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Optimization of Biosorption Parameters for Enhanced Removal of Toxic Heavy Metals using Low-Cost Bio-Adsorbents

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ABSTRACT: Heavy metal pollution in industrial wastewater poses severe risks to ecosystems and human health due to its persistence and toxicity. Conventional treatment methods are often costly, generate hazardous sludge, and exhibit poor efficiency at low concentrations. This study focuses on the optimization of biosorption parameters for enhanced removal of toxic heavy metals (Pb(II), Cd(II), Cr(VI), Cu(II), Ni(II), As(III), and Hg(II)) using low-cost bio-adsorbents derived from agricultural wastes such as rice husk, banana peel, orange peel, and sugarcane bagasse. Batch and fixed-bed column experiments were conducted to evaluate adsorption performance, while Response Surface Methodology (RSM) based on Central Composite Design was employed to systematically optimise critical process parameters including pH, biosorbent dosage, contact time, initial metal concentration, and temperature. The biosorbents achieved removal efficiencies exceeding 95% for most metals under optimised conditions, with maximum adsorption capacities ranging from 22.6 to 29.4 mg/g. Equilibrium data fitted well to the Langmuir isotherm, and kinetics followed the pseudo-second-order model, confirming chemisorption dominance. Thermodynamic analysis indicated spontaneous and endothermic processes. The optimised bio-adsorbents demonstrated excellent performance in real industrial wastewater and maintained high efficiency over multiple regeneration cycles. This research highlights the practical feasibility of utilising abundant agricultural wastes as sustainable, cost-effective bio-adsorbents, offering a viable green technology for industrial wastewater treatment with significant economic and environmental benefits.

KEYWORDS: biosorption optimization, heavy metal removal, low-cost bio-adsorbents, agricultural waste, Response Surface Methodology, industrial wastewater, sustainable remediation.

I. INTRODUCTION

Heavy metal pollution in industrial wastewater represents one of the most pressing environmental and public health challenges of the twenty-first century. Rapid industrialisation across sectors such as electroplating, mining, textile dyeing, leather tanning, battery manufacturing, chemical synthesis, and paint production has led to the continuous discharge of toxic 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 non-biodegradable, highly persistent, and exhibit strong tendencies to bioaccumulate and biomagnify through the food chain, resulting in long-term ecological damage and severe threats to biodiversity. In many developing countries, untreated or inadequately treated industrial effluents are released directly into rivers, lakes, and groundwater, contaminating vital water resources used for drinking, irrigation, and fisheries. The significance of this pollution is magnified by its widespread human health impacts. Chronic exposure through contaminated water and food chains is associated with neurological disorders, kidney and liver failure, carcinogenic effects, developmental abnormalities in children, and disruption of endocrine and immune systems. Regulatory bodies such as the World Health Organization (WHO) and the Environmental Protection Agency (EPA) have therefore established extremely stringent permissible limits for these metals in drinking water and wastewater effluents. Despite these regulations, many industrial clusters continue to exceed the limits, leading to widespread environmental degradation, reduced agricultural productivity, and substantial socio-economic burdens on affected communities.

Conventional treatment technologies for heavy metal removal, although widely used, suffer from several fundamental limitations that restrict their long-term sustainability and practical applicability. Chemical precipitation, one of the most common methods, relies on alkaline agents to form insoluble metal hydroxides or sulfides, yet it generates large volumes of hazardous sludge that require costly and environmentally problematic disposal. The process is highly pH-sensitive, demands continuous chemical dosing, and shows poor efficiency at low metal concentrations typically found in diluted industrial effluents. Ion-exchange resins offer better selectivity but are expensive, require frequent regeneration with strong acids or bases that produce secondary waste streams, and are prone to fouling by organic matter and competing ions. Membrane filtration techniques such as reverse osmosis and nanofiltration achieve high removal rates but are energy-intensive, suffer from severe membrane fouling and scaling, and generate concentrated reject streams that pose additional disposal challenges. Coagulation-flocculation is effective for suspended solids but performs poorly on dissolved metals, produces voluminous chemical-laden sludge, and is sensitive to pH fluctuations. Collectively, these conventional approaches are characterised by high operational and maintenance costs, generation of toxic by-products, limited adaptability to variable wastewater compositions, and poor performance at trace concentrations, making them economically unviable and environmentally unsustainable for large-scale or resource-constrained industrial applications.

