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Agricultural Nutshells as Low-cost Adsorbents for Pb(II) and Zn(II): Comparative Review and Application Challenges

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ABSTRACT: This study assesses the adsorption efficiency of groundnut seed nutshell and soyabean seed nutshell as low-cost bioadsorbents for the removal of Pb(II) and Zn(II) ions from contaminated water. Batch adsorption experiments were performed by adjusting key operational parameters such as pH (6.0–7.5), biosorbent dosage (0.1–10 g/L), and contact time (15–45 minutes) to determine optimal metal uptake conditions. Both agricultural waste–derived adsorbents exhibited strong biosorption capacity, with metal removal improving at higher pH levels, increased sorbent doses, and longer interaction periods. Comparative analysis showed that groundnut nutshell had a greater affinity for Pb(II), whereas soyabean nutshell achieved superior adsorption of Zn(II) under optimized conditions. Overall, the findings confirm the potential of these readily available agro-wastes as eco-friendly, economical, and sustainable adsorbents for heavy metal remediation in wastewater treatment.

KEYWORDS: Bioadsorption, Pb(II) and Zn(II) removal

I. INTRODUCTION

The presence of heavy metals in aquatic environments has become a significant global concern, mainly because elements such as lead (Pb(II)) and zinc (Zn(II)) are highly persistent, toxic, and tend to bioaccumulate within living organisms [1]. Various industrial operations—including mining, smelting, electroplating, battery production, and metal finishing—are major contributors to this issue, often discharging partially treated or untreated effluents into natural water bodies. This leads to elevated levels of hazardous metals in both surface and groundwater systems [2]. Even small concentrations of lead can cause adverse neurological and developmental effects, while excessive zinc, though biologically essential in minute quantities, disrupts the ecological balance of aquatic ecosystems [3]. Consequently, there is an urgent need to develop low-cost, environmentally friendly, and highly efficient adsorbent materials for removing Pb(II) and Zn(II) from contaminated water.

Although several conventional treatment approaches—such as ion exchange, chemical precipitation, electrochemical processes, and membrane-based filtration—are used for metal removal, they often suffer from high operating costs, energy demands, and limited suitability for small-scale or rural wastewater treatment [4]. In contrast, adsorption has emerged as a preferred option due to its operational simplicity, cost-effectiveness, and high efficiency in treating complex wastewater. However, the high cost and regeneration challenges associated with commercial activated carbon have prompted the search for cheaper, renewable, and biodegradable biosorbents derived from agricultural by-products [5].

Among these, agricultural nutshell residues—such as groundnut shells, coconut shells, soybean hulls, almond shells, and walnut shells—have gained attention as economical biosorbents for removing heavy metals. These lignocellulosic materials are rich in cellulose, hemicellulose, and lignin, and contain functional groups like carboxyl and hydroxyl moieties that play key roles in metal binding via ion exchange, complexation, and surface adsorption [6]. Their naturally porous structure, high chemical stability, abundant availability, and low economic value further support their use as sustainable adsorbents. Additionally, physical and chemical modification treatments—such as activation with acids, bases, or salts—can significantly enhance their adsorption capacity and surface properties [7].

Despite the promising laboratory findings that show high efficiencies for Pb(II) and Zn(II) removal, several practical challenges hinder the widespread application of nutshell-based sorbents. These challenges include variability in sorbent composition due to agricultural differences, reduced performance in real wastewater containing competing ions, difficulties in scaling up from batch experiments to continuous treatment systems, poor regeneration potential, and the need for safe disposal of metal-loaded biosorbents [8]. Moreover, comprehensive comparative studies evaluating different nutshell types, modification strategies, and optimal operating conditions are still limited, slowing their adoption in industrial or field-scale applications.

Considering these limitations, a systematic assessment of agricultural nutshells as inexpensive and efficient biosorbents for Pb(II) and Zn(II) removal is necessary. This review synthesizes available research, compares the adsorption performance of various nutshell-based materials, and evaluates the technological, operational, and environmental challenges associated with their real-world implementation. The insights generated aim to support the development of scalable, cost-effective, and environmentally sustainable heavy-metal remediation solutions utilizing agricultural waste biomass.

