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BIOCHAR IN WASTEWATER REMEDIATION: A BRIEF REVIEW OF CHARACTERISTICS AND PREPARATION MATERIALS

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ABSTRACT – The rapid growth of industry has significantly increased water pollution, especially from heavy metals which are not biodegradable and tend to accumulate in living organisms through the food chain. Consequently, the development of a sustainable low-cost wastewater treatment approach has attracted more attention from policymakers and scientists. Traditional methods, such as chemical precipitation, filtration, and activated carbon adsorption, often require high operational and capital costs. Recently, biochar has emerged as a promising sorbent due to its eco-friendliness, favorable surface and structural properties, and high adsorption capacity. Additionally, biochar can be produced from a variety of biomass feedstocks, which will be illustrated in this paper through specific examples. This process not only addresses the issue of heavy metal contamination in wastewater but also provides a viable alternative for managing bio-waste that would otherwise be discarded. While biochar's efficiency in removing contaminants has been well demonstrated at the lab scale, mainly focusing on the sorption of a single metal from spiked solutions, further in situ studies are necessary to evaluate performance with real effluents and assess the environmental impact before its large-scale application.

Keywords: Water pollution, Heavy metals, Biochar, Bio-waste management.

INTRODUCTION

Heavy metals (e.g., Cd, Cr, Cu, Ni, Pb, Hg, Zn) enter the environment primarily through large-scale industries such as leather, metallurgical, petroleum, batteries, textile, fertilizers, nuclear, and pesticides [1]. Once discharged, these metals pose risks to indigenous habitats and human health alike [2].

While certain metals, such as zinc, iron, and chromium, are essential in trace amounts for biological processes, others, such as lead, cadmium, and mercury, are highly toxic and have no biological need in the human body. Thus, the removal of these elements from contaminated water is both important and urgent [3]. Activated carbon typically adsorbs only a few milligrams of metal ions per gram, and regeneration issues further complicate its use. Due to these limitations, there is a growing interest in the scientific community

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in using pyrolyzed biomass – biochar, as a sustainable alternative. Biochar offers even superior adsorption capacities which has consequently attracted growing interest evidenced by the increasing number of published articles over the past decade [4].

Biomass feedstock can include any organic waste materials as shown in Figure 1. Previously considered useless, these wastes are now converted into valuable resources through pyrolysis, finding applications across various fields [5].

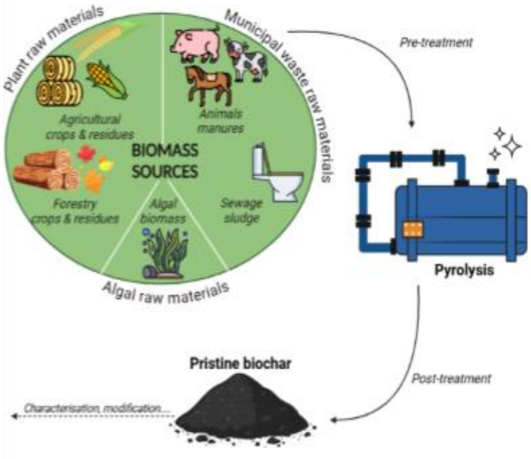

Figure 1 Production of biochar through pyrolisis from various biomass sources

Pyrolysis is the most common method for producing biochar, whereas material obtained through gasification and hydrothermal carbonization generally does not meet the typical definition of biochar [4].

Several factors, including the operating temperature, heating rate, and residence time, influence the resulting biochar's properties. During pyrolysis, the components of the feedstock, such as lignin, cellulose, hemicellulose, and fats, undergo thermal degradation in an oxygen-free environment.

This process enriches the carbon content of the material by removing non-carbon elements like oxygen and hydrogen. As a result, the removal of these elements in the form of gases and volatiles leads to a reduction in the O+N/C and H/C atomic ratios, while enhancing the aromaticity and carbon content, which in turn increases the biochar's stability.

When the pyrolysis temperature exceeds 500°C, the biochar becomes more hydrophobic, with an increase in surface area and micropore volume, making it more suitable for the removal of organic pollutants. In contrast, pyrolysis at temperatures below 500°C produces biochar with smaller pores, lower surface area, and a higher concentration of oxygen-containing functional groups, making it highly amenable for adsorbing inorganic pollutants [6].

However, to ensure the feasibility of biochar in wastewater treatment, the factors involved in its preparation that influence its characteristics and adsorption capacity must be understood [7].

