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The Potential of Biochar for Heavy Metal Adsorption in Acid Mine Drainage Based on Literature Review

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Abstract
Incorporating organic materials that contain biochar is gaining traction as a research area for the cleanup of wastewater contaminated with heavy metals. This study intends to explore the potential of biochar-based materials in removing heavy metals from water sources, with a particular emphasis on rehabilitating aquatic environments affected by mining waste. To understand the topic, identifying some appropriate literature studies in collecting research data from various scientific publications was used. Several biochar manufacturing processes are generated through pyrolysis, gasification, and *Hydrothermal carbonization* (HTC). In this field, studies revealed that using most biochar can achieve relatively high metal removal. Research findings indicate that Cu, Zn, Cd, Pb, Ni, Cr, Co, As, Ag, Fe, Al, and Mn are the metal ions that have received the most attention in this field. This study highlights explicitly the effectiveness of biochars made from orange peel, nutshell, compost, rice husk, oak wood, used coffee grounds, durian bark, Phragmites australis corn cob, dregs of cascara, and hickory wood. The findings show that biochars from these materials, especially those produced at high pyrolysis temperatures (≥500°C), can achieve metal removal efficiencies above (≥90%). Various factors can influence the effectiveness of biochar in removing heavy metal ions, including the pH of the contaminated water, the amount of biochar used, the initial concentration of heavy metals, the properties of the biochar, and the specific forms or speciation of the metals. Biochar's ability to draw in and retain metal ions can be influenced by its characteristics, including its surface area and pore sizes. This study highlights the need for more research in this field going forward. It gives a general review of the use of biochar in removing heavy metals from water, particularly contamination in Acid Mine Drainage (AMD).

1. Introduction

Indonesia, one of the countries with very high potential mineral reserves, faces significant challenges in managing the environmental impacts of mining activities. With the many mining activities in Indonesia, mainly mineral and coal mining, the Acid Mine Drainage (AMD) problem seriously threatens water and soil quality. High acidity, heavy metal contamination, and increased sulfate ion levels are common AMD characteristics, arising from active and closed or rehabilitated mining operations. In general, the concentration of heavy metals in mining wastewater is considered high and dangerous if it exceeds the threshold set by the national government and environmental standards. This threshold value can vary depending on the context and type of metal. In contrast, the standard pH value of wastewater before being released into the environment ranges from 6-9. Therefore, heavy metals must be removed from water sources to safeguard the environment and public health.

The absorption capacity of biochar using processed organic biomass is one of the biological-based processing strategies that can be applied to reduce and remove heavy metals from AMD. Biochar has become a promising alternative compared to conventional remediation methods. Compared with alternative approaches, the use of biochar as an adsorbent for AMD remediation has several advantages, including its physical and chemical characteristics that allow for optimal adsorption of heavy metals, abundant raw materials, lower production costs compared to the use of chemicals, environmentally friendly, and its ability to remove certain heavy metals with an efficiency of over 90% [13]. Biochar is produced by converting biomass into a carbon-rich material at low oxygen levels. This process can be carried out using various techniques, including gasification, hydrothermal carbonization, microwave pyrolysis, and conventional pyrolysis [19]. Biochar is a form of charcoal produced by pyrolysis that is improved with higher carbon content. Biochar is an inexpensive, eco-friendly substance that can enhance the environment sustainably.

The carbon content, high pore volume, specific surface area, and many functional biochar groups give it a stable carbon structure and powerful adsorption capabilities. Biochar's cellulose content provides beneficial qualities for efficiently eliminating heavy metals [20]. Biochar is a flexible adsorbent for environmental restoration because it can remove multiple heavy metals from water at once. Although there are limitations in our current understanding, as well as suggestions for additional research, a thorough analysis of the use of biochar to treat heavy metal pollution in water bodies is still required. This study examines the various forms of biochar for heavy metal treatment, metal reduction methods, and factors influencing metal removal to determine how successful biochar materials are for treating AMD.

2. Methodology

The research phase started by reviewing various scientific works, including national and international journal publications, and comparing past studies using biochar materials to treat industrial wastewater. A literature review thoroughly examines and assesses past research studies [36]. This research method focuses on using biochar materials for the biological adsorption of heavy metals in mining wastewater. The research begins by reviewing previous studies to understand the variety of biochar materials and their applications in removing heavy metal contaminants. This process is followed by identifying the potential results of biochar adsorption in various wastewater sources, which provides insight into its effectiveness. This process then evaluates factors that affect the adsorption ability of biochar, such as the type of material, preparation method, environmental conditions, and wastewater characteristics. Finally, the findings are synthesized into a conclusion, which summarizes and identifies areas for further research on the role of biochar in mining wastewater. The process in this research is illustrated in the diagram (Figure 1).