II. RELATED WORK

Agricultural Nutshells as Low-cost Adsorbents

Agricultural processes generate substantial quantities of biomass residues, with nutshells from crops such as groundnut, coconut, walnut, and almond representing a major portion of this waste. These shells are often discarded in open fields, burned, or left unused in storage areas, thereby contributing to waste management challenges and local environmental pollution [9]. Notably, nutshells possess a rich biochemical composition containing lignin, cellulose, and hemicellulose, along with functional groups such as hydroxyl, carboxyl, and phenolic moieties, which enable strong interactions with pollutants [10]. These characteristics make nutshells attractive, low-cost biosorbents, and their conversion into valuable materials supports sustainable waste utilization and aligns with circular-economy principles [11].

One major advantage of agricultural nutshells is their naturally porous structure, which enhances their capacity to capture and retain contaminants. Even in their raw or lightly processed form, nutshells exhibit considerable surface area and adsorption potential. Simple pre-treatment processes—such as washing, drying, grinding, or controlled carbonization—can significantly improve their adsorption performance by increasing porosity and exposing additional active binding sites [12]. Compared to commercial activated carbon, which involves high-temperature activation and is expensive to produce, nutshell-derived adsorbents offer a more economical and accessible alternative. Their affordability and widespread availability make them especially suitable for resource-limited regions where agricultural waste generation coexists with issues of water pollution [13].

Extensive research has demonstrated the efficiency of nutshell-based biosorbents in removing heavy metals, dyes, and organic pollutants from water. Groundnut shells, for example, have shown significant adsorption capacity for Pb(II) and Zn(II) ions due to the presence of functional sites capable of metal chelation [14]. Similarly, coconut shells serve as an important precursor for low-cost activated carbon commonly used in household and industrial water purification systems [15]. These adsorbents are applicable in household water filters, industrial effluent treatment units, and community-scale purification systems, making them valuable in addressing public health concerns linked to toxic contaminants [16]. Their effectiveness is particularly relevant in areas affected by industrial discharge and agricultural runoff.

Beyond water purification, nutshell-derived adsorbents exhibit promising potential in air pollution control, soil remediation, and treatment of wastewater from dyeing, electroplating, and mining industries [17]. Their biodegradable nature ensures that they do not generate secondary pollution after use, and in many cases, spent adsorbents can be regenerated or repurposed for other environmental applications [18]. Using agricultural nutshells not only reduces reliance on commercially produced sorbents but also promotes sustainable management of agricultural biomass. Overall, the transformation of agricultural nutshell waste into low-cost adsorbents provides an environmentally friendly, economically viable, and socially beneficial solution to contemporary pollution challenges [19].

Heavy Metals

Lead (Pb(II)) is widely recognized as one of the most dangerous toxic metals found in industrial wastewater, particularly from activities such as battery production, mining, electroplating, and paint manufacturing [20]. Since it is non-biodegradable, lead persists in the environment and accumulates in living organisms, creating long-term risks for both ecological systems and human health. Even minimal exposure to Pb(II) can cause neurological issues, kidney damage, developmental and cognitive delays in children, and cardiovascular disorders [21]. Aquatic organisms are equally vulnerable; Pb(II) disrupts metabolic and reproductive processes in fish and other species, leading to severe ecological imbalances [22]. Because of its extreme toxicity, the World Health Organization (WHO) has established stringent limits for lead in drinking water, emphasizing the urgent need for its removal from polluted effluents [23].

Zinc (Zn(II)), although essential in trace quantities for biological functioning in plants, animals, and humans, becomes toxic when present at elevated levels. Industries such as galvanization, metal finishing, fertilizer production, and mining are major contributors to Zn(II) contamination in water bodies [24]. High concentrations of zinc can cause gastrointestinal distress, kidney disorders, and disruptions in metabolic pathways in humans [25]. In aquatic ecosystems, excess Zn(II) adversely affects fish and algae by inhibiting growth, altering enzyme functions, and impairing reproductive activity [26].

Though zinc toxicity occurs at slightly higher concentrations than lead, its widespread industrial application results in frequent contamination in wastewater systems.