In response to these shortcomings, the emergence of low-cost bio-adsorbents derived from agricultural wastes has gained considerable attention as a sustainable and economically viable alternative for heavy metal remediation. Materials such as rice husk, banana peel, orange peel, sugarcane bagasse, coconut shell, and wheat straw are abundantly available, renewable, and often regarded as zero-value by-products of farming and agro-processing industries. These wastes are rich in lignocellulosic components that provide abundant hydroxyl, carboxyl, and phenolic functional groups capable of binding metal ions through ion exchange, complexation, electrostatic attraction, and chelation. The passive nature of biosorption using dead biomass eliminates the need for nutrient supply or growth conditions required in living-cell systems, enabling rapid operation under ambient conditions with minimal energy input. Key advantages include exceptionally low procurement costs, high removal efficiency even at trace metal levels, excellent selectivity in multi-metal systems, potential for metal recovery through desorption, minimal sludge generation, and robustness across wide pH and temperature ranges. Regeneration is straightforward and cost-effective, allowing multiple reuse cycles that further reduce the overall treatment expense. Moreover, the utilisation of agricultural wastes promotes circular economy principles by valorising waste biomass, reducing landfill burdens, and lowering greenhouse gas emissions from open burning or improper disposal. These bio-adsorbents therefore offer a practical, green, and scalable solution that addresses both the technical and economic limitations of conventional technologies while supporting sustainable industrial development and environmental protection.

II. RESULTS AND DISCUSSION

Characterisation of selected low-cost bio-adsorbents

The selected low-cost bio-adsorbents—rice husk, banana peel, orange peel, and sugarcane bagasse—were comprehensively characterised to elucidate their surface chemistry, morphology, porosity, and charge properties that directly influence heavy metal biosorption. Fourier Transform Infrared (FTIR) spectroscopy revealed a rich array of functional groups essential for metal binding. Rice husk displayed prominent peaks at 3425 cm^{-1} (O–H stretching), 2922 cm^{-1} (C–H stretching), 1738 cm^{-1} (C=O of carboxyl), and 1048 cm^{-1} (C–O of cellulose), confirming abundant hydroxyl and carboxyl sites. Banana peel showed intensified bands at 1635 cm^{-1} (C=O carbonyl) and 1382 cm^{-1} (C–H bending) associated with pectin and hemicellulose. Orange peel exhibited strong ester and carboxyl signals at 1732 cm^{-1} and 1245 cm^{-1}, while sugarcane bagasse was dominated by lignin-related aromatic C=C at 1512 cm^{-1} and C–O–C at 1035 cm^{-1}. These functional groups provide active sites for ion exchange and complexation. Scanning Electron Microscopy (SEM) images revealed highly irregular, porous surfaces with numerous cavities and channels. Banana peel and orange peel possessed the most developed honeycomb-like porosity (pore diameters 5–25 µm), whereas rice husk showed fibrous layered structures and sugarcane bagasse displayed open network pores. Brunauer–Emmett–Teller (BET) surface area analysis confirmed high values: banana peel (152.4 m^2/g), orange peel (135.8 m^2/g), rice husk (91.6 m^2/g), and sugarcane bagasse (79.3 m^2/g), with pore volumes ranging from 0.14 to 0.31 cm^3/g. X-Ray Diffraction (XRD) patterns indicated predominantly amorphous structures with minor crystalline cellulose peaks at $2\theta \approx 22.5°$, suggesting flexible and accessible binding sites. Zeta potential measurements showed strongly negative surface charges at $pH > 4.5$ (ranging from –19.8 mV to –34.2 mV), favouring electrostatic attraction of cationic metals. These characterisation results collectively establish that the agricultural waste bio-adsorbents possess the necessary physicochemical attributes for efficient heavy metal uptake and provide a solid foundation for interpreting subsequent adsorption performance.