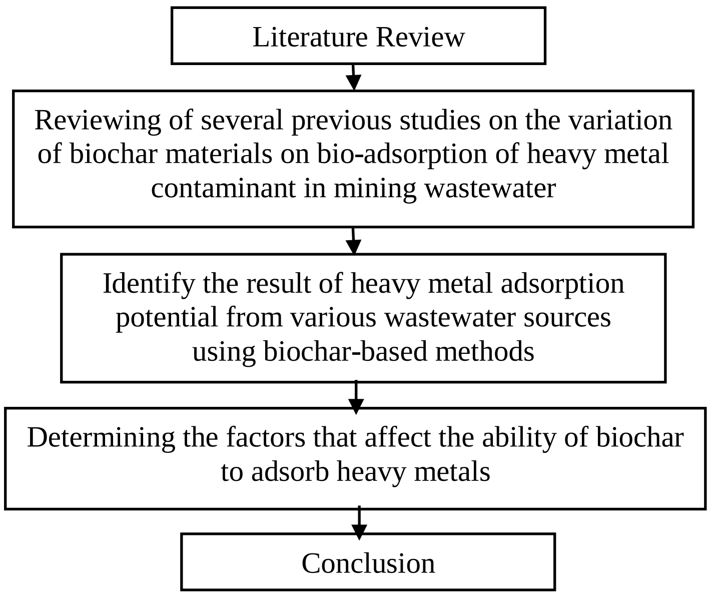

Figure 1. The Research Flow Chart

3. Results and Discussions

3.1 Acid Mine Drainage

Acid mine drainage (AMD) occurs due to the oxidation of sulfide minerals when they interact with air and water during mining operations, leading to the production of sulfuric acid that raises the acidity of the water. Sulfide minerals commonly found in mining activities are pyrite with a chemical composition (FeS_2). When the pH level and metal content in water exceed the tolerable range, it will negatively affect ecosystems and pollute the aquatic environment, so adequate treatment methods are needed to overcome these problems. The typical response that takes place during the creation of acid mine drainage is as follows [37]:

The initial response is sulfide minerals (FeS2) oxidation when interacting with oxygen and water. This reaction releases ferrous iron (Fe2+) and sulfate into the water.

$$FeS_{2\,(s)} + 3.5\ O_{2\,(g)} + H_2O_{(\ell)} \rightarrow Fe^{2+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 4\ H^+_{(aq)} \quad (1)$$

Pyrite + Oxygen + Water → Iron (II)+ Sulfate + Acidity

The second reaction involves the oxidation of ferrous iron to (Fe^{3+}) using oxygen and acidity.

$$Fe^{2+}_{(aq)} + 0.25\ O_{2\,(g)} + H^+_{(aq)} \rightarrow Fe^{3+}_{(aq)} + 0.25\ H_2O_{(\ell)} \quad (2)$$

Iron (II) + Oxygen + Acidity → Iron (III) + Water

The third reaction is a propagation reaction, taking place as long as pyrite and ferric iron minerals are available. In this reaction, ferric iron oxidizes pyrite and accelerates the oxidation rate.

$$FeS_{2\,(s)} + 14\ Fe^{3+}_{(aq)} + 8\ H_2O_{(\ell)} \rightarrow 15\ Fe^{2+}_{(aq)} + 2\ SO_4^{2-}{}_{(aq)} + 16\ H^+_{(aq)} \quad (3)$$

Pyrite + Iron (III) + Water → Iron (II) + Sulfate + Acidity

The fourth reaction is the formation of iron (III) hydroxide precipitates ($Fe(OH)_3$) or "*yellowboy*" in the form of an orange precipitate in water under low pH conditions.

$$Fe^{3+}_{(aq)} + 3\ H_2O_{(\ell)} \rightarrow Fe(OH)_{3\,(s)} + 3\ H^+_{(aq)} \quad (4)$$

Iron (III) + Water → Iron Hydroxide + Acidity

When reactions (1) to (4) are combined, a pyrite oxidation reaction produces acid mine drainage with the products; iron hydroxide, sulfuric acid, and acidity.

$$FeS_{2\,(s)} + 3.75\ O_{2\,(g)} + 3.5\ H_2O_{(\ell)} \rightarrow Fe(OH)_{3\,(s)} + 2\ SO_4^{2-}{}_{(aq)} + 4\ H^+_{(aq)} \quad (5)$$