III. SIGNIFICANCE OF THE SYSTEM

The simultaneous occurrence of Pb(II) and Zn(II) in industrial discharges calls for treatment methods that are both efficient and economically feasible. While conventional techniques such as ion exchange, chemical precipitation, and membrane filtration are effective, they tend to be expensive and often generate secondary wastes [27]. This has increased interest in low-cost biosorbents derived from agricultural waste materials, including various nutshells. Functional groups like hydroxyl, carboxyl, and phenolic structures present in lignocellulosic biomass provide strong binding affinity for Pb(II) and Zn(II), making biosorption an appealing alternative [28]. With their abundance, low processing requirements, and excellent metal-binding potential, agricultural nutshells offer a sustainable and effective approach for treating water contaminated with heavy metals.

IV. METHODOLOGY AND REVIEW

Adsorption Modeling

Adsorption modeling plays a vital role in understanding and forecasting the interactions between pollutants and solid adsorbent materials used in water and wastewater treatment. It provides theoretical insight and mathematical tools that allow scientists to quantify adsorption efficiency, decode the mechanisms involved, and fine-tune operational conditions. In the field of environmental engineering, these models become especially significant when working with low-cost sorbents such as agricultural residues, biosorbents, activated carbon, and industrial waste-derived materials. Through adsorption models, researchers can analyze experimental data more effectively, evaluate the nature of adsorbent–adsorbate interactions, and extend laboratory results to real-world treatment scenarios. Reliable modeling further supports the design of cost-effective and high-performance treatment units targeting contaminants like Pb(II), Zn(II), Cd(II), and various organic pollutants.

Broadly, adsorption modeling comprises four major categories: equilibrium isotherm models, kinetic models, thermodynamic models, and dynamic (column) models, each offering unique perspectives on the sorption phenomenon. Isotherm models interpret the equilibrium distribution of a solute between the liquid phase and the adsorbent surface, helping determine maximum uptake capacity and adsorption affinity. Kinetic models describe the rate of sorption and highlight the underlying mechanisms that control the adsorption process. Thermodynamic models provide information on the feasibility, spontaneity, and energetic changes associated with adsorption reactions. Dynamic column models, on the other hand, replicate continuous-flow conditions commonly encountered in industrial water treatment systems. Together, these modeling approaches create a comprehensive analytical foundation for examining adsorption behaviour and improving the overall efficiency of pollutant removal processes.

1. Adsorption Isotherm Models

Adsorption isotherms describe how adsorbate molecules distribute between the liquid phase and the solid phase when the adsorption process reaches equilibrium. They are represented as plots or equations relating the equilibrium concentration of adsorbate in solution (Ce) to the amount adsorbed per unit mass of adsorbent (qe). The most commonly used isotherm models are the Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich (D–R).

The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface with identical and finite binding sites. It is expressed as:

$$q_e = \frac{q_{\max} b C_e}{1 + b C_e}$$

Here qmax represents maximum adsorption capacity, and b is the equilibrium constant. This model is particularly useful for systems where chemisorption dominates and is widely applied in heavy-metal adsorption studies, including Pb(II) and Zn(II). Langmuir parameters indicate both capacity and affinity, making it essential for comparing different adsorbents.

The Freundlich isotherm is an empirical model describing multilayer adsorption on heterogeneous surfaces. It is given as:

$$q_e = K_F C_e^{1/n}$$

where K_F and n indicate adsorption capacity and surface heterogeneity, respectively. The Freundlich model is highly suitable for agricultural waste adsorbents, which typically possess irregular surfaces and varied active sites.
The Temkin isotherm considers interactions between adsorbate and adsorbent. It suggests that the heat of adsorption decreases linearly with coverage and is expressed as:

$$q_e = B \ln(AC_e)$$

Temkin parameters provide information about the binding energy distribution and electrostatic interactions.
The Dubinin–Radushkevich (D–R) model helps distinguish between physical and chemical adsorption by calculating the mean free energy of adsorption. It is often applied in systems where pore-filling is significant, especially with activated carbons and biomass-derived adsorbents.
Selection of the best-fitting model relies on statistical parameters such as R^2, RMSE, χ^2, and AIC. Nonlinear regression methods are recommended because they provide more accurate parameter estimation than linearized plotting techniques.

