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Research Paper

Exploring Biochar Production, Modification and its Role as an Adsorbent in Heavy Metal Removal from Wastewater: A Review

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Abstract

As industrialization and population expansion have increased, heavy metal poisoning of water has become common, posing substantial dangers to both human health and ecosystems. Untreated wastewater containing toxic compounds discharged by industries such as mining, electroplating, and metal polishing can harm aquatic ecosystem and remain in the environment and accumulate in the food chain, posing longterm ecological and health risks. Biochar, a carbon rich material which is made by pyrolyzing organic waste, has gained popularity as an economical and sustainable alternative for restoration of the environment, notably in wastewater treatment processes. This study employed a comprehensive literature review, sourcing peerreviewed articles from the last decade via databases such as Scopus, ScienceDirect, and Web of Science, focusing on biochar production, modification, and adsorption efficiency. Inclusion criteria were studies with quantified heavy metal removal performance and clear pyrolysis parameters. As a result, it was understood that biochar's adsorption capacity depends on feedstock type, pyrolysis temperature, and surface modifications. Acid, alkaline, and metal impregnation treatments improve surface area, functional groups, and cation exchange capacity. Optimal pyrolysis temperatures (300–600℃) balance yield and surface reactivity, with agricultural residues offering lowcost, abundant feedstocks. Modified biochar demonstrates superior removal of metals such as Pb^{2+}, Cd^{2+}, Cr^{+}, and Cu^{2+}, achieving $>90\%$ removal in some cases. Biochar offers an environmentally friendly, cost effective solution for wastewater treatment, but challenges remain in scaling production, ensuring stability of modifications, and preventing metal leaching. Further research should focus on field scale trials, economic analysis, and safe disposal or regeneration of spent biochar.

Keywords
biochar, biochar as adsorbent, biochar production, heavy metal removal

1. INTRODUCTION

The world's population growth has led to increased industrial and economic growth, resulting in severe heavy metal pollution in surface and groundwater, as well as soils (Gargiulo et al., 2024). This release of heavy metals into the ecosystem has caused several environmental issues as they can accumulate in the environment due to their imperishable qualities and become difficult to decompose in these environments, posing a health risk to humans and animals when consumed directly or indirectly (Li et al., 2021) (Gotore et al., 2024). When they are discharged, the metal ions in water pose a threat to both humans and aquatic life, as they accumulate in food chains (Wang et al., 2012) (Godwin et al., 2019).

Heavy metal remediation techniques for wastewater include conventional removal techniques such as chemical precipitation (Yago et al., 2024), reverse osmosis (Thirugnanasambandham et al., 2016), coagulation flocculation (El Mouhri et al., 2024), ion exchange ((Jasim and Ajjam, 2024), electrochemical method (Kim et al., 2024) and electrodialysis method (Meng et al., 2024), biological techniques such as biosorption (Sabando-Fraile et al., 2024) and phytoremediation (Waseem et al., 2024), membrane filtration techniques including reverse osmosis (Thirugnanasambandham et al., 2016), nanofiltration (Samavati et al., 2023) and ultrafiltration (Aloulou et al., 2022), advanced oxidation processes such as photocatalysis (Bodzek et al., 2021) and photo Fenton process (López-Vinent et al., 2023) and adsorption techniques such as the activated carbon technique and biochar adsorption. Despite their popularity, these strategies are not without restrictions. High operational costs caused by the need for machinery, excessive use of energy, and added chemicals put a significant financial pressure on industrial operations.

Additionally, these techniques usually create substantial amounts of sludge, which demands extra treatment and disposal, increasing operational complexity and expenditures. Recent studies have demonstrated that the adsorption technique employing biochar as an adsorbent is the most cost effective and highly efficient way for removing heavy metals from aqueous environments (Birniwa et al., 2024) (Chai et al., 2021) (Murtaza et al., 2024) (**?**).