Pyrite + Oxygen + Water → Iron Hydroxide + Sulfuric Acid + Acidity

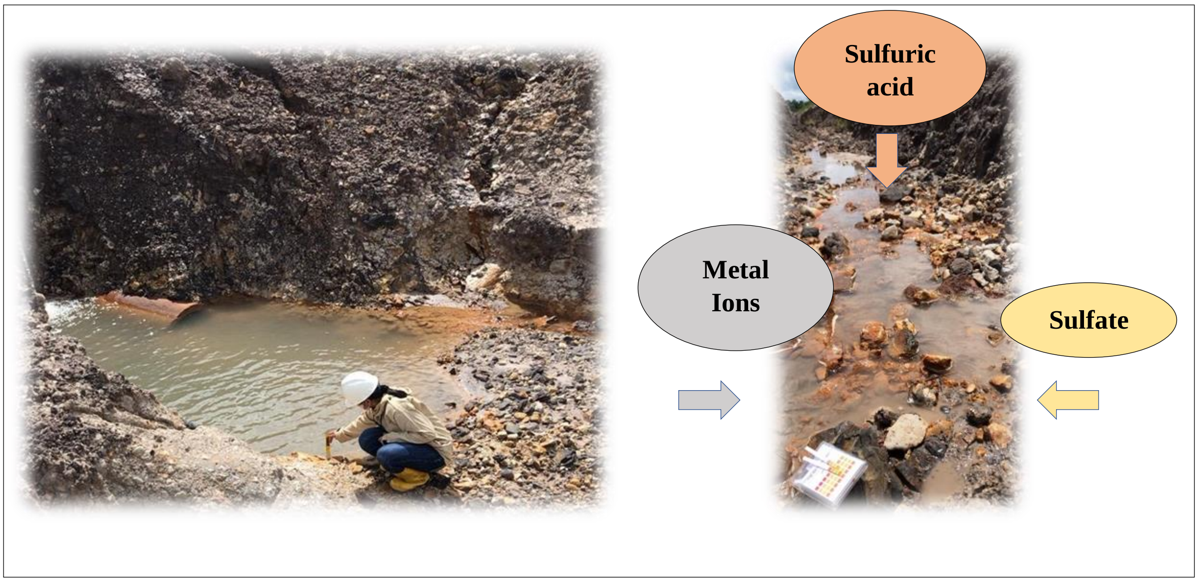

Figure 2. AMD from High-Fe and Mn in Coal Mining Area (documentation, 2024)

3.2 Metal Removal Mechanism by Biochar

When heavy metals are extracted from contaminated solutions, biochar participates in several processes. Surface complexation through functional groups, ion exchange, co-precipitation, surface precipitation, physical adsorption, electrostatic attraction, and reduction are all involved in the processes, as seen in (Figure 3). Several variables might influence these processes, including temperature, pH, metal ion concentration, and adsorbent characteristics [11].

1) Surface Complexation by Functional Groups

When metal ions establish chemical interactions with the functional groups on the adsorbent's surface, surface complexation occurs. The ability of biochar to operate as electron donors is due to the presence of specific negatively charged functional groups on its surface, such as *carboxyl* (-COOH) and *hydroxyl* (-OH) [44]. When present in solution, these functional groups can coordinate with metal ions like Cu^{2+}, Fe^{3+}, or Ag^{2+} to form complexes. These groups may leak H^+ ions into the solution as a result of the stability of the complexes, thereby contributing to changes in the solution's pH. This mechanism is optimal for the binding of metal ions, as the covalent or ionic bonds formed between the functional groups and the metal ions are much stronger than those in physical adsorption. Additionally, biochar's chemical composition, surface modification, and pyrolysis conditions significantly influence its density and type of functional groups, thereby affecting its surface complexation capacity.

2) Ion Exchange

Positive heavy metal ions interact with the negatively charged surface groups on biochar to cause ion exchange. Metal ions in the solution replace other ions, such as Ca^{2+} or Na^{2+} ions attached to the surface of the biochar, during the ion exchange process. Charge-controlled ion exchange is essential to this process, as the functional groups on the biochar, including carboxyl (-COOH) and then hydroxyl (-OH) groups, play a critical role in binding metal ions. The efficiency of ion exchange is influenced by factors such as the pH of the solution, the concentration of competing ions, and the specific properties of the biochar, such as its surface area and porosity.

3) Co-precipitation and Surface Precipitation

When deposits form with other substances, this is known as co-precipitation. It occurs when anions from mineral components such as PO_4^{3-}, $CO_3^{2-,}$ and OH^- combine with metal ions to form insoluble compounds that adhere to and precipitate on the surface of biochar. Direct contact with the surface of the biochar causes surface precipitation. In the form of amorphous, irregular precipitate layers, metal ions adhere to the surface of the biochar and form insoluble compounds. Chemical bonding or electrostatic interactions may be used in this process.

4) Physical Adsorption

Another way to get rid of metals is to attach metal ions to the surface of biochar physically. Physical adsorption occurs when metal ions are attracted to the adsorbent's surface by intermolecular forces such as hydrogen bonds or Van Der Waals forces. Metal ions can be quickly released back into the solution to the formed reversible connections. Physical adsorption on biochar surfaces has been shown in numerous investigations to limit the presence and mobility of particular heavy metal ions [2]. Additionally, biochar's porous structure and large surface area enhance its capacity to adsorb metal ions through these interactions, providing a temporary mechanism for immobilizing heavy metals. However, the efficiency of physical adsorption depends on factors such as pH, temperature, and the specific properties of the biochar and the metal ions.

5) Electrostatic Attraction and Reduction

The electric charge on the surface of biochar influences its interactions with metallic ions. A process known as electrostatic attraction takes place between positively charged metal ions, such as Cu^{2+} and $Pb^{2+,}$ and the negatively charged surface of biochar in a solution. Metal ions can be adsorbed onto the biochar to this interaction. Employing biochar to reduce metal ions entails adsorbing the ions on their surface and moving electrons from the biochar to the ions. Following the reduction process, the metals generated may remain integrated into the structure of the biochar or form deposits on the surface.