2. Adsorption Kinetic Models

Kinetic models explain how adsorption progresses over time and help identify the mechanisms controlling the rate of the process. Adsorption may be controlled by external mass transfer, intraparticle diffusion, surface reaction, or a combination of these steps. The most widely used kinetic models are pseudo-first-order, pseudo-second-order, intraparticle diffusion, and Elovich models.
The pseudo-first-order model assumes that the rate of adsorption is proportional to the number of unoccupied sites. Its linear form is:

$$\log(q_e - q_t) = \log(q_e) - \frac{k_1 t}{2.303}$$

Although commonly used, it often does not fit well for systems involving chemisorption or heterogeneous adsorbents.
The pseudo-second-order model, widely applied in metal ion adsorption, assumes that adsorption rate is proportional to the square of available sites. It is expressed as:

$$t/q_t = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}$$

This model typically fits Pb(II) and Zn(II) adsorption on agricultural biosorbents better than the first-order model, indicating chemisorption involvement such as ion exchange or complexation.
The intraparticle diffusion model (Weber–Morris model) helps determine whether diffusion into pores controls the adsorption. It is written as:

$$q_t = k_{id} t^{1/2} + C$$

If the plot of qt versus $t^{1/2}$ is linear and passes through the origin, intraparticle diffusion is the sole rate-limiting step. However, most adsorption systems show multi-stage diffusion, showing that both film diffusion and intraparticle diffusion contribute.
The Elovich model is used primarily for chemisorption on heterogeneous surfaces. It describes systems where the adsorption rate decreases exponentially with increasing coverage. Each kinetic model helps reveal different aspects of adsorption, and comparing them ensures accurate interpretation of experimental data.

3. Thermodynamic Modeling

Thermodynamic analysis is used to understand the feasibility, spontaneity, and heat changes associated with adsorption. Three major thermodynamic parameters include the Gibbs free energy (ΔG°), enthalpy (ΔH°), and entropy (ΔS°). These are calculated using an equilibrium constant obtained from isotherm data at different temperatures.
Gibbs free energy is calculated as:

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$$\Delta G^\circ = -RT \ln K_c$$

Negative ΔG° values indicate that the adsorption is spontaneous. The Van't Hoff equation relates temperature to adsorption constant:

$$\ln K_c = -\frac{\Delta H^\circ}{RT} + \frac{\Delta S^\circ}{R}$$

A positive ΔH° signifies endothermic adsorption, while negative values indicate exothermic behavior. Positive entropy change suggests increased randomness at the solid–liquid interface. Thermodynamic modeling is essential for understanding the energy characteristics of adsorption mechanisms.

4. Column Adsorption Models

While batch experiments provide equilibrium and kinetic information, real-world water treatment often uses fixed-bed or continuous-flow adsorption columns. Column modeling helps predict breakthrough curves, optimize bed height, and design industrial-scale treatment units.
The Thomas model assumes Langmuir kinetics and plug flow. It is widely used to predict breakthrough time and adsorption capacity in continuous systems.
The Yoon–Nelson model is simpler and predicts the time at which 50% breakthrough occurs, requiring only two parameters.
The Bohart–Adams model is used to study the initial portion of breakthrough curves and evaluate the influence of bed depth and flow rate.
These models are essential for translating laboratory adsorption data into practical engineering designs for water treatment plants.

Factors Affecting the Adsorption Process

Adsorption efficiency is governed by a combination of physical, chemical, and operational factors that collectively influence how effectively contaminants are removed from aqueous systems. Among these, solution pH is often regarded as the most influential parameter, as it alters both the surface charge of the adsorbent and the speciation of the adsorbate. For heavy metal ions, maximum uptake is typically observed under slightly acidic to neutral conditions, where electrostatic attraction between positively charged metal ions and negatively charged functional groups—such as those found on agricultural nutshell biosorbents—is strongest [29]. Extremely high or low pH values can suppress adsorption either by causing proton competition at low pH or by precipitating metal hydroxides at high pH, thereby reducing the number of available sorption sites [30].
Adsorbent dosage is another important variable. Increasing the amount of biosorbent increases the number of accessible active sites, generally improving removal efficiency [31]. However, beyond an optimum dose, additional material often leads to surface site overlapping and particle aggregation, which reduces the effective surface area and causes only marginal improvement in adsorption performance [32]. Similarly, the initial metal ion concentration affects the driving force for mass transfer: higher starting concentrations enhance diffusion toward the adsorbent surface and promote greater uptake, whereas lower concentrations may leave a substantial portion of the active surface unsaturated [33].
Contact time also has a significant influence on adsorption behavior. Most biosorbents exhibit rapid initial adsorption due to abundant available sites, followed by a slower phase governed by intraparticle diffusion as those sites become progressively occupied. The required equilibrium time varies with adsorbent characteristics, contaminant load, and particle size [34]. Temperature further affects adsorption by modifying diffusion rates and sorption energies. Physical adsorption is usually favored at lower temperatures, while chemisorption processes often show enhanced uptake at elevated temperatures due to increased activation energy and reaction rates [35].
The surface characteristics of the adsorbent—including pore structure, specific surface area, particle size, and the abundance of functional groups such as hydroxyl, carboxyl, and amino groups—play a fundamental role in adsorption efficiency [36]. Finely ground adsorbents offer higher surface areas but may present operational challenges such as filtration difficulty. Surface modification or chemical activation can significantly enhance binding affinity toward metal ions by introducing additional functional groups [37]. Furthermore, the presence of competing ions in the solution may hinder adsorption by occupying active sites or altering surface charge, especially in multi-contaminant wastewater systems [38].

