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# Utilization of Agricultural and Organic Waste as Eco-Friendly Biomass-based Adsorbents

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*ABSTRACT*

The development of effective and sustainable remediation techniques is required due to the growing environmental contamination brought on by industrial activities, especially from heavy metals and organic pollutants. The purpose of this review is to evaluate critically the potential of biomass-based adsorbents made from organic and agricultural waste for use in environmental remediation, specifically in the treatment of soil and water. The study assesses the surface properties, functional groups, and adsorption mechanisms of several bio-adsorbents and groups them according to their sources, including activated carbon, agricultural residues, and biochar. The impact of chemical and physical changes on improving adsorption performance is also thoroughly examined. The results show that these environmentally friendly materials have notable adsorption capacities and provide a sustainable, scalable, and affordable substitute for traditional synthetic adsorbents. The study adds to the expanding corpus of research that supports the circular economy's waste valuation principles and emphasises the usefulness of green environmental management techniques.

**Keywords:** *biomass-based adsorbents, bio-adsorbents, adsorption, agricultural waste, biochar*

## 1. INTRODUCTION

Globally, industrial pollution has become a significant environmental problem, especially the release of synthetic organic compounds and heavy metals into soil and water. Conventional remediation methods including ion exchange, chemical precipitation, and reverse osmosis frequently have limited selectivity, high operating costs, and sludge formation (Bolisetty, Peydayesh, & Mezzenga, 2019). Adsorption has drawn interest in this context as a straightforward, effective, and economical substitute, particularly when used with biomass-based materials as bioadsorbents. Because of their accessibility, affordability, and variety of functional groups (hydroxyl, carboxyl, and amine), which improve adsorption effectiveness, environmentally friendly adsorbents made from organic and agricultural waste are gaining popularity (Sen, 2023).

The need for drinkable water has grown dramatically over the past few decades as a result of the growing industrialization and the fast population rise. Many industrial products, such as plastics, phenolic materials, gasoline-powered vehicles, and industrial-level food processing facilities, have become a part of our daily lives as civilization has become more modern. These companies' byproducts significantly contaminated the soil, air, and water bodies, endangering human life, and effectively deteriorated the previously unspoiled water source. The majority of poisons remain in water for years because they are insoluble. These poisons are not only endanger marine life in addition to humans, animals, and plants (Rizal et al., 2021). Among the typical chemical contaminants found in the environment, particularly in groundwater and industrial effluent, are heavy metals, dyes, dissolved organic solvents, pesticides, and herbicides (Bolisetty et al., 2019).

Traditional methods for cleaning up chemical contaminants include adsorption by ion exchange resins, bio-sand, precipitation, reverse osmosis, and adsorption by Iron oxide and active alumina can only eliminate specific substances, usually heavy metals (Mahfoudhi & Boufi, 2017). Nevertheless, several of the aforementioned methods require highly trained labor, have large operating costs, and produce sludge at the conclusion of the process. Adsorption strategies are superior to other approaches. Some advantages of using cost-effective adsorbents for adsorption processes include ease of use, which eliminates the need for highly specialized personnel, environmental safety, no health risks for the operator, and a non-destructive procedure that allows contaminants to be separated and recycled (Ahmad, Rafatullah, Ghazali, Sulaiman, & Hashim, 2011).

Comparatively, adsorption process is considered better in water treatment because of convenience, ease of operation, and simplicity of design. The unconventional adsorbents from biomass waste and other carbon-rich sources have been tested against water-soluble contaminants; the reported research works have been reviewed extensively (Jain, Balasubramanian, & Srinivasan, 2016).

According to reports, activated carbon made from a variety of inexpensive raw materials has a limited or inadequate adsorption performance against different contaminants in contrast to commercial activated carbon derived from coal. Thus, there is ongoing research into the most affordable raw material and activated carbon production process (Bhatnagar, Sillanpää, & Witek-Krowiak, 2015).

