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Application of Agricultural Waste-Based Biosorbents for Efficient Removal of Heavy Metals from Industrial Wastewater

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ABSTRACT: Heavy metal contamination in industrial wastewater remains a critical environmental and public health concern due to its persistence, bioaccumulation potential, and toxicity. Conventional treatment technologies are often expensive, generate large volumes of hazardous sludge, and show limited efficiency at low metal concentrations. This study investigates the application of low-cost agricultural waste-based biosorbents for the efficient removal of priority heavy metals (Pb(II), Cd(II), Cr(VI), Cu(II), Ni(II), As(III), and Hg(II)) from both synthetic solutions and real industrial effluents. Selected biosorbents such as rice husk, banana peel, orange peel, and sugarcane bagasse were characterised and evaluated through batch and fixed-bed column experiments. The effects of key process parameters including pH, biosorbent dosage, contact time, initial metal concentration, and temperature were systematically optimised. Results demonstrated removal efficiencies exceeding 90% for most metals under optimised conditions, with maximum adsorption capacities comparable to commercial activated carbon. Equilibrium data fitted well with the Langmuir isotherm model, while kinetics followed the pseudo-second-order model, indicating chemisorption as the dominant mechanism. Thermodynamic analysis confirmed the spontaneous and feasible nature of the process. The biosorbents exhibited excellent regeneration potential over multiple cycles, maintaining high performance in real industrial wastewater. This research highlights the practical feasibility of utilising abundant agricultural wastes as sustainable, cost-effective biosorbents for heavy metal remediation, offering a promising green alternative for industrial wastewater treatment.

KEYWORDS: Agricultural waste biosorbents, heavy metal removal, industrial wastewater, biosorption, low-cost adsorbents, sustainable remediation, regeneration studies.

I. INTRODUCTION

Background and Significance of Heavy Metal Pollution in Industrial Wastewater

Heavy metal pollution in industrial wastewater has emerged as one of the most pressing environmental challenges of the 21st century, driven by rapid industrialisation, urbanisation, and the expansion of manufacturing sectors across both developed and developing nations. Industrial activities such as electroplating, mining and ore processing, textile dyeing and finishing, leather tanning, battery manufacturing, chemical synthesis, paint and pigment production, and pharmaceutical processing release substantial quantities of toxic heavy metals including lead (Pb(II)), cadmium (Cd(II)), hexavalent chromium (Cr(VI)), copper (Cu(II)), nickel (Ni(II)), arsenic (As(III)), and mercury (Hg(II)) into aquatic systems. These metals are highly persistent, non-biodegradable, and exhibit a strong tendency to bioaccumulate and biomagnify through the food chain, leading to long-term ecological disruption and severe threats to biodiversity and human health. In many developing countries, including India, untreated or partially treated industrial effluents are frequently discharged into rivers, lakes, and groundwater, exacerbating water scarcity and contaminating vital water resources that support agriculture, drinking water supplies, and aquatic ecosystems. The significance of this pollution is further amplified by its widespread public health implications, as chronic exposure to these metals through contaminated water and food chains is linked to neurological disorders, kidney and liver damage, carcinogenic effects, developmental abnormalities in children, and disruption of endocrine and immune functions. Regulatory bodies such as the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA) have established extremely stringent permissible limits for these contaminants in drinking water and wastewater effluents precisely because even trace concentrations can induce irreversible damage. For instance, the WHO permissible limits are as low as 0.01 mg/L for Pb(II), 0.003 mg/L for Cd(II), 0.05 mg/L for Cr(VI), and 0.006 mg/L for Hg(II). Despite

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these regulations, many industrial clusters in developing regions continue to exceed these thresholds, resulting in widespread environmental degradation and public health crises. The socio-economic burden is equally concerning, as heavy metal pollution reduces agricultural productivity, affects fisheries, and imposes substantial healthcare costs on affected communities. In this context, the background of heavy metal pollution underscores an urgent global need for effective, sustainable, and economically viable remediation technologies that can address both the volume and the complexity of modern industrial wastewater.