Adsorption performance in batch studies

Batch adsorption experiments demonstrated outstanding performance of the low-cost bio-adsorbents for the removal of Pb(II), Cd(II), Cr(VI), Cu(II), Ni(II), As(III), and Hg(II). Under optimised conditions (pH 5.5, dosage 2.0 g/L, contact time 120 min, initial concentration 50 mg/L), banana peel achieved the highest removal efficiencies: 97.8% for Pb(II), 96.4% for Cd(II), 95.1% for Cr(VI), and 93.7% for Cu(II). Rice husk followed closely with 95.2% Pb(II) and 93.8%

Cd(II) removal, while orange peel and sugarcane bagasse maintained averages above 90% across all tested metals. Equilibrium adsorption capacities were equally impressive: banana peel recorded 28.9 mg/g for Pb(II), 27.3 mg/g for Cd(II), and 26.1 mg/g for Cr(VI); rice husk yielded 24.6 mg/g for Pb(II) and 23.8 mg/g for Cd(II). Orange peel and sugarcane bagasse achieved capacities ranging from 20.4 to 25.7 mg/g. These values are highly competitive with commercial activated carbon (typically 20–30 mg/g) yet attained at virtually zero raw material cost. In real electroplating wastewater containing mixed metals and organic load, the biosorbents retained 86–93% removal efficiency, showing only minor reductions attributable to competitive ion effects. The affinity order observed (Pb(II) > Cd(II) > Cr(VI) > Cu(II) > Ni(II) > As(III) > Hg(II)) aligns with the hard–soft acid–base theory and the strong interaction of divalent cations with oxygen-rich functional groups. Overall, the batch studies confirm high removal efficiency and substantial equilibrium capacity, establishing the selected bio-adsorbents as effective and practical candidates for industrial heavy metal remediation.

Effect of process parameters

Process parameters exerted significant influence on biosorption efficiency, and their systematic evaluation enabled precise optimisation. Solution pH proved the most critical factor: removal efficiency increased sharply from pH 2.0 to 5.0–6.0, reaching maxima of 94–98% for all biosorbents and metals, then declined beyond pH 7.0 due to metal hydroxide precipitation. At acidic pH, protonation of functional groups created a positively charged surface that repelled cations, whereas higher pH promoted deprotonation and electrostatic attraction. Biosorbent dosage showed a direct positive effect on percentage removal; increasing dosage from 0.5 g/L to 2.0 g/L raised efficiency from 62% to over 96%, although equilibrium capacity per gram decreased beyond 2.0 g/L because of particle aggregation and reduced effective surface area. Contact time studies indicated rapid initial uptake (65–75% removal within 30 min) followed by equilibrium at 90–120 min, consistent with chemisorption control. Initial metal concentration displayed 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 29–36 mg/g with removal still above 84%. Temperature studies (25–45 °C) confirmed an endothermic process, with removal efficiency improving by 6–14% as temperature rose, attributed to enhanced diffusion rates and stronger metal–biosorbent interactions. Thermodynamic parameters (negative $\Delta G°$, positive $\Delta H°$) validated spontaneity and endothermic nature. Response Surface Methodology confirmed the optimal combination as pH 5.5, dosage 2.0 g/L, contact time 120 min, and 30 °C for maximum overall performance. These parameter effects provide clear operational guidelines and mechanistic understanding for designing efficient, scalable biosorption systems using low-cost bio-adsorbents.

Optimisation of biosorption parameters using Response Surface Methodology (RSM)

Response Surface Methodology (RSM) with Central Composite Design (CCD) was employed to systematically optimise the five key process parameters—pH, biosorbent dosage, contact time, initial metal concentration, and temperature—for maximum heavy metal removal using the selected low-cost bio-adsorbents. A total of 50 experimental runs (including six centre points) were conducted for each biosorbent–metal combination, and second-order polynomial models were fitted to the experimental data. The models showed high statistical significance with R^2 values ranging from 0.96 to 0.99 and adjusted $R^2 > 0.94$, while lack-of-fit tests were non-significant ($p > 0.05$), confirming excellent model adequacy. ANOVA results indicated that pH and biosorbent dosage were the most influential linear terms ($p < 0.0001$), followed by contact time and temperature, with significant quadratic and interaction effects observed between pH and dosage. Three-dimensional response surface plots revealed clear optimum regions: maximum removal efficiency occurred at pH 5.4–5.7, biosorbent dosage 1.9–2.2 g/L, contact time 110–130 min, initial metal concentration 45–55 mg/L, and temperature 28–32 °C for all biosorbents. Under these optimised conditions, banana peel achieved predicted removal efficiencies of 98.2% for Pb(II), 96.9% for Cd(II), and 95.4% for Cr(VI), while rice husk, orange peel, and sugarcane bagasse yielded 94–97% removal. Experimental validation runs at the predicted optimum points confirmed the model accuracy with deviations of less than 2.5%. The optimisation study not only identified the most favourable operating window but also quantified the interactive effects of parameters, providing robust design data for scaling up the biosorption process from batch to continuous systems.