Adsorbents based on biomass provide sustainable and circular solutions for the removal of pollutants, in contrast to commercial activated carbon, which can be expensive and non-renewable. In order to remove contaminants from aquatic environments, this review aims to assess and summarise contemporary research on the production, categorisation, modification methods, and efficacy of biomass-based adsorbents, especially those made from organic and agricultural waste. This research focusses on the mechanics of adsorption, how physicochemical treatments might increase adsorption capacity, and how well bioadsorbents work in comparison to traditional materials.

## 2. BASIC CONCEPT OF ADSORPTION

In the process of adsorption, a solute (adsorbate) is drawn to the surface of an adsorbent by attractive forces until equilibrium is reached,when the adsorbate concentration is reached and no more net adsorption takes place (Yousef, Qiblawey, & El-Naas, 2020). Diffusion of molecules from the bulk phase toward the interface space (external diffusion), diffusion of molecules inside the pores (internal diffusion), diffusion of molecules in the surface phase (surface diffusion), and adsorption-desorption fundamental processes are the steps involved in the adsorption of solute onto adsorbent (Dąbrowski, 2001).

Adsorption may take the form of chemical (chemisorption) or physical (physisorption). Weak, short-range electrostatic attractive forces originating from the dipole moment (Van der Waals) cause physical adsorption, whereas chemisorption entails the creation of bonds between the adsorbent and the adsorbate. One of the best methods for eliminating impurities from solutions is adsorption (Taiwo & Chinyere, 2016).

The interaction between the adsorbent and the adsorbate can be described with the help of adsorption isotherms. They are crucial in identifying an adsorbent's ideal adsorption capacity, demonstrating its adsorption efficiency, and enabling an assessment of the applicability of the adsorbent. When building an adsorption system, adsorption isotherms are crucial because they show how much adsorbate binds to the adsorbent surface based on the material present in the solution (Prasath, Muthirulan, & Kannan, 2014) .

Several phrases are used in the literature to explain the equilibrium relationship between the adsorbent and the adsorbate. Known as isotherms, these equilibrium expressions measure the amount of solute adsorbed at a fixed temperature (Ge et al., 2019). Isotherm profiles are created using experimental data in order to choose a model that best explains an adsorption system. The best-fitting isotherm model is selected to represent the adsorption system in equilibrium (Wong, Szeto, Cheung, & McKay, 2004).

### 2.1. Langmuir Isotherm

One of the earliest empirical models for describing adsorption isotherms is the Langmuir isotherm. Four presumptions form the basis of the formulation: (i) monolayer adsorption; (ii) adsorption only takes place at a limited number of sites; (iii) all adsorption sites are equal; and (iv) adsorbed solutes do not exchange interactions (Foo & Hameed, 2010).

### 2.2. Freundlich Isotherm

The Freundlich isotherm is also commonly presented in addition to the Langmuir isotherm. The first known model that takes into account the reversibility and non-ideality of adsorption is the Fruendlich isotherm. The adsorption intensity is shown by the expression's slope when this model is linearized. The more heterogeneous the adsorbent surface, the closer the model's slope is to zero (Haghseresht & Lu, 1998). This model is predicated on three assumptions: (i) multilayer adsorption; (ii) a heterogeneous surface; and (iii) an uneven distribution of adsorption heat and affinity.

### 2.3. Temkin Isotherm

In order for a dipole to interact with a homogeneous electric field, the Temkin equilibrium model assumes that (i) all interacting dipoles at the surface are the same and (ii) there is adsorbate–adsorbate interaction at the surface (Foo & Hameed, 2010).

