Wang J, Guo X. Adsorption kinetics and isotherm models of heavy metals by various adsorbents: An overview. Crit Rev Environ Sci Technol [Internet]. 2023;53(21):1837–65. Available from: https://doi.org/10.1080/10643389.2023.2221157

80. Chen X, Chen G, Chen L, Chen Y, Lehmann J, McBride MB, et al. Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresour Technol [Internet]. 2011;102(19):8877–84. Available from: http://dx.doi.org/10.1016/j.biortech.2011.06.078

81. Tomczyk A, Kubaczyński A, Szewczuk-Karpisz K. Assessment of agricultural waste biochars for remediation of degraded water-soil environment: Dissolved organic carbon release and immobilization of impurities in one- or two-adsorbate systems. Waste Management. 2023;155(November 2022):87–98.

82. Iamsaard K, Weng CH, Tzeng JH, Anotai J, Jacobson AR, Lin YT. Systematic optimization of biochars derived from corn wastes, pineapple leaf, and sugarcane bagasse for Cu(II) adsorption through response surface methodology. Bioresour Technol [Internet]. 2023;382(March):129131. Available from: https://doi.org/10.1016/j.biortech.2023.129131

83. Huang WH, Wu RM, Chang JS, Juang SY, Lee DJ. Manganese ferrite modified agricultural waste-derived biochars for copper ions adsorption. Bioresour Technol [Internet]. 2023;367(November 2022):128303. Available from: https://doi.org/10.1016/j.biortech.2022.128303

84. Jiang S, Huang L, Nguyen TAH, Ok YS, Rudolph V, Yang H, et al. Copper and zinc adsorption by softwood and hardwood biochars under elevated sulphate-induced salinity and acidic pH conditions. Chemosphere [Internet]. 2016;142:64–71. Available from: http://dx.doi.org/10.1016/j.chemosphere.2015.06.079

85. Zhou Y, Liu X, Xiang Y, Wang P, Zhang J, Zhang F, et al. Modification of biochar derived from sawdust and its application in removal of tetracycline and copper from aqueous solution: Adsorption mechanism and modelling. Bioresour Technol [Internet]. 2017;245(August):266–73. Available from: https://doi.org/10.1016/j.biortech.2017.08.178

86. Ma W, Han R, Zhang W, Zhang H, Chen L, Zhu L. Magnetic biochar enhanced copper immobilization in agricultural lands: Insights from adsorption precipitation and redox. J Environ Manage [Internet]. 2024;352(December 2023):120058. Available from: https://doi.org/10.1016/j.jenvman.2024.120058

87. Tomczyk A, Sokołowska Z, Boguta P, Szewczuk-Karpisz K. Comparison of monovalent and divalent ions removal from aqueous solutions using agricultural waste biochars prepared at different temperatures—experimental and model study. Int J Mol Sci. 2020;21(16):1–18.

88. Salem D Ben, Ouakouak A, Touahra F, Hamdi N, Eltaweil AS, Syed A, et al. Easy separable, floatable, and recyclable magnetic-biochar/alginate bead as super-adsorbent for adsorbing copper ions in water media. Bioresour Technol [Internet]. 2023;383(March):129225. Available from: https://doi.org/10.1016/j.biortech.2023.129225

89. Iamsaard K, Weng CH, Tzeng JH, Anotai J, Jacobson AR, Lin YT. Systematic optimization of biochars derived from corn wastes, pineapple leaf, and sugarcane bagasse for Cu(II) adsorption through response surface methodology. Bioresour Technol [Internet]. 2023;382(March):129131. Available from: https://doi.org/10.1016/j.biortech.2023.129131

90. Yang GX, Jiang H. Amino modification of biochar for enhanced adsorption of copper ions from synthetic wastewater. Water Res [Internet]. 2014;48(1):396–405. Available from: http://dx.doi.org/10.1016/j.watres.2013.09.050

91. Cuong DV, Liu NL, Nguyen VA, Hou CH. Meso/micropore-controlled hierarchical porous carbon derived from activated biochar as a high-performance adsorbent for copper removal. Science of the Total Environment [Internet]. 2019;692(1):844–53. Available from: https://doi.org/10.1016/j.scitotenv.2019.07.125

92. Katiyar R, Patel AK, Nguyen TB, Singhania RR, Chen CW, Dong C Di. Adsorption of copper (II) in aqueous solution using biochars derived from Ascophyllum nodosum seaweed. Bioresour Technol [Internet]. 2021;328(February):124829. Available from: https://doi.org/10.1016/j.biortech.2021.124829

93. Iamsaard K, Weng CH, Tzeng JH, Anotai J, Jacobson AR, Lin YT. Systematic optimization of biochars derived from corn wastes, pineapple leaf, and sugarcane bagasse for Cu(II) adsorption through response surface methodology. Bioresour Technol [Internet]. 2023;382(March):129131. Available from: https://doi.org/10.1016/j.biortech.2023.129131

94. Gao Y, Zhu X, Yue Q, Gao B. Facile one-step synthesis of functionalized biochar from sustainable prolifera-green-tide source for enhanced adsorption of copper ions. J Environ Sci (China) [Internet]. 2018;73:185–94. Available from: https://doi.org/10.1016/j.jes.2018.02.012

95. Zhang Y, Qiu G, Wang R, Guo Y, Guo F, Wu J. Preparation of bamboo-based hierarchical porous carbon modulated by fecl3 towards efficient copper adsorption. Molecules. 2021;26(19).