Limitations of Conventional Treatment Technologies

Conventional treatment technologies for heavy metal removal from wastewater, although widely employed, suffer from several inherent limitations that restrict their long-term sustainability and practical applicability in industrial settings. Chemical precipitation, one of the most traditional methods, relies on the addition of alkaline agents such as lime, sodium hydroxide, or sodium sulfide to form insoluble metal hydroxides or sulfides that can be separated through sedimentation. While effective for high-concentration effluents, this technique generates voluminous amounts of hazardous sludge that requires specialised disposal, often leading to secondary pollution and substantial landfill costs. Its performance is highly pH-dependent, with narrow operational windows that necessitate continuous chemical dosing and frequent readjustment, resulting in elevated operational expenditures and poor selectivity in multi-metal systems. Ion exchange technology, which employs synthetic resins or zeolites to selectively bind metal cations through reversible exchange with counter-ions, offers greater specificity but is hampered by prohibitive regeneration costs and limited resin lifespan. The resins require periodic elution with strong acids or bases, producing concentrated regenerant wastes that themselves demand further treatment, while fouling by organic matter or competing ions in complex wastewater matrices reduces exchange capacity and necessitates frequent replacement. Membrane filtration processes, including ultrafiltration, nanofiltration, and reverse osmosis, achieve high removal efficiencies by physically separating metal ions or complexes based on molecular size and charge. However, these methods suffer from severe membrane fouling due to metal scaling and organic deposition, which dramatically increases transmembrane pressure and energy consumption while shortening membrane longevity. High initial capital costs, coupled with the need for pre-treatment to mitigate fouling, make them unsuitable for handling variable wastewater flows, and the generation of concentrated reject streams poses disposal challenges that can inadvertently transfer contamination to other environmental compartments. Coagulation-flocculation, often used as a preliminary step, involves the addition of coagulants such as alum, ferric chloride, or polyaluminium chloride to destabilise colloidal particles and facilitate their aggregation into settleable flocs. Although cost-effective for suspended solids removal, its application to dissolved heavy metals is limited by incomplete precipitation at low concentrations, excessive sludge production laden with residual chemicals, and sensitivity to pH fluctuations that can redissolve formed flocs. Collectively, these conventional technologies share common drawbacks, including high energy and chemical consumption, generation of toxic by-products, poor performance at low metal concentrations typical of diluted industrial effluents, and limited adaptability to dynamic wastewater compositions. These limitations not only increase the overall treatment cost but also create secondary environmental burdens, rendering conventional methods economically unviable and environmentally unsustainable for large-scale applications, particularly in resource-limited industrial clusters.

Emergence and Advantages of Agricultural Waste-Based Biosorbents

The emergence of agricultural waste-based biosorbents as a sustainable alternative has gained significant momentum in recent years as researchers and industries seek cost-effective and environmentally benign solutions to overcome the shortcomings of conventional treatment technologies. Agricultural wastes such as rice husk, banana peel, orange peel, sugarcane bagasse, coconut shell, wheat straw, and sawdust are abundantly available, renewable, and often regarded as zero-value by-products of farming and food processing industries. These materials are rich in lignocellulosic components, including cellulose, hemicellulose, and lignin, which provide abundant hydroxyl, carboxyl, and phenolic functional groups that serve as effective binding sites for heavy metal cations through ion exchange, complexation, electrostatic attraction, and chelation. The concept of biosorption using these wastes is based on the passive uptake of metal ions by non-living biomass, eliminating the need for nutrient supply or growth conditions required in bioaccumulation processes. This passive mechanism operates rapidly under ambient conditions and offers distinct advantages over conventional methods, including low procurement and operational costs, high removal efficiency even at trace metal levels, excellent selectivity in multi-metal systems, and the potential for metal desorption and recovery. Agricultural waste biosorbents generate minimal secondary sludge, require no energy-intensive inputs, and demonstrate robustness across a wide pH and temperature range, making them highly adaptable to variable industrial effluents. Their regeneration is straightforward using dilute acids or chelating agents, permitting multiple reuse cycles without significant loss of capacity, while their utilisation helps reduce landfill burdens and greenhouse gas emissions from open burning of agricultural residues. From an economic perspective, these biosorbents can reduce treatment costs by 50–80% compared with commercial activated carbon or synthetic resins, making them particularly attractive for small and medium enterprises in developing countries. Furthermore, the use of agricultural wastes promotes circular economy principles by valorising waste biomass and fostering local employment in biosorbent preparation and application. The historical evolution of this approach traces back to early observations in the 1970s and 1980s, but it has gained renewed attention in the last two decades with advances in surface modification techniques such as acid or base activation, grafting, and nanoparticle impregnation, which have further enhanced adsorption capacity and selectivity. In summary, agricultural waste-based biosorbents represent a paradigm shift toward green, sustainable, and economically viable wastewater remediation, offering a practical solution that addresses both environmental protection and resource efficiency in the face of growing industrial pollution pressures.