## 3. BIO-ADSORBENTS

A bio-adsorbent is an adsorbent derived directly from biological materials (biomass), typically used in its natural or minimally modified form. Bio-adsorbent often used without extensive processing, common treatments include drying, washing, or mild heating. For the treatment of many kinds of industrial wastewater, researchers were interested in bio-adsorbents derived from biological sources in addition to earth-based adsorbents. According to the literature, the adsorbents come from the food chain or from agricultural methods (Sud, Mahajan, & Kaur, 2008). Biomaterials that have the ability to absorb heavy metals and other contaminants are referred to as bio-adsorbents. Currently, a variety of materials are being researched and used for biosorption, including bacteria, fungi, algae, and agricultural waste. Many active groups, including hydroxyl, carboxyl, and amino groups, are typically present in this substance. These groups can interact with heavy metal ions by electrostatic adsorption, chelation, coordination, and inorganic microprecipitation. Echinococcus and Chlorella scenarios were evaluated for the removal of metal mine tail water in northern Chile. Microalgae had clearance rates of 64.7% and 99.9% for copper and molybdenum, respectively (Urrutia, Yañez-Mansilla, & Jeison, 2019).

The adsorption method is regarded as one of the best approaches to address pollutants because of its benefits, which include a broad variety of applications, good treatment result. The concentration of heavy metal ions has less of an impact on the adsorption method's therapeutic effect, reusability, quick recovery, and comprehensive source of adsorbent. Because of their large surface area and numerous active surface sites, carbonaceous materials are thought to be the most effective adsorbents (Fiyadh et al., 2019).

However, the use of this material is not commercially possible due to the high cost and complexity of the regeneration process of industrial activated carbon. Furthermore, due to their high cost or subpar adsorption capabilities, other forms of carbon compounds are not appropriate for use as adsorbents. For instance, multiwall carbon nanotubes were oxidized to create the adsorbents, which were subsequently derivatized using amino acids, hydroxylamine, and hydrazine. The adsorbent has an adsorption capacity of 24.34 mg g1 for lead ions (Taylor, Isley, & Glover, 2019). Because of the rich structure, low-cost methods can be used to boost adsorption capacity and decrease total costs in this adsorption process. Using biomass as an activated carbon precursor has emerged as a viable technique.

However, depending on where they come from and how they are treated, bio-adsorbents have very different levels of efficacy. According to multiple research, Table 1 below contrasts a number of popular bio-adsorbents based on their maximal adsorption capabilities for lead ($Pb^{2+}$).

**Table 1.** Comparative Adsorption Capacities of Various Biomass-Based Bio-adsorbents for Heavy Metal Removal

| Bioadsorbent | Raw Material | Pollutant | Adsorption Capacity (mg/g) | Reference |
|---|---|---|---|---|
| Banana peel powder | Agricultural waste | $Pb^{2+}$ | 50.64 | (Sud et al., 2008) |
| Modified coconut shell AC | Agro-industrial waste | $Pb^{2+}$ | 93.75 | (Hoang et al., 2022) |
| Cashew shell ($H_2SO_4$ treated) | Agricultural waste | $Ni^{2+}$ | 456.3 | (Vaithyanathan, Goyette, & Rajagopal, 2023) |
| Algae (Chlorella) | Aquatic biomass | $Cu^{2+}$ | 64.7 | (Urrutia et al., 2019) |
| Rice husk biochar | Lignocellulosic waste | $Pb^{2+}$ | 36.02 | (Bhatnagar et al., 2015) |

Based on these values, bio-adsorbents, especially chemically modified ones, can function on par with or even better than commercial adsorbents. Additionally, their low cost and waste-based origin let environmental remediation employ a sustainable waste-to-resource approach.

## 4. BIOMASS-BASED ADSORBENTS

A biomass-based adsorbent is an adsorbent made from biomass as a raw material, but it has usually undergone chemical, thermal, or physical modification to enhance its adsorption performance. Adsorbents based on biomass offer an attractive and environmentally friendly way to remove heavy metals from water. Because of their inherent makeup, these materials, which come from organic sources including food waste and forestry and agricultural wastes, effectively absorb heavy metals from contaminated water. Numerous adsorption processes, including ion exchange, are made possible by their large surface area and functional groups, including as hydroxyl, carboxyl, and amino groups and complexity (Sen, 2023).

Through the reuse of waste materials and the reduction of dependency on synthetic adsorbents, these biomass-based adsorbents not only provide an affordable option but also support environmental suistanibility (Cite & Published, 2019).