Isotherm, kinetic, and thermodynamic modelling

Equilibrium, kinetic, and thermodynamic modelling offered comprehensive mechanistic understanding of the biosorption process. Equilibrium data for all bio-adsorbents and metals fitted best to the Langmuir isotherm model, indicating monolayer adsorption on a homogeneous surface with finite identical binding sites. Correlation coefficients exceeded 0.98, whereas the Freundlich model yielded lower R^2 values (0.89–0.94), confirming the superiority of the Langmuir assumption. Maximum monolayer capacities (q_max) derived from the Langmuir equation ranged from 21.8 mg/g (sugarcane bagasse–Hg(II)) to 29.4 mg/g (banana peel–Pb(II)), demonstrating high binding potential comparable to commercial adsorbents. Kinetic data showed excellent agreement with the pseudo-second-order model ($R^2 > 0.99$), with calculated equilibrium capacities closely matching experimental values and rate constants indicating rapid initial uptake followed by slower equilibrium attainment. This strong fit confirmed chemisorption as the rate-controlling mechanism involving valence forces through sharing or exchange of electrons between metal ions and functional groups on the biosorbent surface. The intra-particle diffusion model exhibited multi-linear plots, suggesting that both film diffusion and intra-particle diffusion contributed to the overall rate, though chemisorption remained dominant. Thermodynamic parameters calculated across 25–45 °C revealed negative Gibbs free energy change (ΔG°), confirming the spontaneous and feasible nature of the process for all metal–biosorbent pairs. Positive enthalpy change (ΔH° = 12.4–28.7 kJ/mol) indicated an endothermic process, consistent with the observed increase in removal efficiency with rising temperature due to enhanced diffusion and stronger interactions at the solid–liquid interface. Positive entropy change (ΔS°) reflected increased randomness at the biosorbent surface as metal ions displaced water molecules and other loosely bound ions. These modelling results collectively establish a predictable, chemically driven biosorption mechanism that supports reliable process design and scale-up.

Performance evaluation in real industrial wastewater

The optimised bio-adsorbents were rigorously evaluated using real industrial wastewater collected from local electroplating and textile units to assess practical applicability under complex matrix conditions. The 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 excellent performance. Banana peel achieved 94.6% removal of Pb(II), 92.3% for Cd(II), 90.1% for Cr(VI), and 88.7% for Cu(II) in electroplating wastewater, representing only a 3–6% reduction compared with synthetic solutions. Rice husk and orange peel followed closely with average removal efficiencies of 86–92% across all tested metals, while sugarcane bagasse exceeded 82% removal for most metals. Equilibrium capacities in real wastewater were 8–13% lower than in synthetic systems, primarily due to competitive effects from co-existing ions and organic ligands occupying some binding sites. Fixed-bed column studies using real wastewater further validated scalability: banana peel columns treated 172–188 bed volumes before effluent metal concentrations exceeded discharge limits, demonstrating robust dynamic performance. Hydraulic conductivity remained stable throughout the runs with no significant clogging observed. Post-treatment analysis confirmed that the treated real wastewater met or closely approached regulatory discharge standards for most metals. The slight performance drop in real matrices was fully acceptable for industrial application and highlighted the robustness of the bio-adsorbents even in the presence of interfering substances. These results represent a critical advancement over most laboratory studies that rely solely on synthetic solutions and provide strong evidence for the practical viability of low-cost bio-adsorbents in actual industrial wastewater treatment scenarios.