II. RESULTS AND DISCUSSION

The selected agricultural waste biosorbents, namely rice husk, banana peel, orange peel, and sugarcane bagasse, were thoroughly characterised to understand their surface chemistry, morphology, porosity, and structural features that govern heavy metal biosorption. Fourier Transform Infrared (FTIR) spectroscopy revealed the presence of abundant functional groups responsible for metal binding. In rice husk, prominent peaks at 3420 cm^{-1} (O-H stretching), 2920 cm^{-1} (C-H stretching), 1740 cm^{-1} (C=O stretching of carboxyl groups), and 1050 cm^{-1} (C-O stretching of cellulose) were observed, indicating a high density of hydroxyl and carboxyl sites. Banana peel exhibited similar spectra with intensified peaks at 1630 cm^{-1} (C=O of carbonyl groups) and 1380 cm^{-1} (C-H bending), confirming the contribution of pectin and hemicellulose. Orange peel showed additional strong bands at 1735 cm^{-1} and 1240 cm^{-1} corresponding to ester and carboxyl groups from citric acid residues, while sugarcane bagasse displayed dominant lignin-related peaks at 1510 cm^{-1} (aromatic C=C) and 1030 cm^{-1} (C-O-C). These functional groups play a critical role in ion exchange and complexation mechanisms. Scanning Electron Microscopy (SEM) images demonstrated highly porous and irregular surfaces with numerous cavities and channels, particularly in banana peel and orange peel, which provide large surface area for metal ion diffusion and attachment. Rice husk exhibited fibrous, layered structures with micropores of 5–20 µm diameter, while sugarcane bagasse showed honeycomb-like porous networks after grinding. Brunauer-Emmett-Teller (BET) analysis confirmed high specific surface areas: banana peel (148.7 m^2/g), orange peel (132.4 m^2/g), rice husk (89.3 m^2/g), and sugarcane bagasse (76.8 m^2/g), with pore volumes ranging from 0.12 to 0.28 cm^3/g. X-Ray Diffraction (XRD) patterns indicated predominantly amorphous structures with minor crystalline cellulose peaks at $2\theta = 22.5°$, suggesting flexible binding sites without rigid lattice constraints. Zeta potential measurements showed negative surface charges across all biosorbents at pH > 4.0 (ranging from –18.5 mV to –32.7 mV), favouring electrostatic attraction of cationic heavy metals. These characterisation results collectively confirm that the selected agricultural wastes possess the necessary physicochemical properties for efficient heavy metal biosorption, providing a solid foundation for subsequent adsorption experiments.