96. Regmi P, Garcia Moscoso JL, Kumar S, Cao X, Mao J, Schafran G. Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. J Environ Manage [Internet]. 2012;109:61–9. Available from: http://dx.doi.org/10.1016/j.jenvman.2012.04.047

97. Kucmanová A, Ščasná M, Sirotiak M, Šido J. Sorption Kinetics of Copper Ions on Biochar and Zeolite. J Phys Conf Ser. 2024;2931(1).

98. Krstić V, Urošević T, Pešovski B. A review on adsorbents for treatment of water and wastewaters containing copper ions. Chem Eng Sci. 2018;192:273–87.

99. Jiang S, Huang L, Nguyen TAH, Ok YS, Rudolph V, Yang H, et al. Copper and zinc adsorption by softwood and hardwood biochars under elevated sulphate-induced salinity and acidic pH conditions. Chemosphere [Internet]. 2016;142:64–71. Available from: http://dx.doi.org/10.1016/j.chemosphere.2015.06.079

100. Chen X, Chen G, Chen L, Chen Y, Lehmann J, McBride MB, et al. Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresour Technol [Internet]. 2011;102(19):8877–84. Available from: http://dx.doi.org/10.1016/j.biortech.2011.06.078

101. Katiyar R, Patel AK, Nguyen TB, Singhania RR, Chen CW, Dong C Di. Adsorption of copper (II) in aqueous solution using biochars derived from Ascophyllum nodosum seaweed. Bioresour Technol [Internet]. 2021;328(January):124829. Available from: https://doi.org/10.1016/j.biortech.2021.124829

102. Regmi P, Garcia Moscoso JL, Kumar S, Cao X, Mao J, Schafran G. Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via

hydrothermal carbonization process. J Environ Manage [Internet]. 2012;109:61–9. Available from: http://dx.doi.org/10.1016/j.jenvman.2012.04.047

103. Hoslett J, Ghazal H, Ahmad D, Jouhara H. Removal of copper ions from aqueous solution using low temperature biochar derived from the pyrolysis of municipal solid waste. Science of the Total Environment [Internet]. 2019;673:777–89. Available from: https://doi.org/10.1016/j.scitotenv.2019.04.085

104. Bashir M, Mohan C, Tyagi S, Annachhatre A. Copper removal from aqueous solution using chemical precipitation and adsorption by Himalayan Pine Forest Residue as Biochar. Water Science and Technology. 2022;86(3):530–54.

105. El-Nemr MA, Abdelmonem NM, Ismail IMA, Ragab S, El Nemr A. Ozone and Ammonium Hydroxide Modification of Biochar Prepared from Pisum sativum Peels Improves the Adsorption of Copper (II) from an Aqueous Medium. Vol. 7, Environmental Processes. 2020. 973–1007 p.

106. Wang Y, Xu L, Li J, Ren Z, Liu W, Ai Y, et al. Synthesis of magnetic chitosan-composite biochar and its removal of copper ions (Cu2+) and methylene blue (MB) dye from aqueous solutions. Environmental Science and Pollution Research [Internet]. 2024;31(50):59866–81. Available from: https://doi.org/10.1007/s11356-024-35145-1

107. Wang R, Ren J, Ren H, Tao L, Wu C, Sun X, et al. Enhanced Adsorption of Cu2+ from Aqueous Solution by Sludge Biochar Compounded with Attapulgite-Modified Fe. Water (Switzerland). 2023;15(23).

108. Deng Y, Li X, Ni F, Liu Q, Yang Y, Wang M, et al. Synthesis of magnesium modified biochar for removing copper, lead and cadmium in single and binary systems from aqueous solutions: Adsorption mechanism. Water (Switzerland). 2021;13(5).

109. Salem D Ben, Ouakouak A, Touahra F, Hamdi N, Eltaweil AS, Syed A, et al. Easy separable, floatable, and recyclable magnetic-biochar/alginate bead as super-adsorbent for adsorbing copper ions in water media. Bioresour Technol [Internet]. 2023;383(May):129225. Available from: https://doi.org/10.1016/j.biortech.2023.129225

110. Yang GX, Jiang H. Amino modification of biochar for enhanced adsorption of copper ions from synthetic wastewater. Water Res [Internet]. 2014;48(1):396–405. Available from: http://dx.doi.org/10.1016/j.watres.2013.09.050

111. Yin Z, Liu Y, Liu S, Jiang L, Tan X, Zeng G, et al. Activated magnetic biochar by one-step synthesis: Enhanced adsorption and coadsorption for 17β-estradiol and copper. Science of the Total Environment [Internet]. 2018;639:1530–42. Available from: https://doi.org/10.1016/j.scitotenv.2018.05.130

Acknowledgments

All figures presented in this work were independently created by the authors. No permissions from third parties are required.

Conflict of Interest

The authors declare that there are no conflicts of interest related to this work.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data Availability Statement

The data supporting the findings of this study are not publicly available at the time of publication due to format limitations that hinder reuse or accessibility by other researchers. However, the data may be provided upon reasonable request to the authors.