This study aims to review the relevant literature to identify types of biomass that have demonstrated effectiveness in removing specific metals from water samples and to provide a broader perspective on other potential materials that could be further explored.

CORE CONCEPTS OF BIOCHAR

Characterizing biochar after preparation is crucial for understanding its chemical composition, morphology, and surface properties, which directly influence its performance in applications like adsorption. Commonly used analytical techniques, such as X-ray diffraction (*XRD*), Fourier transform infrared spectroscopy (*FTIR*), X-ray photoelectron spectroscopy (*XPS*), and Nuclear magnetic resonance (*NMR*), provide insights into the biochar's chemical structure, functional groups, and surface characteristics. In addition, techniques like Brunauer-Emmett-Teller (*BET*) surface area analysis, extended X-ray absorption fine structure (*EXAFS*), scanning electron microscopy (*SEM*), and energy dispersive X-ray spectroscopy (*EDX*) provide information on surface area, porosity, and morphology, all of which are critical for adsorption performance. Together, these methods give a comprehensive view of biochar's properties, helping predict its adsorption capabilities and guide potential modifications to optimize its functionality [4].

Researchers worldwide are working on different methods of biochar preparation to enhance its efficiency. Pristine biochar refers to biochar produced directly from biomass through pyrolysis, without any significant modifications. Engineered or designer biochar, on the other hand, is biochar that has been intentionally modified or tailored to possess specific properties. These modifications aim to improve certain characteristics making biochar more suitable for specialized applications.

The adsorption capacity of biochar is closely linked to its physicochemical properties, such as surface area, pore size distribution, functional groups, and cation exchange capacity. These properties can vary depending on the preparation conditions, and various chemical or physical modification methods have been adopted to improve them. In addition to traditional modifications, researchers have also started creating biochar-based composite materials by incorporating synthetic materials to further enhance biochar's efficiency [8].

These composites not only improve the physicochemical properties of biochar but also combine their advantages with those of other materials. Biochar-based composites can be specifically designed for target pollutants by adding functional materials, magnetic substances, or nanoparticles, resulting in materials enriched with functional groups that address the limitations of pristine biochar in environmental remediation [9].

In the course of the adsorption processes, modified biochar works on both physical and chemical adsorption. However, the dominant adsorption mechanisms may differ depending on the type and properties of the adsorbed pollutant. While ion exchange and electrostatic interactions are found to be common mechanisms of metal removal which in turn depends on the nature of biomass, process conditions, and metal, it is found that modifications and mechanisms are strongly interrelated [3].

Figure 2 illustrates the different biochar modifications alongside the key adsorption mechanisms. While these two aspects are not directly related in the figure, it serves to visually summarize the modification methods and adsorption processes discussed, giving a clearer understanding of how biochar's properties can be tailored for various applications.

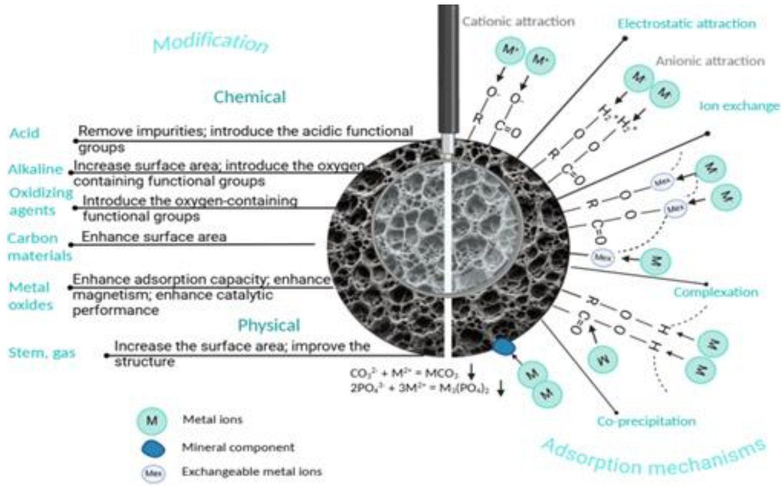

Figure 2 Biochar modifications and associated adsorption mechanisms

LITERATURE REVIEW

Direct comparison of adsorption capacities is challenging due to inconsistencies in the data found in the literature. The reported sorption capacities are measured under varying conditions such as different pH levels, temperatures, adsorbate concentration ranges, biochar doses, particle sizes, and surface areas. Additionally, biochars are applied to treat a variety of water sources, including groundwater, drinking water, synthetic industrial wastewater, and real-world wastewater, each with distinct types and concentrations of interfering ions. Another challenge in comparing biochar adsorbents is the variation in preparation conditions, such as temperature, time, and atmosphere. Studies that prepare biochar from the same feedstock using different methods and then test it with the same adsorbates are limited. Similarly, to evaluate reproducibility, it is essential to conduct studies using identical biochar preparations from the same feedstock and test them with the same adsorbates [2].