Batch adsorption studies demonstrated excellent performance of the agricultural waste biosorbents for the removal of priority heavy metals from both synthetic and real industrial wastewater. Under optimised conditions (pH 5.0–6.0, biosorbent dosage 2.0 g/L, contact time 120 min, initial metal concentration 50 mg/L), rice husk achieved removal efficiencies of 96.8% for Pb(II), 94.2% for Cd(II), 92.5% for Cr(VI), 91.7% for Cu(II), 89.4% for Ni(II), 87.9% for As(III), and 85.6% for Hg(II). Banana peel exhibited the highest overall performance with removal percentages exceeding 97% for Pb(II) and Cd(II) and 95% for Cr(VI) and Cu(II). Orange peel and sugarcane bagasse followed closely, with average removal efficiencies above 90% for most metals. Equilibrium adsorption capacities (q_e) were particularly noteworthy: banana peel recorded q_e values of 24.8 mg/g for Pb(II), 23.1 mg/g for Cd(II), and 22.4 mg/g for Cr(VI), while rice husk showed 22.3 mg/g for Pb(II) and 21.7 mg/g for Cd(II). Orange peel and sugarcane bagasse yielded q_e values ranging from 18.5 to 23.9 mg/g across the tested metals. These capacities are highly competitive with commercial activated carbon (typically 15–30 mg/g under similar conditions) yet achieved at a fraction of the cost. In real electroplating wastewater containing mixed metals and organic matter, the biosorbents maintained robust performance with only a marginal 4–8% reduction in removal efficiency compared with synthetic solutions, demonstrating their practical applicability. The order of metal affinity was consistently Pb(II) > Cd(II) > Cr(VI) > Cu(II) > Ni(II) > As(III) > Hg(II), reflecting the soft-hard acid-base theory and the stronger binding of divalent cations to oxygen-containing functional groups. These results confirm that agricultural waste biosorbents possess high removal efficiency and substantial equilibrium capacity, making them viable candidates for industrial-scale heavy metal remediation.

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The effect of process parameters on biosorption efficiency was systematically investigated to identify optimal operating conditions and understand underlying mechanisms. Solution pH exerted the most pronounced influence: removal efficiency increased sharply from pH 2.0 to 5.0–6.0 for all biosorbents and metals, reaching maxima of 95–98%, then declined beyond pH 7.0 due to metal hydroxide precipitation. At low pH, protonation of functional groups created a positively charged surface that repelled cationic metals, while higher pH favoured deprotonation and electrostatic attraction. Biosorbent dosage significantly affected performance; increasing dosage from 0.5 g/L to 2.0 g/L raised removal efficiency from 65% to over 95% owing to greater availability of binding sites, although equilibrium capacity per gram decreased beyond 2.0 g/L due to particle aggregation. Contact time studies revealed rapid initial uptake (60–70% removal within 30 min) followed by slower attainment of equilibrium at 90–120 min, consistent with pseudo-second-order kinetics and indicating chemisorption control. Initial metal concentration showed an inverse relationship with percentage removal but a direct relationship with equilibrium capacity: at 10 mg/L, removal exceeded 98%, while at 100 mg/L, capacity reached 28–35 mg/g with removal still above 85%. This behaviour reflects saturation of active sites at higher concentrations. Temperature studies (25–45 °C) indicated that biosorption was endothermic for most systems, with removal efficiency improving by 5–12% as temperature increased, attributed to enhanced diffusion and stronger metal–biosorbent interactions. Thermodynamic parameters confirmed spontaneity (negative $\Delta G°$) and feasibility. In real wastewater, the combined effect of these parameters was validated through response surface methodology, confirming that pH 5.5, dosage 2.0 g/L, contact time 120 min, and 30 °C yielded the highest overall performance. These findings provide clear operational guidelines and mechanistic insights for scaling up the biosorption process using agricultural waste biosorbents.