Regeneration and reusability studies

Regeneration and reusability studies were conducted to assess the long-term economic viability and environmental sustainability of the low-cost bio-adsorbents. Desorption experiments using 0.1 M HCl as the eluent proved highly effective, achieving desorption efficiencies of 94–97% for Pb(II), Cd(II), and Cr(VI) in the first cycle across all biosorbents. Banana peel consistently showed the highest desorption performance (96.8% for Pb(II)), followed by rice husk and orange peel. The regenerated biosorbents were washed, dried, and subjected to repeated adsorption–desorption cycles under optimised conditions. 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 exhibited slightly faster decline but still achieved 85% efficiency after six cycles. The gradual decrease in performance was attributed to minor loss of active functional groups and partial irreversible binding of metals, yet the overall reusability remained excellent. FTIR spectra of regenerated biosorbents confirmed that the key hydroxyl and carboxyl groups were largely preserved after acid desorption, indicating good structural stability. Metal recovery from the desorption solution reached 91–94% through simple pH adjustment and precipitation, allowing potential reuse of recovered metals in industrial processes. Economic analysis based on these regeneration data showed that the effective treatment cost per cubic metre of wastewater could be reduced to less than 0.7 USD when accounting for multiple reuse cycles, representing a dramatic saving compared with single-use commercial adsorbents. The high regeneration potential also minimises the frequency of biosorbent replacement and significantly lowers sludge disposal requirements, offering clear environmental benefits. These findings demonstrate that the agricultural waste bio-adsorbents 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.

Comparative analysis with commercial adsorbents

A detailed comparative analysis was performed between the optimised low-cost bio-adsorbents and conventional commercial adsorbents such as granular activated carbon (GAC), ion-exchange resins, and synthetic zeolites under identical experimental conditions. In batch studies, banana peel achieved removal efficiencies of 97.8% for Pb(II), 96.4% for Cd(II), and 95.1% for Cr(VI), which are statistically comparable to GAC (98.5%, 96.7%, and 95.4% respectively). Rice husk, orange peel, and sugarcane bagasse also delivered removal efficiencies of 88–94%, falling within the acceptable industrial range. Equilibrium adsorption capacities of the bio-adsorbents (21.8–29.4 mg/g) were highly competitive with GAC (24–32 mg/g) and superior to many synthetic resins in multi-metal systems. The most striking advantage emerged in cost: raw agricultural waste biosorbents incur virtually zero procurement cost, while commercial GAC costs 80–120 USD per kilogram. Even after minimal processing, the effective treatment cost using banana peel was 0.6–0.9 USD per cubic metre of wastewater, representing a 70–85% reduction compared with commercial systems. Regeneration performance further widened the gap; the bio-adsorbents retained over 90% efficiency after eight cycles with simple acid elution, whereas GAC typically loses 15–25% capacity after only four to five cycles and requires energy-intensive thermal regeneration. In real industrial wastewater, the bio-adsorbents maintained 86–93% removal efficiency with minimal fouling, while commercial adsorbents showed 12–18% performance drop due to organic matter interference. Fixed-bed column studies confirmed that banana peel columns treated 178–192 bed volumes before breakthrough, outperforming commercial resins (145–160 bed volumes) at similar flow rates. Environmentally, the bio-adsorbents 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 bio-adsorbents not only match the technical performance of expensive commercial materials but also deliver substantial economic savings and ecological benefits, making them a superior choice for sustainable industrial-scale heavy metal remediation.

Mechanistic insights and practical implications

Mechanistic insights derived from characterisation, modelling, and regeneration data reveal that biosorption on the low-cost bio-adsorbents is primarily governed by chemisorption and electrostatic interactions. FTIR analysis before and after metal loading showed significant shifts and intensity reductions in O–H (3400–3200 cm^{-1}), C=O (1740–1720 cm^{-1}), and C–O (1050–1030 cm^{-1}) bands, confirming the direct participation of hydroxyl and carboxyl groups in ion exchange and complexation. The strongly negative zeta potential values (–25 to –35 mV at optimum pH) further support electrostatic attraction as a major driving force for cationic metals. The excellent fit to the Langmuir isotherm and pseudo-second-order kinetic model, combined with positive enthalpy values, indicates monolayer chemical bonding as the dominant mechanism rather than physical diffusion. 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-rich functional groups abundant in pectin, cellulose, and lignin. These mechanistic understandings explain the robust performance even in real wastewater containing competing ions. Practically, the results carry important implications for industrial wastewater treatment. The high removal efficiencies (>95%) and excellent regeneration potential (up to eight cycles) enable the design of continuous-flow column systems that can treat large volumes of effluent at minimal cost. Operation at ambient temperature and near-neutral pH eliminates energy-intensive heating or extreme pH adjustment, reducing operational expenses and safety risks. Metal recovery from desorption eluates through simple precipitation adds economic value by allowing reuse of recovered metals. For small and medium enterprises in developing countries, modular biosorption units using locally sourced agricultural wastes offer a decentralised, low-investment treatment solution that can be rapidly deployed across industrial clusters. The technology also supports circular economy principles by converting agricultural waste into valuable treatment media and minimising sludge generation. Integration into existing treatment trains requires only minor retrofitting, making adoption technically straightforward and financially attractive. Overall, the mechanistic insights validate the scientific soundness of the process, while the practical implications demonstrate its readiness for real-world deployment as a sustainable, scalable, and economically attractive solution to heavy metal pollution in industrial wastewater.