Natural adsorbents provide attractive alternatives for wastewater treatment due to their unique characteristics and benefits (Li et al., 2024). Renewable materials, such as agricultural waste or natural minerals, are readily available and affordable in cost (Mkilima et al., 2024). Their biodegradability helps the environment by reducing nonbiodegradable waste from typical treatment methods (Karić et al., 2022). Natural adsorbents are extremely effective at selectively removing pollutants, especially heavy metals, from wastewater. The degree of selectivity enables the targeted removal of certain pollutants, hence increasing effectiveness of treatment and reducing resource utilization. It also offers ecofriendly and affordable decrease in pollution (Gholamifard et al., 2023). Biochar's various physical and chemical properties make it an attractive adsorbent for heavy metal elimination (Kasera et al., 2022). Multiple research investigations have been conducted to extract heavy metals from wastewater using different adsorbents (Jiang et al., 2023).(Murtaza et al., 2024) explored the use of modified and pristine biochar derived from woody and nonwoody feedstocks to remove chromium hexavalent from wastewater. They concluded that nonwoody biochar is better suited for this purpose (Murtaza et al., 2024). (Gargiulo et al., 2024) studied that mesoporous iron oxide/rice husk composites had considerably better metal adsorption capabilities than virgin carbonized rice husk and iron components alone. The carbonized rice husk and iron oxide phases work together to improve heavy metal adsorption from aqueous solutions, iincluding Pb^{2+} and Cu^{2+}. Biochar formed from waste materials is gaining popularity for removing emerging pollutants from wastewater. This review examines the production and effectiveness of biochar as an adsorbent material for removing heavy metals from wastewater.

2. METHOD

This study was conducted as a literature review to evaluate the use of biochar for heavy metal removal from wastewater. Peer-reviewed articles published between 2012 and 2024 were retrieved from Scopus, Web of Science, and ScienceDirect using the *biochar, adsorption, heavy metal removal, wastewater* in the title, abstract, and keywords fields, with Boolean operators *(AND/OR)* applied to refine the search. Studies were included if they reported quantitative removal efficiency for at least one heavy metal, clearly specified biochar feedstock, pyrolysis temperature, and modification method, and were relevant to wastewater treatment applications. Articles without experimental data, unclear methodologies, or not focused on wastewater applications were excluded. The initial search yielded multiple studies, which were screened for duplicates and relevance, resulting in a total of 91 articles retained for detailed analysis. Data were synthesized thematically, focusing on feedstock type, pyrolysis parameters, modification techniques, and adsorption performance, providing a comprehensive overview of current research trends and knowledge gaps in biochar-based heavy metal removal.

3. RESULTS

3.1 Biochar Production

The study field focusing on the manufacture and use of biochar derived from agricultural waste has long existed, but with the increased interest in transforming waste into valuable goods, new insights are emerging (Cantrell et al., 2012). In separate studies, Kumar et al., (Khedulkar et al., 2023) (Mkilima et al., 2024).. demonstrated the cost effectiveness and sustainability of creating biochar from various agricultural wastes for a variety of applications. Similar studies by (Danesh et al., 2023) and (Phadtare and Kalbande, 2022) verified the efficacy of the thermo chemical processes in turning agricultural waste into biochar. These studies demonstrate that agricultural waste is a viable, cost effective, easily available, and sustainable feedstock for large scale biochar production (Machhan and Könke, 2021) (Al-Kahtany et al., 2023). Biochar can persist in soil for 1,000 to 10,000 years, with an average lifespan of 5,000 years, without undergoing microbial breakdown. The framework of biochar is largely made up of carbon and minerals, with varying pore sizes. Micropores are responsible for biochar's large surface area and high adsorption capacity; mesopores aid in liquid-solid adsorption processes; and macrospores are necessary for soil aeration, water movement, root growth, and soil structure preservation (Pandit et al., 2023)). The size and distribution of pores in biochar are determined by the feedstock content and the pyrolysis temperature used during production. Scanning electron microscopy can be used to examine the shape and pore size distribution of biochar derived from various feedstocks. The porous structure of biochar, which is high in aromatic compounds and functional groups formed from lignin based biomass, promotes the flow of nutrient rich soil solutions while also providing a habitat for soil bacteria (Lee et al., 2018).