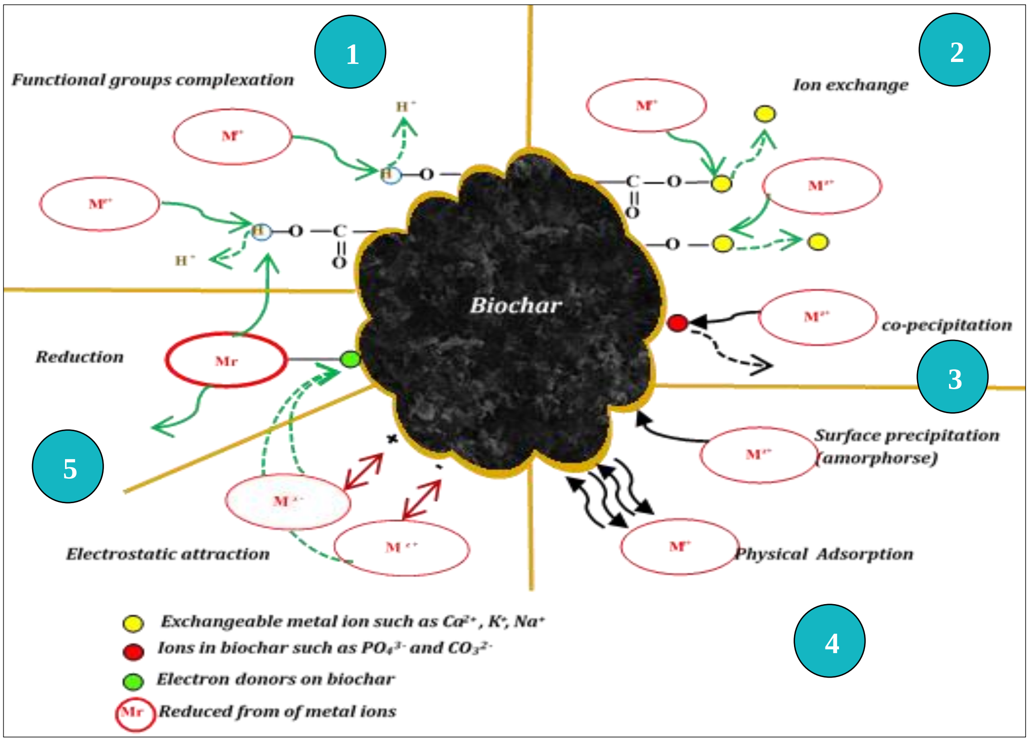

Figure 3. The Mechanism of Heavy Metal Removal using Biochar, modified from [24].

3.2 Production of Biochar

Usually made from natural organic resources, biochar is a porous, carbon-rich charcoal produced by biomass pyrolysis. Heat conversion is the primary process for producing biochar, which modifies the biomass's chemical composition. Biochar can be made from almost any biomass, although its properties might vary greatly depending on the raw material. Conventional pyrolysis, gasification, and hydrothermal carbonization produce biochar [34]. It is crucial to understand which conversion processes are appropriate for particular biomass sources to make the most of these feedstocks. The preparation technique and the source material greatly influence the final properties of biochar. Therefore, selecting the right feedstock is the first stage in the creation of biochar. The techniques used to create biochar can affect characteristics like its function, area of surfaces, and size of pores, which then affect how much it can absorb [12].

Thermal decomposition is the result of a process called pyrolysis, which takes place at high temperatures with little oxygen present. Numerous studies demonstrate the exceptional sorption capabilities of biochar produced by gasification or pyrolysis. However, researchers discovered that hydrothermally carbonized biochar has more surface area and pore volume, increasing its capacity to absorb heavy metals [54]. The varied processing parameters of these techniques lead to variations in the composition, structure, and surface area of biochar, which contribute to various physicochemical properties. To choose the best biochar application and increase its effectiveness, it is crucial to comprehend the properties of biochar produced using different thermal procedures.

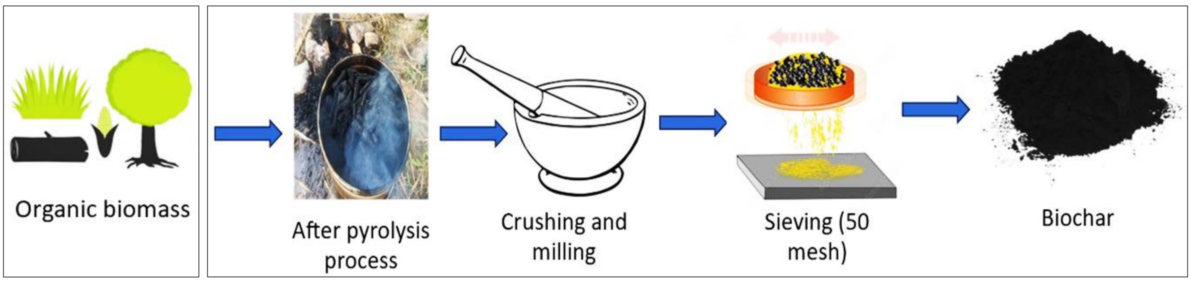

Figure 4. Biochar Production from Organic Biomass, modified from [45].