Since the properties of biochar are influenced by the type of feedstock, it is essential to select appropriate materials to achieve the desired characteristics in the produced biochar [1]. Figure 3 provides an overview of some notable materials that have been used in biochar production, offering perspectives on potential feedstocks for future improvements and innovations.

In natural waters, various heavy metals often coexist with other pollutants, leading to competition for sorption sites on the biochar surface between metals, other ions, and organic pollutants. Currently, only a few studies have explored the competitive sorption of metals by biochar, and there are no reports of biochar being used in field applications to remove heavy metals from contaminated wastewater [26]. Given this complexity, machine learning (*ML*) techniques offer a promising solution by helping to optimize biochar properties and predict its behavior in competitive sorption scenarios. By analyzing large datasets, ML algorithms can identify key factors influencing biochar's performance, allowing for more efficient and targeted use of biochar in environmental remediation [5].

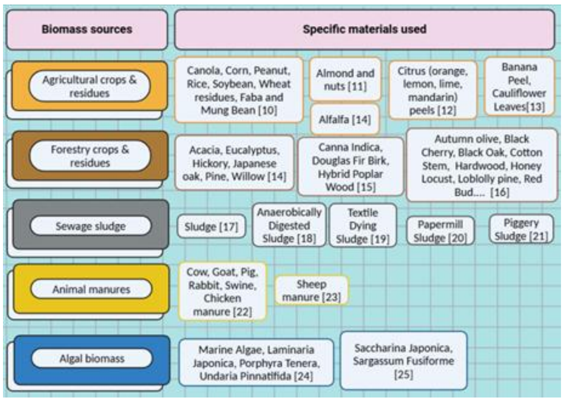

Figure 3 Overview of materials used in biochar production

TREATMENT OF USED BIOCHAR

Commonly used separation methods for segregating biochar from treated water are filtration, sedimentation, or centrifugation. However, managing adsorbents saturated with heavy metals presents a significant environmental challenge, as these materials can become hazardous waste. Therefore, implementing appropriate strategies for their safe handling, such as stabilization and disposal at specialized facilities, is highly needed. Until now, the disposal of end-of-life adsorbents and the subsequent recovery of contaminants has been a major practical challenge. The spent adsorbents are typically either regenerated for reuse as soil amendments, capacitors, and catalysts, or safely disposed of through incineration and landfilling. Although incineration can reduce waste volume, it requires substantial energy and generates harmful emissions. The resulting ash can be solidified afterward, but care must be taken to prevent the leaching of metals. A different approach would include utilizing biochar in the construction industry, where biochar containing immobilized metals could be used as a construction material providing an energy-efficient solution. Another viable option is desorption, where metals are extracted from the biochar using dilute acids like HCl or HNO_3. This process allows for further processing or reuse of the metals. Additionally, regenerating the adsorbent facilitates its repeated use, leading to cost savings. Selecting appropriate desorption agents is crucial to preserve the biosorbent's effectiveness and ensure environmental safety [27].

CONCLUSION

Due to the rising concern regarding health issues caused by heavy metals found in wastewater, biochar is being profoundly studied. Biochar has been identified as a great solution for purifying contaminated waters, offering several advantages that have been discussed in this paper. However, the biggest obstacle remains the process of scaling it up on the industry and market level. The papers published so far are entirely based on laboratory experiments, showing outstanding results and the potential for using biochar in the future. The real-world environment is much more complex, with pollutants often coexisting, which leads to uncertainty about its practical application. This paper provides a foundation for exploring the variety of materials that can be used for biochar production, highlighting the potential for a range of feedstocks in wastewater treatment. In order for biochar to be recognized as a standard practice in wastewater treatment, further research needs to be conducted under industrial circumstances, including studies that explore the competitive properties of pollutants during sorption.

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