3.1.1 Feedstock Selection

Biochar is a solid, carbon rich substance formed by thermally transforming biogenic waste in a low oxygen environment. This process employs a variety of carbon rich feedstocks, including agricultural leftovers, food waste, cow dung, and other biowaste, which are dried and heated under standard pressure in oxygen restricted circumstances. Pyrolysis releases volatile gases such as H2, CH4, and CO2, resulting in a dense carbon substance. The type of feedstock utilized has a significant impact on the characteristics and quality of the biochar produced. Crop residues, for example, have less ash, a higher calorific value, and fewer holes than woody biomass or organic waste such as manure and sewage sludge (Tomczyk et al., 2020). (Ji et al., 2022) demonstrated that agricultural residue has been found as a valuable feedstock for biochar production via pyrolysis, providing a sustainable supply for biochar synthesis. The features of these feedstocks have a direct impact on the efficiency and results of the pyrolysis process, eventually determining the quality of the biochar produced. The suitability of crop residues for biochar synthesis is assessed using three important factors: proximate analysis, ultimate analysis, and lignocellulosic composition. Wood, energy crops, and agricultural byproducts are all examples of lignocellulosic biomass that contribute significantly to biochar production. This form of biomass is distinguished by its high moisture content, poor calorific value, and low natural grindability. It is mostly composed of cellulose, hemicellulose, and lignin, with trace amounts of organic extractives and ash. These components vary greatly depending on their biological origin, location, and season of cultivation. According to (Díez et al., 2020) and Jung et al.,(2015) woody biomass consists of 40%-44% cellulose, 20%-30% hemicelluloses, and 10%-30% lignin. Proximate analysis focusses on the fixed carbon, volatile matter, ash, and moisture content of the biomass. Average ranges for these components in agricultural residual feedstocks are 3-26% for fixed carbon, 65-90% for volatile matter, 1-15% for ash, and 0-10% for moisture content. The kind of feedstock influences the fixed carbon and ash content of the resultant biochar, whereas volatile mat-ter content and biochar production are more susceptible to pyrolysis temperature (Usman et al., 2015).

3.1.2 Conventional Pyrolysis techniques

The yield of biochar varies based on carbonization temperature, residence duration, and heating rate. As temperature increases, the yield drops. Biochar is primarily created by three thermochemical conversion methods such as slow pyrolysis, rapid or fast pyrolysis, and gasification (Patra et al., 2021) (Gao and Wu, 2011) (Wang et al., 2020). The type of pyrolysis depends on the operating parameters. The temperature during py-rolysis is the most important element in determining biochar output. Low temperatures result in high biochar yields, while higher temperatures significantly reduce yields (Luo et al., 2015). Apart from yield, pyrolysis temperature can also impact biochar qualities such as carbon structure, functional groups, and physical/chemical characteristics. Longer residence time (600–6000 s), moderate reaction temperatures (300–700 °C), and modest heating rates (0.1–1 °C/s) are a requirement for slow pyrolysis (Okolie et al., 2022). Whereas on the other hand, high heating rates and reaction temperatures of around 500–1000 °C are required for fast and flash pyrolysis. Slow pyrolysis (15-40%) yielded more than fast pyrolysis (10-25%) (Sadegh et al., 2024). Gasification, like pyrolysis, can produce biochar by heating biomass at high tem-peratures in a controlled environment with restricted oxygen. However, syngas production prioritizes energy targets over biochar generation. Pyrolysis has an impact on adsorbent biochar by increasing its polarity, aro-maticity, pH, elemental composition, and ash concentration. Lower temperatures increase biochar output and promote the synthesis of oxygen-containing functional groups (Ye et al., 2022). Biochar's characteristics vary based on biomass and pyrolysis temperatures, as illustrated in Fig. 1 (Cantrell et al., 2012). Variations in py-rolysis temperature have a substantial impact on biochar's physicochemical properties, particularly pH and specific surface area (Sizmur et al., 2017). According to (Kumar et al., 2009) while temperature constitutes approximately 18% and 17% of the variance in pH and specific surface area, respectively, the model's great usability is evidenced from a Prob>F value of less than 0.001, showing a robust match to these associations. At pyrolysis temperatures below 400°C, increasing the temperature resulted in a significant improvement in the pH of the biochar. As the temperature went from 400°C to 600°C, the pH gradually improved. Meanwhile, specific surface area increased slowly with growing pyrolysis temperatures, notably below 800°C. This pattern is consistent with prior findings that indicate comparable patterns in pH and specific surface area differences in biochar made from the same raw material at different temperatures. However, it should be emphasized that at very high pyrolysis temperatures, above 800°C, the influence on specific surface area is minor, as confirmed by previous research (Laghari et al., 2016) (Bridgwater, 2012). Fig. 2 demonstrates how biochar production temperature affects the adsorption process, surface functional groups, and pollutants.