Table 1. Processing Techniques in the Manufacture of Biomass as Biochar

Biochar Production	Affect the Result and Characteristics	Temperature	Results
Conventional Pyrolysis	Temperature, rate of heating, size of particles, characteristics of solids, and duration of residence.	Pre-pyrolysis: room temperature-200ºC Primary pyrolysis: 200 ºC - 500ºC. Formation of carbon products: >500 ºC.	Low temperatures produce high biochar production, while higher temperatures substantially reduce production. Usually long heating times (hours- days).
Gasification/Fast Pyrolysis	Depending on controlling and optimizing in four steps: drying, pyrolysis, partial oxide, and reduction.	Carbon materials are subjected to high temperatures (>600º C) with shorter operating times.	Produced more bio-oil than biochar (60% bio-oil, 20% biochar). This gives a higher reaction rate due to the higher operating temperature.
Hydrothermal Carbonization (HTC)	Variations in processing conditions like temperature, elevated pressure, and the existence of water.	The organic substance undergoes heating between 180ºC-260ºC and pressures between 2-6 MPa in a closed reactor container for 5-240 minutes.	Despite the generation of organic acids, HTC can process various wet raw materials without the need for pre-drying, resulting in a high-quality product that is reliable, consistent, and easy to handle.

3.3 Research Result

A total of 35 papers about the application of biochar for treating industrial wastewater were examined; this research was taken from various scholarly publications published between 2007 and 2021. These investigations used a range of pyrolysis and modification methods in addition to biochars made from diverse feedstocks. Although the investigation's effectiveness differed, the results showed that heavy metals were effectively removed from wastewater. Table 2 below provides an overview of the biochar used to remove heavy metals, with natural organic resources serving as the primary feedstock.

Table 2. Organic-Based Biochar Used for Heavy Metal Removal

Raw Materials	Temp.	Production Method	Source	Metal Ions	Results/capacity	Reference
Hardwood	450ºC	Pyrolysis	$NaNO_3$ solution with Cu and Zn metal ions	Cu(II) Zn(II)	Cu(II) 6,79 mg/g, Zn(II) 4,54 mg/g	Chen et al., (2011) [4]
Corn straw	600ºC/ 2 hours	Pyrolysis			Cu(II) 12,52 mg/g, Zn(II) 11,0 mg/g	
	400 ºC / 2 hours	Pyrolysis in a muffle furnace	Mixed solution Of $Cd(NO_3)_2$ and $Pb(NO_3)_2$	Cd Pb	Cd 38,9 mg/g and Pb 29,0 mg/g (Efficiencies of 99,24% and 9,62%).	Chi et al., (2017) [5]
Bagasse	500 ºC	Small-scale biochar production plant	Solution of $Pb(NO_3)_2$	Pb(II)	Sugarcane Bagasse (Pb 86,96 mg/g), Orange Peel (Pb 27,86 mg/g)	Abdelhafez and Li, (2016) [1]
Orange Peel	400 ºC - 800 ºC/ 24 hours	Pyrolysis	Solution of $Cd(NO_3)_2$	Cd	Cd adsorption capacity of 114,69 mg/g with (Efficiencies 80 - 90%).	Tran et al., (2016) [43]