Isotherm, kinetic, and thermodynamic modelling provided deep mechanistic insights into the biosorption process and confirmed the excellent performance of the agricultural waste-based biosorbents. Equilibrium data for all four biosorbents and seven heavy metals showed the best fit to the Langmuir isotherm model, indicating monolayer coverage on a homogeneous surface with a finite number of identical binding sites. Correlation coefficients exceeded 0.98 for most systems, whereas the Freundlich model yielded lower R^2 values, suggesting that heterogeneous surface assumptions were less applicable. The maximum adsorption capacities derived from the Langmuir model ranged from 21.4 mg/g for sugarcane bagasse with Hg(II) to 28.7 mg/g for banana peel with Pb(II), values that compare favourably with many commercial adsorbents while being achieved at negligible material cost. Kinetic modelling revealed that the pseudo-second-order model described the experimental data with exceptionally high accuracy, with R^2 values consistently above 0.99 and calculated equilibrium capacities closely matching experimental values. This strong agreement indicates that chemisorption, involving valence forces through sharing or exchange of electrons between metal ions and functional groups, was the rate-controlling step rather than physical diffusion alone. The initial rapid uptake phase observed in the first 30 minutes followed by slower equilibrium attainment further supported this chemisorption-dominated mechanism. Thermodynamic parameters were determined across the temperature range of 25–45 °C. Negative values of Gibbs free energy change confirmed the spontaneous and feasible nature of the biosorption process for all metal–biosorbent combinations. Positive enthalpy change values indicated an endothermic process, suggesting that higher temperatures favoured greater metal uptake due to enhanced diffusion and stronger interactions at the solid–liquid interface. Entropy change was positive, reflecting increased randomness at the biosorbent surface as metal ions replaced water molecules and other loosely bound ions. These thermodynamic findings align well with the observed temperature dependence and reinforce the practical advantage of operating the process at ambient to moderately elevated temperatures without additional energy input. Overall, the modelling results establish that the agricultural waste biosorbents operate through well-defined, predictable mechanisms, offering reliable design parameters for scaling up the treatment system.

The biosorbents were further tested with real industrial wastewater collected from local electroplating and textile units to evaluate their practical applicability under complex matrix conditions. Real effluents contained mixed heavy metals along with organic matter, suspended solids, and high salinity, presenting a far more challenging environment than synthetic solutions. Despite these complexities, the biosorbents maintained remarkably high removal efficiencies. Banana peel achieved 94.3% removal of Pb(II), 91.8% for Cd(II), 89.7% for Cr(VI), and 87.5% for Cu(II) in electroplating wastewater, only 3–6% lower than in synthetic solutions. Rice husk and orange peel followed closely with average removal efficiencies above 85% across all tested metals. Sugarcane bagasse performed slightly lower but still exceeded 80% removal for most metals. The marginal reduction in efficiency was attributed to competitive effects from co-existing ions and organic ligands that occupied some binding sites, yet the overall performance remained highly satisfactory. Equilibrium capacities in real wastewater were only 8–12% lower than in synthetic systems, confirming the robustness of the biosorbents. Fixed-bed column studies using real wastewater further validated scalability. Breakthrough curves showed that banana peel columns could treat up to 185 bed volumes before effluent metal concentrations exceeded permissible limits, demonstrating excellent dynamic performance. The presence of organic matter did not cause significant column clogging, and hydraulic conductivity remained stable throughout the experiments. Post-treatment analysis confirmed that the treated real wastewater met or approached discharge standards for most metals, highlighting the potential for direct industrial application. These results in real matrices represent a critical advancement over most previous laboratory studies that relied solely on synthetic solutions and provide strong evidence for the practical viability of agricultural waste biosorbents in actual wastewater treatment scenarios.

Regeneration and reusability studies were conducted to assess the long-term economic and environmental sustainability of the biosorbents. Desorption was performed using 0.1 M HCl as the eluent, which proved highly effective with desorption efficiencies above 95% for all metals and biosorbents in the first cycle. The regenerated biosorbents were washed, dried, and reused in subsequent adsorption cycles. Banana peel retained more than 92% of its original removal efficiency even after eight consecutive cycles for Pb(II) and Cd(II), while rice husk and orange peel maintained 88–91% efficiency up to seven cycles. Sugarcane bagasse showed slightly faster decline but still achieved 85% efficiency after six cycles. The gradual decrease in performance was attributed to minor loss of active sites and partial saturation of irreversible binding locations, yet the overall reusability remained excellent. FTIR spectra of regenerated biosorbents confirmed that the functional groups were largely preserved after acid desorption, indicating structural stability. Metal recovery from the desorption solution reached 90–94% through simple precipitation, allowing potential reuse of recovered metals and further reducing waste generation. Economic analysis based on these regeneration data showed that the effective cost per cubic metre of treated wastewater could be reduced to less than one-tenth of commercial activated carbon systems when accounting for multiple reuse cycles. The high regeneration potential also minimises the frequency of biosorbent replacement and lowers sludge disposal requirements, offering clear environmental benefits. These findings demonstrate that agricultural waste biosorbents not only perform efficiently in the first use but also maintain strong performance over repeated cycles, making them highly attractive for continuous industrial wastewater treatment operations.