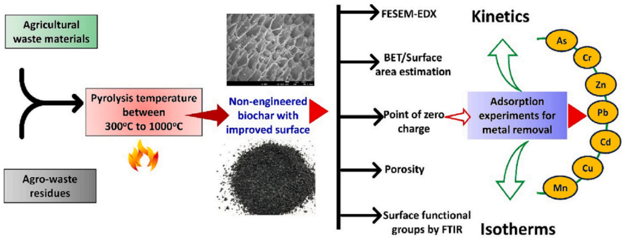

Figure 1. Fig 1: The image depicts the synthesis of biochar using pyrolysis process, its characterization, and the subsequent adsorption isotherm study to evaluate biochar's adsorption capabilities (Cantrell et al., 2012)

Slow pyrolysis has a relatively low heating rate of 0.1 to 1 °C/s, a lengthy dwelling period of 300 to 7200 seconds, and a pyrolysis temperature of 300 to 700 °C (Li et al., 2020). This low heating rate reduces sec-ondary pyrolysis and thermal cracking in biomass, promoting biochar as the principal product (Tan et al., 2021). Biswas et al. adopted slow pyrolysis to turn four different types of crop waste into bio-based products. These tests employed a pyrolysis temperature range of 300 to 450 °C, a uniform residence period of 3600 seconds, and an average heating rate of 0.33 °C/s. When pyrolyzed at 300 °C, rice husk produced the greatest percentage of biochar (43.3%) of the four feedstocks tested. However, as the pyrolysis temperature was gradually increased from 300 to 450 °C, the biochar being generated reduced abruptly from 43.3% to 35.0% (Biswas et al., 2017).

Similarly, Zhang et al. carried out slow pyrolysis on residues from agriculture such as wheat, corn, and rice straws, adjusting the pyrolysis temperature between 300 and 600 °C while keeping the heating rate and residence time constant at 0.17 °C/s and 3600 seconds, respectively. Across several feedstocks, the pattern was consistent: biochar yield declined as pyrolysis temperature rose (Zhang et al., 2020). The intermediate pyrolysis system uses a coaxial dual screw reactor with an interior and exterior screw that runs at temperatures ranging from 450°C to 550°C. This technique provides for a much longer solids residence period of 2 to 10 minutes when as opposed to standard fast pyrolysis. Product outputs vary according to feedstock and processing conditions, but generally yield 10–30% liquid (pyrolysis oil and water), 15–20% gas and 50–75% char (Yang et al., 2017). (Liu et al., 2012) discovered that intermediate pyrolysis reactors can treat low value feedstocks and high ash wastes such as sewage sludge, which are not suited for fast pyrolysis.

These reactors use screw conveyors that can effectively handle a wide range of bulk materials, from sluggish to free flowing (Liu et al., 2012). Fast pyrolysis is a technology for increasing the production of excellent liquid oil, which acts as a dense intermediate energy fuel that can be upgraded to the hydrocarbons found in petrol and diesel. Organic matter is thermally processed in the absence of oxygen at temperatures ranging from 600 to 650 °C, with heating rates reaching 1000 °C/sec. This high temperature allows the organic molecules to decompose easily, resulting in primarily vapors and aerosols, with modest amounts of petrol and charcoal. This approach has generated significant interest because to its ability to produce large amounts of high quality fuel oil, which may be used as an energy source in manufacturing operations such as motors, turbines, and boilers (Goyal et al., 2008).

Flash carbonization is a form of pyrolysis that involves an extremely high heating rate that must be at least 1000 $^{\circ}C\ s^{-1}$, temperatures ranging from 700 to 1000 °C, and a residence duration of just under 30 minutes. The key benefit of this technique is its quick processing time, even though biochar output typically ranges between 20 and 30%. To optimize fluidization and ensure successful thermochemical conversion, the biomass feedstock is prepared in a dry state. Throughout the process, the raw material is fed into a packed bed reactor, and a constant pressure of 1 to 2 bar is delivered by air. A flame heats the reactor's bottom, causing air to flow downstream and the flame to climb, so heating the entire loaded bed (Meyer et al., 2011)