Raw Materials	Temp.	Production Method	Source	Metal Ions	Results/capacity	Reference
Almond shells	650 °C	Pyrolysis	Solution $Ni(NO_3)_2$ and $Co(NO_3)_2$	Ni(II) Co(II)	Ni(II) 22,22 mg/g, and Co(II) 28,09 mg/g.	Kilic et al., (2013) [15]
Effluent sludge	550 °C	Pyrolysis	Solution of $Pb(NO_3)_2$	Pb^{2+}	Pb^{2+} capacity of 30,8 mg/g.	Lu et al., (2012) [21]
Peanut and soybean straw	400 °C	Pyrolysis in a muffle furnace	Mixed solution of $Cu(NO_3)_2$	Cu(II)	Cu(II) capacity 37,12-89,6 mg/g, (peanut straw > soybean straw)	Tong et al., (2011) [41]
Paper mill waste	270 °C - 720 °C	Pyrolysis	Mixed solution of As(V) and Cd(II)	As(V) Cd(II)	As(V) 22,8 mg/g, and Cd(II) 41,6 mg/g.	Yoon et al., (2017) [52]
Nutshells, wheat straw, plum seeds, grape stems and skins	600 ° C/ 30 min.	Pyrolysis in a muffle furnace	Solution of $Cd(NO_3)_2$ and $Pb(NO_3)_2$	Cd Pb	Cd and Pb reduction efficiencies varied between 43,8% - 100% for all four biochars.	Trakal et al., (2014) [42]
Compost, rice husk, citrus waste, olive pulp	Hydro-thermal (300°C) Pyrolysis (300°C & 600° C)	Hydrothermal and pyrolysis	Solution $Cu(NO_3)_2$	Cu(II)	Adsorption efficiency of 93,6%, 90,1%, 88,7% and 77,8% by each biochar	Pellera et al., (2012) [30]
Rice straw mixture (Fe_3O_4 and $CaCO_3$)	400°C/ 2 hours	Pyrolysis, coprecipita-tion and calcination	Stock solution of $NaAsO_2$ and $Cd(NO_3)_2$	As(III) Cd(II)	As(III): 6,34 mg/g, and Cd(II): 10,07 mg/g.	Wu et al., (2018) [47]
Oak wood and bark	400 °C and 450 °C	Pyrolyzed and magnetized	Stock solution of Pb and Cd	Pb^{2+} Cd^{2+}	The reduction of Pb^{2+} was almost 100% in some cases, while Cd^{2+} was between 53-99%.	Mohan et al., (2014) [23]
	400 °C and 450 °C	Pyrolysis	Solution of $Cd(NO_3)_2$, $NaAsO_2$, and $Pb(NO_3)_2$	Cd(II) As(III) Pb(II)	Can remove about 70% As, 50% Cd, and almost 100% of Pb.	Mohan et al. (2007) [22]
Used coffee grounds	400 °C	Pyrolysis in an electric furnace	Acid Mine Drainage Sample	Cd, Cu, Pb & Zn	Cd 99%, Cu 88%, Pb > 99%, Zn 99%.	Kim et al., (2014) [16]
Coconut shell	400 °C modif. of $MgCl_2$	Pyrolysis	Solution of $Cd(NO_3)_2$ $Pb(NO_3)_2$	Pb Cd	Pb: 271,53 mg/g, and Cd: 91,95 mg/g.	Wu et al, (2019) [48]
Durian bark and acacia tree	500 °C /30 min modif. of Fe/Zn	Pyrolysis	Solution of $Cd(NO_3)_2$	Cd(II)	Cd removal reached 99,81% and 71,08%, respectively.	Yang et al., (2021) [51]
Aloevera peel	700 °C/ 2 hours	Carbonized in a furnace	Solution of $AgNO_3$	Ag	Ag removal efficiency 98,3% (243,90 mg/g).	Beigzadeh et al, (2016) [3]
Phragmites australis	450 °C	Pyrolysis of biomaterials	Acid Mine Drainage Sample	Fe, Al, Ni, Zn, and Mn	Dissolved metal ion concentration reduced from (89,0% - 98,0%) (Fe≈Al > Ni≈Zn > Mn)	Mosley et al., (2015) [24]

Raw Materials	Temp.	Production Method	Source	Metal Ions	Results/capacity	Reference
Sesame straw	700 ºC / 4 hours	Pyrolysis	Stock Solution of $Pb(NO_3)_2$ $Cd(NO_3)_2$ $Cr(NO_3)_3$ $Cu(NO_3)$ $Zn(NO_3)_3$	Pb, Cd, Cr, Cu, and Zn	Pb 102 mg/g > Cd 86 mg /g > Cr 65 mg /g > Cu 55.0 mg /g > Zn 34.0 mg /g.	Park et al., (2016) [29]
Rice husk and Corn Cob	700 ºC / 1 hour	Pyrolysis	Solution of $Pb(NO_3)_2$	Pb	Doses of 16 g rice husk and 8 g corn cob with Pb removal up to 95,43% and 99,28%, respectively.	Subarkhah and Titah, (2023) [38]
Rice Husk	500 ºC/ 30 min.	Pyrolysis	Mixed solution of $K_2Cr_2O_7$	Cr	Cr efficiency reaches of 59%.	Faris et al., (2024) [9]
Siwalan fiber	100 ºC/ 1 hours	Heated using a furnace	Waste liquid solution of $CuSO_4$	Cu	Reduced Cu levels to 20,512 ppm with an adsorption capacity of 60,488 mg/g.	Syafitra et al., (2020) [39]
Dregs of the Cascara	500 ºC/ 1 hours	Pyrolysis/ carbonization	Stock solution of Pb ion	Pb	Absorption efficiency at optimum conditions 98,11%.	Octaviani, R A., (2024) [29]
Palm Shell	400 ºC- 500 ºC	Pyrolysis	Solution of $Pb(NO_3)_2$	Pb	The modified biochar H_2SO_4- have an adsorption capacity of 0.96 mg/g for Pb.	Nurkhalifa, (2024) [25]
Palm Fronds	100 ºC/ 3 hours	Heated using a furnace	Peat Water	Mn	Mn reduction with bentonite biochar combination is 82,23%	Prasetyo, D., (2021) [31]
Hickory Wood	600 ºC/ 2 hours	Pyrolysis	Mixed Metal Solution	Pb, Cu, Cd, Zn, Ni	Recovery efficiency of Pb^{2+} (94%), Cu^{2+} (85,1%), Ni^{2+} (46,3%), Zn^{2+} (0,2%), and Cd^{2+} (34,7%).	Ding et al., (2016) [8]
Phoenix Tree Leaf	500 ºC/ 2 hours	Pyrolysis	Mixed solution of $K_2Cr_2O_7$	Cr	Adsorption capacity of Cr(VI) is 18,2 mg/g	Shi et al., (2018) [35]
Switchgrass	300 ºC/ 30 min.	Pyrolysis	Mixed solution of Cd and Cu ions	Cd Cu	Removal capacity of Cd 1,5 mg/g , and Cu 4,0 mg/g.	Regmi et al., (2012) [33]
Banana peel	105 ºC/ 1 day	Pyrolysis in a tuular furnace	Solution of $KMnO_4$ and $Fe(NH_4)_2$	Fe Mn	Adsorption capacity of Fe 27,36 mg/g and Mn 0,8 mg/g	Kim et al., (2020) [18]
Poplar wood powder	a.300 ºC b.500 ºC c.700 ºC	Pyrolysis	Stok solution of $Pb(NO_3)_2$	Pb(II)	Respective decrease of Pb according to temperature a. 41,53% b. 80,32% c. 59,74%	Xu et al., (2021) [50]
Plum seeds	500 ºC/ 1 hours	Pyrolysis	Mixed solution of Pb and Cr	Pb(II) Cr(III)	Adsorption capacity of Pb(II) 28,79 mg/g and Cr(III) 14,02 mg/g	Pap et al., (2018) [27]
Apricot Seeds					Pb(II) 23,89 mg/g and Cr(III) 12,68 mg/g	