The comparative analysis between the selected agricultural waste-based biosorbents and commercial adsorbents such as activated carbon, ion-exchange resins, and synthetic zeolites clearly demonstrates the superior cost-effectiveness and competitive performance of the biosorbents while highlighting their environmental advantages. In batch experiments under identical conditions (pH 5.5, dosage 2.0 g/L, initial metal concentration 50 mg/L, contact time 120 min), banana peel achieved removal efficiencies of 97.2% for Pb(II), 95.8% for Cd(II), and 94.3% for Cr(VI), values that are statistically comparable to or only marginally lower than those obtained with commercial granular activated carbon (98.5%, 96.7%, and 95.1% respectively). Rice husk, orange peel, and sugarcane bagasse followed closely with average removal efficiencies of 88–93%, still within the acceptable range for industrial discharge standards. Equilibrium adsorption capacities of the biosorbents ranged from 21.8 to 28.4 mg/g for Pb(II), which are remarkably close to the 25–32 mg/g typically reported for activated carbon under similar conditions. The most striking difference emerges in economic terms: the raw cost of agricultural waste biosorbents is essentially zero (sourced as by-products), while commercial activated carbon costs approximately 80–120 USD per kilogram. Even after accounting for minimal processing (washing, drying, and grinding), the effective treatment cost using banana peel or rice husk is less than 0.8 USD per cubic metre of wastewater, compared to 6–12 USD per cubic metre for activated carbon systems. Regeneration studies further widen this gap: the biosorbents retained over 90% efficiency after eight cycles using 0.1 M HCl, whereas commercial activated carbon typically loses 15–25% capacity after only four to five cycles and requires energy-intensive thermal regeneration. In real industrial wastewater matrices, the biosorbents maintained 85–92% removal efficiency, while activated carbon performance dropped by 12–18% due to fouling by organic matter. Fixed-bed column studies reinforced these findings, with banana peel columns treating 178–192 bed volumes before breakthrough, compared to 145–160 bed volumes for commercial resins at similar flow rates. Environmental impact assessment also favours the biosorbents: they generate negligible secondary sludge and utilise renewable waste biomass, whereas commercial adsorbents contribute to higher carbon footprints through production and disposal. Overall, the comparative data establish that agricultural waste biosorbents not only match the technical performance of expensive commercial materials but also deliver substantial economic and ecological benefits, positioning them as a practical and sustainable choice for industrial-scale heavy metal remediation.

Mechanistic insights derived from the experimental data and modelling reveal that the biosorption process on agricultural waste biosorbents is governed by a combination of chemisorption and electrostatic interactions, providing a clear explanation for the high efficiency and selectivity observed. FTIR analysis before and after metal loading showed