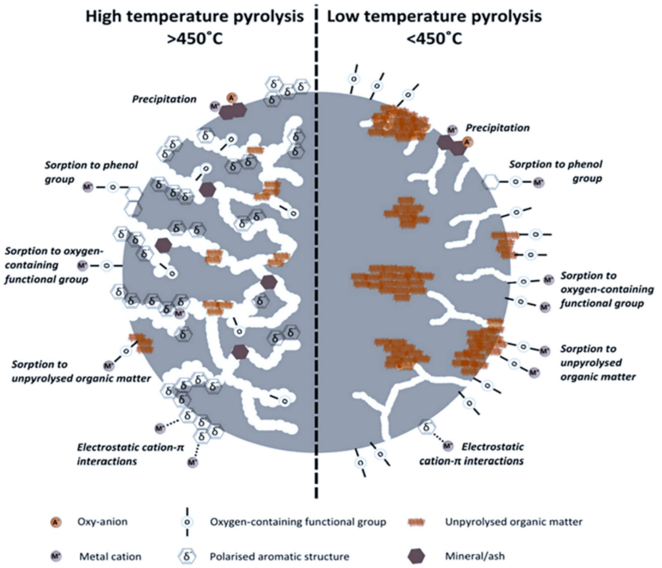

Figure 2. Fig. 2: An illustration of how different biochar production temperatures affect the adsorption process, surface functional groups, and type of pollutants (Sizmur et al., 2017)

3.1.3 Biochar modification

Using unmodified or pristine biochar can involve numerous issues or cannot provide the expected results. Contrary to modified biochar, pure biochar has a smaller surface area and fewer functional groups, making it less effective at absorbing water contaminants. Unmodified biochar has a low specific surface area and a small pore size, resulting in a lower adsorption capacity (Dey and Ahmaruzzaman, 2023). The stability of the material can also be impaired under certain situations, such as high temperatures, pressure, and variable pH levels, which limits its possible applications (Jin et al., 2014). Although pure biochar has little efficiency, several activation procedures can improve its surface functional groups, enhancing its reactivity to pollutants. However, it tends to be less successful in removing certain contaminants (Qu et al., 2023).

To increase the pollutant adsorption capacity of biochar, several changes to its original structure and surface characteristics are required. These modifications, known as engineering or designer BC, are produced via a variety of standard modification techniques. Chemical treatments, including HCl, HNO3, H2SO4, and H3PO4, as well as alkaline treatments with NaOH and KOH, are commonly used (Liu et al., 2012). Another way for improving biochar characteristics is amination, which involves the application of chemicals such as ammonium hydroxide and triethylenetetramine (Li et al., 2020). Surfactant modifications use cationic surfactants like cetyltrimethyl ammonium bromide or anionic surfactants like sodium dodecyl sulphate. Nano MnO2 impregnation and magnetic alterations using ferrous sulphate or ferric chloride have been demonstrated to improve the functionality of biochar (El-Nemr et al., 2021). Physical activation procedures, including as steam or gas activation and ball milling, are also used to improve biochar's physicochemical qualities. These numerous adjustments produce a more effective and specialized biochar suitable for certain environmental purposes (Mahdi et al., 2019).

Biochar's unique features, such as high surface area, porosity, cation exchange capacity, and an abundance of functional groups, make it a flexible material for environmental restoration (Kasera et al., 2022). Biochar is commonly made from a variety of organic materials such as agricultural waste, municipal solid waste, and sludge, and its performance is significantly impacted by the feedstock composition and pyrolysis conditions used (Ahmad et al., 2012). However, the unaltered or pristine form of biochar may have reduced adsorption capacity for certain contaminants. Chemical changes are frequently used to improve biochar's adsorption capacity and effectiveness in removing heavy metals from water and soil. This method modifies the material's characteristics to increase its overall efficacy in environmental usage, especially wastewater treatment (Mohan et al., 2014)(Gao et al., 2019).