Present scenario

Agricultural nutshells have emerged as one of the most promising categories of low-cost adsorbents for heavy-metal removal from water, particularly for Pb(II) and Zn(II). Every year, millions of tonnes of peanut shells, coconut shells, walnut shells, hazelnut shells, and pistachio shells are generated worldwide as agricultural residues. Instead of being discarded or burned, these lignocellulosic wastes are now recognized as valuable materials for environmental remediation due to their availability, porosity, and rich surface functional groups. According to Narloch et al. (2024), nutshells contain lignin, cellulose and hemicellulose with abundant –OH, –COOH and phenolic groups that enhance metal-binding capacity. Similarly, Chan (2022) emphasized that coconut and walnut shells possess naturally high fixed carbon content, making them suitable precursors for activated carbons used in adsorption-based treatment systems.

Recent studies have shown that both raw and modified nutshells are effective sorbents for Pb(II) due to the strong affinity of lead ions toward oxygen-containing functional groups. Wu et al. (2024) demonstrated that peanut-shell biochar modified with acidic oxygenated groups significantly enhanced Pb(II) uptake compared to untreated shells. Duan et al. (2023) reported that Ba-modified peanut biochar exhibited even higher adsorption, confirming that chemical modification improves both surface area and metal-binding functionality. For Zn(II), adsorption capacities are generally lower than Pb(II), but significant improvements occur after thermal activation or acid treatment (Moreno-Virgen, 2024). A comparative assessment by Sarker and colleagues (2023) found that coconut-shell activated carbon consistently shows higher Zn(II) and Pb(II) removal efficiency compared to other nutshell-based adsorbents due to its high microporosity.

The mechanisms governing the adsorption of Pb(II) and Zn(II) onto nutshell biomass are closely linked to ion exchange, complexation, electrostatic attraction, and physical adsorption. According to Khairul et al. (2021), modified nutshell adsorbents exhibit increased active binding sites, enabling better interaction with Pb(II), which has a greater electronegativity and a higher tendency to form surface complexes. Zn(II), although divalent, has a weaker affinity toward carboxyl groups, often resulting in slightly lower adsorption capacities. Despite these differences, both ions respond well to surface modification techniques such as phosphoric-acid activation, alkali treatment (NaOH/KOH), and thermal pyrolysis at temperatures between 350–600°C. For example, Kaliappan et al. (2022) showed that KOH-activated coconut shells achieved excellent adsorption efficiency for both metals due to increased pore volume and enhanced functionalization.

Comparative reviews widely agree that coconut-shell activated carbon performs best among nutshell-based adsorbents, especially for continuous flow applications. Research by Azeez et al. (2022) demonstrated high adsorption capacities for Pb(II) (>250 mg/g) using coconut-shell activated carbon in fixed-bed column systems. In contrast, peanut and walnut shells are more commonly used in batch experiments at laboratory scale, though modified variants of these materials have also shown promising results. Pistachio shells, for instance, have been highlighted by Sepideh et al. (2021) for their potential after minimal chemical treatment, making them suitable for community-scale treatment units. A study by Mohan and Pittman (2022) compared multiple agricultural wastes and confirmed that nutshells remain one of the most economically viable biosorbents due to low processing costs and high global availability.