Raw Materials	Temp.	Production Method	Source	Metal Ions	Results/capacity	Reference
Coffee Skin	600 ºC	Pyrolysis	Mixed Solution of Pb and As	As(V) Pb(II)	Adsorption capacity As(V) 3,46 mg/g Pb(II) 3,60 mg/g	Cruz et al. (2020) [7]
Corn Cob					As(V) 1,99 mg/g Pb(V) 10,75 mg/g	
Spruce bark chips	900 ºC	Pyrolysis	Mixed Metal Solution	Cr(VI) Pb(II) Cd(II)	Adsorption capacity Cr(VI) 33,5 mg/g Pb(II) 84,1 mg/g Cd(II) 18,0 mg/g	Herath et al., (2021) [10]
Branch. twig	500 ºC	Pyrolysis	Stock solution of Cd ion	Cd(II)	Adsorption capacity Cd(II) 4,26 mg/g	Tan et al., (2022) [40]

3.4 Parameter Effect of Adsorption Capacity of Biochar

1) pH of Contaminated Water

The effectiveness of biochar in removing heavy metals largely depends on the contaminated water's acidity. According to some research, solutions with a pH between 5 and 6 are ideal for removing as much Cu, Pb, and Cd as possible. Nonetheless, there are situations in which a pH higher than 8 maximizes the adsorption efficiency of Cd. The electrostatic interactions between metal ions and the surface of biochar explain this [28]. Extra protonation of charcoal causes competition for binding sites between H_3O^+ and Cd^{2+} at lower pH values. Higher pH values, on the other hand, increase the sorption potential by making sorption sites available.

2) Biochar Dosage

Most research indicates that a more significant proportion of biochar in water results in a greater reduction of heavy metals. However, biochar's ability to remove heavy metals tends to wane over time. This suggests that while more biochar can remove more heavy metals, its effectiveness declines with increasing amounts. According to the research, selecting the correct quantity of biochar is crucial for efficient metal removal, particularly in practical situations. Proper biochar can save costs and produce the best outcomes [30].

3) The initial concentration of heavy metals

Higher metal concentrations lead to a higher probability of metal ions interacting with the surface of the biochar. This implies that additional metal ions may be absorbed, increasing the amount of metal absorbed by biochar. Interactions between metal ions and biochar facilitate the release of H^+ ions from the surface of the biochar, giving metal ions the chance to occupy binding sites. On the other hand, a high metal content may cover the surface of the biochar.

4) Biochar characteristics and metal speciation

The surface area and pore size of biochar can impact the efficiency of heavy metal adsorption. Because some kinds of metal are more easily absorbed, different chemical variations of metals, known as metal speciation, can affect biochar's ability to absorb heavy metals. Other competing ions may impact the efficiency of biochar's sorption in the solution. The adsorption of heavy metals depends on the functional groups on the surface of biochar [48].

3.5 Directions for Further Research

1) Biochar Composite

More studies are required to create biochar combinations that are specially tailored to remove particular heavy metals. Studies could employ novel techniques, particularly raw materials, and innovative biochar composites, to increase the ability to remove heavy metals from contaminated water. To achieve optimum removal effectiveness, the adsorption process can be enhanced by changing the characteristics of the adsorbent or solution.