Biochar, in both its pristine and modified forms, has specific properties that influence its usefulness in environmental applications. Pristine biochar, which is made by pyrolyzing organic feedstocks under controlled conditions, has a large surface area, porosity, and a variety of functional groups, including hydroxyl (-OH), carboxyl (-COOH), and carbonyl (Qiu et al., 2022). These qualities are inextricably linked to the type of feedstock and the exact pyrolysis conditions, such as temperature and oxygen supply (da Silva and Dos Santos, 2023). However, the ability to absorb pollutants of pure biochar might be limited by parameters such as ash concentration and generally constant pore structure. To address these constraints, biochar is frequently chemically or physically changed to improve its physicochemical qualities, such as increased surface area, pore volume, and functional group intensity. For example, modifications that include the introduction of nano-silica or the removal of ash can improve the surface characteristics and functional group distribution, enhancing its adsorption efficiency and compatibility in various applications, such as heavy metal removal from wastewater or incorporation into cement composites. Moreover, modifications can alter the alkalinity and stability of biochar, further optimizing its performance for specific environmental and industrial uses. Consequently, while pristine biochar offers several beneficial properties, its modification is often essential to maximize its effectiveness and suitability for targeted remediation and other applications (Liu et al., 2012). Based on previous studies various modification methods for biochar such as alkaline treatment, carbon materials, steam, and gas, can significantly enhance its surface area and functional properties. Alkaline, steam, and gas modifications primarily increase the surface area by altering the biochar structure, while carbon material modifications achieve this through synergistic effects between biochar and carbon materials. However, carbon based modifications, like those using graphene, are limited by high costs, and steam and gas modifications are also relatively expensive, whereas alkaline modification offers a more cost effective approach (Gupta et al., 2017). The elemental composition, particularly the ratios of carbon, nitrogen, and ox-ygen, plays a critical role in determining biochar's properties; the nitrogen to carbon ratio affects the basic nature of biochar, while the oxygen to carbon ratio influences its hydrophilicity. Alkaline modification has been shown to increase surface aromaticity and the nitrogen to carbon ratio, while reducing the oxygen to carbon ratio compared to acid modification (Ahmed et al., 2016), thereby enhancing the basicity and reducing the hydrophilicity of biochar (Ding et al., 2014) (Zhou et al., 2013). Additionally, the nitrogen content in biochar provides active sites for catalytic reactions, and alkaline and oxidizing agents can introduce oxygen containing functional groups, such as hydroxyl and carboxylic groups (Kleitou et al., 2021).

Numerous studies have demonstrated the enhanced performance of modified biochar over pristine biochar in the adsorption of heavy metals. While these modifications enhance biochar's properties, they also introduce complexities, particularly concerning the treatment of acid or alkaline solutions used in the process. Sequential modifications using both acid and alkaline treatments could offer a solution by allowing for neutralization, simplifying waste management. Although oxidizing agent modifications effectively increase oxy-gen-containing groups on the biochar surface, their application is limited by high costs and the challenges of managing oxidizing agents (Zhou et al., 2013). Recycling these agents could reduce costs. Modifications with metals or metal oxides can create more active sites for adsorption and catalysis, but there is a risk of metal ion leaching, which requires further research to improve the stability of these modifications. Steam and gas purging methods, while eliminating the need for post treatment of solutions, increase preparation costs and require optimized conditions between pyrolysis and purging processes (Ahmed et al., 2016).

4. DISCUSSION

The efficiency of biochar in adsorbing heavy metals is essentially determined by its specific surface area, the presence of surface active functional groups, and cation exchange capacity (Gupta et al., 2020). Given the multiple elements that influence the adsorption process, as well as the intricacy of the underlying systems, even the same heavy metal can have a different adsorption mode. Thus, studying the mechanisms by which biochar adsorbs heavy metals is critical to creating a theoretical understanding of the process. Current research reveals various essential adsorption mechanisms, including as physical adsorption, ion exchange, electrostatic attraction, precipitation, complexation, and reduction. In the last few years, experts have concentrated on the calcination of biomass to make biochar and composites.

Calcination is the process that involves heating substances that are inorganic to improve their crystallinity while also removing any im-purities and volatile components from the surface (Ahuja et al., 2022). Adsorption of heavy metals by bio-char is often driven by many mechanisms rather than one. For example, (Lu et al., 2012). discovered that sludge-derived biochar adsorbs Pb^{2+} by numerous processes, including ion exchange, surface complexation of functional groups, and surface precipitation. The study found that 38.2–42.3% of Pb^{2+} was removed by complexation with organic functional groups such as -OH and -COOH on the biochar surface, while the re-maining percentage of 57.7-61.8% was adsorbed via precipitation with minerals stored inside the biochar. (Sanka et al., 2020) examined biochar produced using two distinct feedstocks, rice husks and maize husks, at a pyrolysis temperature of 600°C. Adsorption studies were carried out on industrial wastewater with a pH of 7.37 and metal concentrations ranging from 1.59 to 9.28 mg/L, with a biochar dose of 10 g/L. Rice husk based biochar outperformed the other two forms of biochar in terms of heavy metal removal, eliminating 65% of chromium (Cr), 90% of iron (Fe), and more than 90% of lead. In contrast, maize husk based biochar eliminated 20% of Cr and more than 35% of Pb. Rice husk biochar has a greater surface area (635.79 m^2/g) compared to maize husk biochar (575.81 m^2/g), resulting in improved heavy metal adsorption capacity.