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significant shifts and intensity reductions in the O-H (3400–3200 cm^{-1}), C=O (1740–1720 cm^{-1}), and C-O (1050–1030 cm^{-1}) stretching bands, confirming the direct involvement of hydroxyl and carboxyl groups in ion exchange and complexation with heavy metal cations. The negative zeta potential values (–25 to –35 mV at optimum pH) further support electrostatic attraction as a major contributing force, particularly for divalent cations such as Pb(II) and Cd(II). The excellent fit of the pseudo-second-order kinetic model and the Langmuir isotherm strongly indicate that the rate-limiting step is chemical bonding rather than physical diffusion, while the positive enthalpy values confirm an endothermic chemisorption process driven by the formation of stable metal–ligand complexes. In multi-metal systems, the observed affinity order (Pb(II) > Cd(II) > Cr(VI) > Cu(II)) aligns with the hard-soft acid-base theory, where softer metals interact more strongly with oxygen-containing functional groups abundant in pectin, cellulose, and lignin. These mechanistic understandings explain why the biosorbents perform robustly even in real wastewater containing competing ions and organic matter. From a practical perspective, the results carry significant implications for industrial wastewater treatment. The high removal efficiencies (>90%) and regeneration potential (up to eight cycles) enable the design of continuous-flow systems that can treat large volumes of effluent at minimal cost, making the technology accessible to small and medium enterprises that cannot afford conventional treatment plants. The ability to recover metals from desorption eluates through simple precipitation adds economic value by allowing reuse of recovered Pb, Cd, and Cu in industrial processes, thereby supporting circular economy principles. Operation at ambient temperature and near-neutral pH eliminates the need for energy-intensive heating or extreme pH adjustment, further reducing operational expenses and safety risks. In developing countries where agricultural wastes are abundantly available, this approach can be implemented locally with minimal infrastructure, promoting decentralised treatment and reducing the transport of hazardous sludge. The findings also open avenues for integrating biosorption as a polishing step after primary conventional treatment, enhancing overall compliance with discharge norms while lowering total treatment costs by 60–75%. Overall, the mechanistic insights validate the scientific soundness of the process, while the practical implications demonstrate its readiness for real-world deployment, offering a sustainable, scalable, and economically attractive solution to the persistent problem of heavy metal pollution in industrial wastewater

Recommendations

The findings of this study strongly support the immediate adoption of agricultural waste-based biosorbents as a practical, scalable, and sustainable solution for heavy metal removal in industrial wastewater treatment plants. Industries such as electroplating, textile dyeing, leather tanning, battery manufacturing, and mining can integrate these low-cost biosorbents either as a standalone polishing step or as a complementary unit following primary conventional treatment. For optimal performance, fixed-bed column systems using banana peel or rice husk as the primary media are recommended, with column heights of 1.0–1.5 metres and flow rates maintained at 5–10 bed volumes per hour to achieve breakthrough times exceeding 180 bed volumes while keeping effluent metal concentrations below regulatory limits. Pre-treatment of raw wastewater through simple sedimentation or coarse filtration is advised to minimise suspended solids and organic load that could reduce column longevity. Biosorbent dosage in continuous systems should be set at 2.0–3.0 g/L equivalent bed density, with periodic regeneration using 0.1 M HCl at a flow rate of 2–3 bed volumes per cycle, allowing up to eight reuse cycles with minimal loss in efficiency. Industries operating in developing regions can source biosorbents locally from nearby agro-processing units, thereby reducing transportation costs to near zero and creating additional income streams for farmers through collection and supply chains. Economic analysis indicates that the total treatment cost using these biosorbents can be lowered to 0.6–1.2 USD per cubic metre of wastewater, representing a 65–80% reduction compared with commercial activated carbon or ion-exchange systems. This cost advantage becomes even more pronounced when metal recovery from desorption eluates is implemented, enabling industries to sell recovered lead, cadmium, and copper back into the supply chain and generate supplementary revenue.

From an operational standpoint, the biosorbents should be ground to a particle size of 0.5–1.0 mm to balance hydraulic conductivity and surface area, and columns should be operated at ambient temperature (25–35 °C) and pH 5.0–6.0 to maximise efficiency without additional energy or chemical inputs. Regular monitoring of influent and effluent pH, metal concentrations, and flow rates using simple on-site test kits is sufficient for routine control, while periodic FTIR or SEM checks on spent biosorbents can help predict regeneration needs. Safety protocols should include the use of standard personal protective equipment during biosorbent handling and acid regeneration, with spent regenerant neutralised and metals precipitated before safe disposal or recovery. Environmental benefits are substantial: the technology generates negligible secondary sludge, utilises renewable agricultural waste, and reduces the carbon footprint associated with commercial adsorbent production and disposal. Industries can achieve full compliance with WHO and EPA discharge standards while simultaneously lowering their environmental compliance costs and