2) Acid Mine Drainage (AMD)

To increase the efficacy and improve the use of biochar in treating AMD, more research is required for a number of studies. By combining modified biochar with microbial treatment and phytoremediation techniques, heavy metals can be removed more effectively while lowering environmental risks. Consequently, it is advised to gain a more thorough grasp of the possible advantages of biochar in addressing AMD. One concrete experimental design could involve a pilot study at an active mining site where biochar, derived from agricultural waste or forestry residues, is applied in combination with selected plant species known for their phytoremediation potential, such as *Eichhornia crassipes*. Experimental design could explore the impact of biochar modification to enhance metal removal. Parameters such as biochar dosage, plant growth rate, metal concentration, pH would be systematically screened to generate optimal conditions for enhancing metal removal efficiency. This integrated approach would offer valuable insights for advancing biochar-based technologies for AMD remediation.

Figure 5. AMD from coal mining Area (**A**) and Experimental Design (**B**), modified from [45].

3) Utilization of Used Biochar

Research and development initiatives are essential to finding safe and effective ways to use biochar that has absorbed heavy metals. While further research and improvement indicate possibilities for creating sustainable methods of treating trash polluted with heavy metals, stabilizing and releasing absorbed heavy metals are two viable strategies to accomplish this goal. A multidisciplinary approach that combines materials science and environmental engineering is recommended to improve this strategy. By combining material innovations, such as the development of biochar modifications that increase its capacity to retain heavy metals, with environmental engineering techniques, such as bioremediation systems, we can create more environmentally friendly solutions for managing waste containing biochar. This integrated approach will enable the development of safer and more sustainable methods for recycling or disposing of biochar without compromising environmental quality.

4) Sustainable Energy Solutions

In line with the need for sustainable energy solutions, biochar is being converted into materials for supercapacitor electrodes and catalysts. This field of study highlights the importance of carbon nanostructures in creating cutting-edge materials for energy storage. To learn more about how the kind of biomass waste utilized as a precursor affects the characteristics of the final carbon materials used in supercapacitor electrodes, more research is needed.

4. Conclusion and Recommendations

According to the study, biochar can physically adsorb metals on its surface, which can help remove them from solutions. Hydrothermal Carbonization (HTC), gasification, and pyrolysis are some processes used to create biochar. Surface complexation, ion scavenging, co-precipitation, surface precipitation, physical adsorption, electrostatic attraction, and reduction are the primary methods by which biochar extracts heavy metals from contaminated fluids. By lowering the concentration of metal ions in the solution, these processes make biochar an optimal tool for removing and neutralizing metal pollutants in aquatic environments.

Various forms of biochar made from organic sources are used to remove heavy metals from contaminated solutions. Hardwood, corn straw, bagasse, orange peel, almond shells, sewage sludge, peanut straw, soybean straw, paper mill waste, peanut shells, wheat straw, plum seeds, grape skins, compost, rice husks, citrus waste, olive pulp, rice straw, wood, ironwood bark, used coffee grounds, coconut shells, durian bark, acacia tree bark, aloe vera bark, and *Phragmites australis* are just a few of the materials that can be used to make these biochars. They have demonstrated remarkable efficacy in removing heavy metals from water through adsorption and precipitation. Essential variables that affect the properties of biochar and its ability to extract metals are the pyrolysis temperature and the selection of feedstock materials.

Several variables, including water pH, biochar quantity, beginning metal concentration, biochar properties, and metal shape, might affect how well biochar removes heavy metal ions. The surface area and pore size of biochar are two characteristics that can affect how well it absorbs metal ions. These links may improve biochar's ability to absorb heavy metals and lessen pollution under specific circumstances. According to research in the literature, using various forms of biochar can remove metals with remarkable efficacy. The results also show that this field's most frequently studied and investigated metal ions are Cu, Zn, Cd, Pb, Ni, Cr, Co, As, Ag, Fe, Al, and Mn. This study highlights explicitly the effectiveness of biochars made from orange peel, nutshell, compost, rice husk, oak wood, used coffee grounds, durian bark, Phragmites australis corn cob, dregs of cascara, and hickory wood. The findings show that biochars from these materials, especially those produced at high pyrolysis temperatures (≥500°C), can achieve metal removal efficiencies above (≥90%).

Combining biochar has much potential as a cutting-edge strategy for successful heavy metal removal. These composites may offer an optimal and sustainable way to address heavy metal contamination in various contexts by combining the unique qualities of biochar with certain additions and methods. Advanced research and development have made using biochar to remove heavy metals from water easier, leading to more advanced methods to address this significant environmental problem. However, other biochar applications, such as developing new biochar composites and testing various treatment techniques for heavy metal reduction, require further research.

To establish efficient biochar techniques for heavy metal removal, this research provides essential data for academics, policymakers, and industry stakeholders. By expanding on this, policymakers and industry leaders should also consider the broader sustainability aspects of biochar beyond just heavy metal recovery. Biochar can potentially improve soil quality and promote carbon sequestration, making it a valuable tool in combating climate change and advancing sustainable land management practices. Therefore, integrating biochar into long-term environmental strategies can solve pollution control and sustainability challenges.

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