Metals are removed through physical adsorption when metal ions diffuse into the pores of the sorbent without forming chemical connections. This technique works better at higher carbonization temperatures because they enhance the surface area and pore volume of the biochar. The film pore diffusion model better explains this mechanism. A large surface area improves heavy metal adsorption on modified charcoal adsorbents. However, this sort of surface adsorption frequently lacks selectivity, especially for positively charged metal cations and negatively charged anions in water. To boost modified biochar adsorption capacity, the above-mentioned strategies must be thoroughly investigated and implemented (Liu et al., 2012). The ion exchange mechanism involves the exchange of ionizable cations on the sorbent surface with heavy metal ions in solution. The efficiency of this procedure is determined by the pollutants' size and the sorbent's surface functioning. According to studies, biochar generated from non-woody and grassy biomass have better cation exchange capabilities due to their high oxygen content and acidic sites (Harvey et al., 2011).

The greater cation exchange capacity in biochar leads to higher metal adsorption. However, they discovered that when the pyrolysis temperature exceeds 350°C, the cation exchange capacity decreases.(El-Shafey, 2010) investi-gated the extraction of Hg^{2+} and Zn^{2+} from contaminated water utilizing rice husk biochar at 180°C. Their findings demonstrated that the biochar had a higher adsorption of Hg ions than Zn. Metal complexation happens when metal molecules bind and form multi atom complexes. The functional groups that contain oxygen on the surface of biochar may interact with heavy metal ions. Because of its functional groups that contain oxygen, such as phenolic, lactone, and carboxyl groups, biochar produced at temperatures that are lower can effectively bind to heavy metals.

The presence of these oxygen groups increases the surface oxidation of the biochar, which improves its propensity to form metal complexes.(Pan et al., 2013) used the technique of scanning electron microscopy to analyse the biochar and discovered the existence of insoluble complexes on the biochar surface both before and after heavy metal sorption. Energy dispersive Xray spectroscopy (EDS) examination revealed that these insoluble complexes were made up of ionized heavy metals from the solution (Mohan and Pittman Jr, 2007). Chemical bonding physically involves the migration of metal ions into the sorbent's pores, where chemical bonds develop. The carbonization temperature influences the pore volume and surface area of sorbents like biochar. K (Kumar et al., 2017) examined uranium adsorption with biochar generated from pinewood at carbonization temperatures of 300 °C and 700 °C. Their findings revealed that biochar produced at higher temperatures was substantially more successful in uranium removal than biochar produced at lower temperatures. This improved effectiveness was attributable to the increased surface area and pore volume caused by greater carbonization temperatures.

Lastly, while incorporating biochar into wastewater eco treatment systems appears to be an environmentally friendly solution to fostering circular economy and ecosystem sustainability, further investigation into underlying mechanisms and longterm economic analyses is still required. Although biochar has numerous benefits, it may not address all issues and there are still significant concerns. Therefore, we need to spend more on exploring biochar interactions and customizing it to different field settings (Wu and Wu, 2019).

5. CONCLUSION

Heavy metal contamination raises environmental concerns, necessitating the use of effective and sustainable treatment procedures. Biochar has been demonstrated to be an effective adsorbent, with its specific characteristics determined by both its feedstock and the pyrolysis method. Agricultural waste, when transformed into biochar, provides a low cost and environmentally beneficial alternative for reducing heavy metal pollution in aquatic bodies. Currently there are several research methodologies being tested out with different types of feedstocks being pyrolyzed at different temperatures and conditions. This alters the physical and chemical properties of biochar, such as surface area, functional groups, pore structure, which are the crucial factors in heavy metal adsorption. Furthermore, modifying biochar with both physical and chemical treatments improves its adsorption characteristics, making it a versatile material for a variety of environmental purposes. For instance, acid activation helps increase in pore structure and surface area, hence improving the adsorption capacity. Despite the promise of biochar, difficulties such as high manufacturing costs for specific modifications and probable leaching of adsorbed metals must be addressed through additional research.

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CONFLICT OF INTEREST

There is no conflict of interest between the authors.

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