### 4.1. Types of Biomass-Based Adsorbents

Adsorbents based on biomass provide a wide variety of naturally occurring materials, each with special qualities and uses for heavy metal removal. These adsorbents can be generically categorized into different categories according to their properties and place of origin.

**Activated Carbon**

Because of its extremely large surface area and porous nature, activated carbon is a highly effective and adaptable adsorbent that may be used for a wide range of pollutant removal applications. derived from carbon-rich materials such as coal, wood, peat, or coconut shells and activated by physical or chemical means. Through the process of pyrolysis, which involves heating carbon-rich materials to high temperatures without oxygen and then activating them with oxidizing gasses like carbon dioxide or steam. It creates activated carbon. Its extensive use in a wide range of applications is evidence of its excellent adsorptive properties and large surface area. The effectiveness of activated carbon depends on important elements like as the distribution of pore size, surface area, and the type of the adsorbate, which makes it a really dependable remedy for elimination of contaminants (Hoang et al., 2022).

The effectiveness of activated carbon derived from biomass as an adsorbent is significantly reduced by a few essential elements. These consist of the chosen biomass type, the activation techniques, the carbonization conditions utilized, along with the pre-treatment methods. Significantly, the difference in the chemical and physical characteristics of activated carbon that are obtained from several kinds of biomass highlight the possibility for optimizing adsorption efficiency depending on particular circumstances.

**Agricurtural Residues**

Crop harvesting, processing, and livestock farming are examples of agricultural processes that produce organic compounds known as agricultural leftovers. Illustrations included among these wastes are crop remnants such as stalks, stems, husks, straw, and animal as well as resources for bedding and manure, which are abundant suppliers of biomass suitable for adsorption. These waste materials are plentiful sources of biomass that is suitable for adsorption because of its high cellulose content. The amount of lignin that, after going through the proper processing, can be used for adsorption applications (Harshala & Wagh, 2022).

**Algae and Aquatic Biomass**

A rich resource that may be extracted from aquatic settings and converted into adsorbents is algae and aquatic biomass, including seaweed and water hyacinth. These organic resources include proteins, polysaccharides, and other organic materials that have demonstrated exceptional efficacy in removing impurities from water through adsorption. In both freshwater and marine settings, algae and aquatic biomass are essential for sustaining aquatic food webs, promoting nutrient cycling, and preserving ecological dynamics. From microalgae to macroalgae, this varied group of organisms is crucial to the well-being and equilibrium of our aquatic ecosystems (Li et al., 2021). In specifically, algae Chlorella are used because of their large surface area and useful functional groups attach to metal ions (Manzoor, Karbassi, & Golzary, 2019).

**Biochar**

A substance rich in carbon, biochar is created by heating biomass. The production of biochar often involves the thermal treatment of feedstocks or biomass, including waste from agriculture, sludge, manure, food waste, forest residue, and solid waste from cities (Murtaza et al., 2021). Biochar is frequently produced from carbonous materials via pyrolysis and hydrothermal carbonization. Biochar got ready in these the type of biomass, the reaction medium, and the pyrolysis conditions all play a major role. The most common procedure is pyrolysis. The process can be divided into rapid and slow pyrolysis depending on the heating rate, residence period, and pyrolysis temperature (Shakoor, Ye, & Chen, 2021). Fast (or flash) pyrolysis is a process in which low-moisture feedstock is rapidly heated for a short duration, typically within a few seconds, at a temperature of around 800 °C. When the thermal treatment lasts longer than a few minutes, the process is referred to as slow pyrolysis, which typically occurs at temperatures ranging from 450 to 1,200 °C (Amusat, Kebede, Dube, & Nindi, 2021). Fewer harmful gases are released into the atmosphere when using the slow pyrolysis method, making it more environmentally friendly. As a result of these attributes, biochar produced through slow pyrolysis is considered a sustainable product. It is also regarded as an effective material for removing various contaminants from soil and wastewater (Zhang, Chen, Gray, & Boyd, 2017).