Despite strong laboratory performance, the field application of nutshell-based adsorbents faces several technical challenges. A frequently cited limitation is feedstock variability: nutshell composition changes with species, age, climate and processing method. According to Singhal et al. (2023), this inconsistency can lead to fluctuating adsorption capacities, making standardization difficult. Another challenge relates to real wastewater complexity. Most studies, such as those reviewed by Wang et al. (2022), are conducted in controlled conditions with single-ion solutions, whereas industrial wastewater contains competing ions (Ca^{2+}, Mg^{2+}, Na^{+}), suspended solids, and organic matter, all of which reduce adsorption efficiency. Duan et al. (2023) identified that even well-modified peanut-shell biochar showed 20–30% reduced capacity when used in multi-metal systems.

Mechanical limitations also present obstacles. Finely powdered nutshell sorbents offer higher adsorption but are unsuitable for column applications due to clogging and high pressure drops. To overcome this, researchers such as Patel et al. (2024) have explored pelletization and composite formation using biochar and activated carbon blends. However, these value-added processes increase production costs, partially offsetting the low-cost advantage. Regeneration and reusability represent additional concerns. While acid or EDTA regeneration is effective for Pb(II), it often causes structural degradation of the biosorbent (Chan, 2022). Thermal regeneration, though feasible, is energy-intensive and may release volatilized contaminants if not properly controlled.

Environmental safety of spent adsorbents also requires attention. Lead- and zinc-loaded nutshell adsorbents must be stabilized or processed to prevent leaching. Moreno-Virgen (2024) recommended immobilization into bricks or cementitious materials as a sustainable end-of-life management strategy. Alternatively, metal recovery through acid desorption followed by precipitation could add economic value to the treatment chain, as proposed by Gupta and Babu (2023).

Current research trends are increasingly focused on improving application viability rather than simply optimizing batch performance. Pilot-scale demonstrations are gaining attention; for instance, Omar et al. (2023) implemented coconut-shell activated carbon in small-scale community water filters with promising results. Magnetic modification is another growing trend: magnetized walnut-shell biochar has been reported by Li et al. (2024) to enhance recoverability and reduce the operational cost of solid–liquid separation. Hybrid composites combining nutshell biochar with metal oxides (e.g., Fe_3O_4, MnO_2) have shown selective adsorption of Pb(II) even in the presence of competing ions.

In terms of sustainability, nutshell-derived adsorbents align well with circular-economy principles. They convert agricultural waste into valuable water-treatment materials while reducing reliance on expensive commercial activated carbon. As highlighted by OECD Environmental Outlook (2023), low-income and rural communities are increasingly adopting such biosorbents due to affordability and local availability. Furthermore, the carbon-neutrality potential of biochar production complements global climate mitigation strategies.

V. CONCLUSION AND FUTURE WORK

Despite the promising performance of bioadsorbents in laboratory studies, several challenges hinder their large-scale application. One major issue is scalability, as many plant-based and microbial bioadsorbents exhibit high adsorption capacity in controlled conditions but show reduced efficiency in real wastewater with fluctuating pH, ionic strength, and mixed contaminant [39]. Selectivity is another limitation; bioadsorbents often fail to distinguish between target and non-target ions in complex industrial effluents, leading to competitive adsorption that decreases removal efficiency [40]. Additionally, the regeneration and reuse of biosorbents remain problematic because repeated cycles of adsorption–desorption may cause structural degradation, loss of active sites, and reduced mechanical stability (Volesky, 2001). These challenges must be addressed to ensure consistent and reliable performance outside laboratory settings.

Looking ahead, the future of bioadsorption technology lies in integrating advanced modification techniques, hybrid treatment systems, and industrial-scale optimization. Chemical treatments, nano-functionalization, and surface activation can significantly enhance the selectivity and uptake capacity of natural bioadsorbents, making them more suitable for complex effluents [41]. Combining biosorption with membrane filtration, ion exchange, or phytoremediation could provide sustainable multi-step treatment systems for industrial wastewater [42]. Moreover, scaling up requires developing cost-effective processing methods, standardized production of biosorbents, and pilot-scale demonstrations to prove their economic viability. With advancements in biotechnology and material engineering, bioadsorbents have strong potential to become commercially viable, eco-friendly alternatives for industrial wastewater treatment in the future.

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