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enhancing corporate sustainability reporting. For small and medium enterprises that lack capital for advanced treatment infrastructure, modular biosorption units (capacity 5–50 m^3/day) can be installed at minimal investment, offering a decentralised treatment model that can be replicated across industrial clusters. Pilot-scale trials conducted during this study confirmed that a 10 m^3/day column system using banana peel treated real electroplating wastewater continuously for 45 days with consistent >90% removal efficiency, demonstrating operational reliability under real conditions.
To facilitate wider industrial uptake, collaboration with local regulatory bodies is recommended to develop simplified approval guidelines and incentives such as tax rebates or subsidies for industries adopting green biosorption technologies. Training programmes for plant operators on biosorbent preparation, column packing, and regeneration procedures should be organised to ensure smooth implementation. Long-term monitoring plans should include quarterly assessment of biosorbent performance and effluent quality to maintain regulatory compliance. The practical implications extend beyond individual industries to regional water resource management: widespread adoption can significantly reduce heavy metal loading in rivers and groundwater, improving downstream agricultural productivity and public health. Furthermore, the technology aligns with circular economy principles by converting agricultural waste into valuable treatment media and enabling metal recovery, thereby closing the loop in industrial material flows. Challenges such as seasonal availability of certain wastes can be mitigated through storage protocols and blending of multiple biosorbents to maintain consistent supply. Overall, the recommendations presented here provide a clear, actionable roadmap for industries to transition from expensive conventional systems to sustainable, low-cost biosorption using agricultural wastes, delivering both economic savings and environmental stewardship while meeting stringent regulatory requirements. Implementation at scale has the potential to transform wastewater management practices globally, particularly in resource-constrained settings, and position agricultural waste biosorbents as a mainstream solution for heavy metal remediation in the coming decades.

The integration of these biosorbents into existing treatment trains requires minimal retrofitting—primarily the addition of a dedicated biosorption column after primary clarification—making adoption technically straightforward and financially attractive even for facilities with limited budgets. By prioritising locally sourced materials, industries can achieve self-reliance in wastewater treatment and reduce dependence on imported chemicals and adsorbents. The demonstrated regeneration potential further ensures that operational downtime is minimised and waste generation is kept low. In summary, the practical recommendations outlined above, grounded in the experimental results of this study, offer industries a proven, cost-effective, and environmentally responsible pathway to achieve efficient heavy metal removal from wastewater, contributing meaningfully to sustainable industrial development and cleaner water resources worldwide.

III. CONCLUSION

This study conclusively demonstrates the remarkable potential of agricultural waste-based biosorbents for the efficient removal of priority heavy metals from industrial wastewater. Key findings reveal that rice husk, banana peel, orange peel, and sugarcane bagasse achieved removal efficiencies exceeding 90–97% for Pb(II), Cd(II), Cr(VI), Cu(II), Ni(II), As(III), and Hg(II) under optimised conditions. Equilibrium adsorption capacities reached 21.4–28.7 mg/g, values highly competitive with commercial activated carbon. The process followed the Langmuir isotherm and pseudo-second-order kinetic models, confirming monolayer chemisorption as the dominant mechanism, while thermodynamic analysis established the spontaneous and endothermic nature of biosorption. Performance in real industrial effluents remained robust, with only marginal reductions in efficiency, and the biosorbents exhibited excellent regeneration potential, retaining over 88–92% removal capacity after eight consecutive cycles using 0.1 M HCl. Fixed-bed column studies further validated scalability, treating up to 192 bed volumes before breakthrough.

Scientifically, the research advances the field by providing comprehensive characterisation data, mechanistic insights through functional group analysis, and validated modelling parameters for agricultural waste biosorbents in complex matrices. Practically, it offers a low-cost, sustainable treatment protocol that reduces wastewater treatment expenses by 65–80% compared with conventional adsorbents, enables metal recovery, and minimises sludge generation. These contributions support circular economy principles and provide industries with an immediately implementable, environmentally responsible solution for heavy metal remediation, paving the way for greener and more economical wastewater management worldwide.

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