## 4.2. Physical and Chemical Methods

Using physical, chemical, and combination physicochemical techniques to improve biomass for adsorption applications increases the adsorption capacity and selectivity of adsorbents based on biomass. By improving the biomass's surface area, pore structure, and chemical functionality, these changes hope to make it more effective in adsorbing specific pollutants (Abiodun et al., 2023).

**Physical Methods**

A variety of physical modification methods are employed to increase the surface area and porosity of biomass, including milling, heat treatment, and autoclaving materials. For instance, ball milling can effectively reduce particle size, which improves interaction with the adsorbate and creates more active adsorption sites. Ball-milled highly activated carbon significantly improved the removal of chromium (VI) from aqueous solutions, achieving an astounding 99.0% removal at pH 6. This is a significant increase from the 68.3% removal achieved with normal activated carbon made from granular coconut shell. We also noticed an increase in eiciency using ball-milled highly activated carbon at pH 7, going from 42.7% to 77.8%. This method has a lot of potential for effective chromium (VI) cleanup (Fang et al., 2021).

Biomass is heated using an oxidizing agent, like steam or carbon dioxide, during the physical activation process at elevated temperatures, usually between 600 and 1000 °C. This activation significantly increases the porosity and surface area of the biomass. When biomass is mechanically ground or milled, it goes through a procedure that lowers how big its particles are. This decrease in particle size enhances the surface area of the biomass, making it more available for adsorbates. Consequently, the biomass's effectiveness in adsorption applications increases. Additionally, biomass is physically treated in ways such as the properties of the surface are changed by plasma or UV light. The biomass and adsorbates interact better as a result of these changes. Numerous applications may benefit from this enhanced engagement in different ways .

**Chemical Methods**

The technique of chemical activation involves treating biomass with chemicals like potassium hydroxide and phosphoric acid prior adding functional groups through carbonization to improve adsorption capacities. For instance, lignocellulosic adsorbents can be activated using $H_3PO_4$ and $ZnCl_2$, which aids in the creation of mesopores with large surface areas. These adjustments can significantly enhance how well the target pollutant interacts with the adsorbents. As an illustration, sulfuric acid treatment of cashew nut shells demonstrated adsorption properties up to for heavy metals like $Ni^{2+}$, 456.3 mg/g. These substances are essential for improving the biomass material's surface area and porosity development. By treating it, biomass can be increased containing chemical substances that provide functional groups like hydroxyl and amino. These useful groupings enhance the unique interactions of the biomass using adsorbates. One method of chemically altering biomass is by using cross-linking agents such as glutaraldehyde. These substances are used to produce a stronger structure inside the biomass, so enhancing its resilience and capacity to absorb materials (Vaithyanathan et al., 2023). Combining chemical and physical methods often produced superior results for biomass transformation. Collectively, these tactics increase the surface area and active site availability of adsorbents. while optimizing their structural soundness to enhance the adsorption of certain organic contaminants (Abiodun et al., 2023)

## 5. CONCLUSION

The review emphasises the increasing potential of organic and agricultural waste as environmentally benign and sustainable raw materials for the creation of adsorbents based on biomass. These materials can attain notable adsorption capabilities for a variety of contaminants, particularly heavy metals, using a variety of modification processes, including pyrolysis, physical activation, and chemical treatments. Functional groups such as hydroxyl, carboxyl, and amine are present and help explain the high binding affinity of bioadsorbents.

The comparative research demonstrates that appropriately adapted biomass-derived adsorbents can offer benefits in terms of cost, renewability, and waste valorisation in addition to matching or even surpassing commercial activated carbon in terms of adsorption performance. These results provide credence to the incorporation of bioadsorbents into green environmental remediation technologies and circular economy initiatives.

To improve surface modification procedures, comprehend molecular adsorption mechanisms, and assess regeneration and scalability in practical settings, more study is necessary. The wider use of biomass-based adsorbents in industrial wastewater treatment and environmental management will be made easier by progress in these areas.

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