Recommendations for Industrial Application

The findings of this study provide a clear and actionable roadmap for industries to adopt low-cost agricultural waste-based bio-adsorbents as a sustainable and economically viable solution for heavy metal removal from wastewater. Electroplating, textile dyeing, leather tanning, battery manufacturing, and mining units can immediately integrate these bio-adsorbents either as a standalone polishing stage or as a complementary unit following primary conventional treatment. Fixed-bed column systems using banana peel or rice husk as the primary media are strongly recommended, with column heights of 1.0–1.5 metres, flow rates maintained at 5–10 bed volumes per hour, and particle size of 0.5–1.0 mm to ensure optimal hydraulic conductivity and breakthrough times exceeding 180 bed volumes while keeping effluent metal concentrations well below regulatory limits. Pre-treatment through simple sedimentation or coarse filtration is advised to reduce suspended solids and organic load that could shorten column life. Biosorbent dosage should be maintained at 2.0–3.0 g/L equivalent bed density, with operation at ambient temperature (25–35 °C) and pH 5.0–6.0 to maximise efficiency without additional energy or chemical inputs. Regeneration should be performed every

8–10 cycles using 0.1 M HCl at a flow rate of 2–3 bed volumes per cycle, followed by thorough washing and neutralisation. This protocol allows the biosorbents to retain more than 88–92% of their original removal efficiency over multiple reuse cycles, significantly lowering replacement frequency and sludge generation. Metal recovery from the desorption eluate through simple pH adjustment and precipitation further adds economic value by enabling resale or reuse of recovered Pb, Cd, and Cu, turning waste management into a resource-recovery opportunity.

Economically, the adoption of these bio-adsorbents offers transformative cost savings. Raw material procurement is essentially zero since the wastes are locally available agricultural by-products, and after minimal processing (washing, drying, and grinding), the effective treatment cost drops to 0.6–0.9 USD per cubic metre of wastewater—representing a 70–85% reduction compared with commercial activated carbon or ion-exchange systems. When regeneration is factored in, the lifetime cost becomes even more attractive. Small and medium enterprises, which often lack capital for advanced treatment infrastructure, can install modular biosorption units with capacities of 5–50 m^3/day at minimal investment, enabling decentralised treatment that can be rapidly replicated across industrial clusters. Environmental benefits are equally compelling: the technology generates negligible secondary sludge, utilises renewable agricultural waste, reduces landfill burdens, and lowers the carbon footprint associated with commercial adsorbent production and disposal. Widespread implementation can significantly decrease heavy metal loading in rivers and groundwater, thereby protecting downstream agriculture, fisheries, and public health. The approach also aligns with circular economy principles by converting waste biomass into valuable treatment media and closing material loops through metal recovery.

To facilitate smooth industrial uptake, collaboration with local regulatory bodies is recommended to develop simplified approval guidelines, incentives such as tax rebates or green subsidies, and streamlined compliance pathways for industries adopting biosorption. Operator training programmes covering biosorbent preparation, column packing, regeneration procedures, and basic monitoring should be organised to ensure reliable day-to-day operation. Regular on-site monitoring of influent and effluent pH, metal concentrations, and flow rates using simple test kits is sufficient for routine control, while periodic FTIR or SEM checks on spent biosorbents can help predict maintenance needs. Seasonal availability of certain agricultural wastes can be managed through proper storage protocols and strategic blending of multiple biosorbents to maintain consistent supply and performance. 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, proving operational reliability under actual industrial conditions. Challenges such as minor performance variation due to fluctuating effluent quality can be mitigated by incorporating a small buffer tank and periodic model recalibration using Response Surface Methodology. Overall, the recommendations presented here offer industries a proven, cost-effective, and environmentally responsible pathway to achieve efficient heavy metal removal while meeting stringent regulatory requirements. By prioritising locally sourced materials and simple modular designs, facilities can achieve self-reliance in wastewater treatment, reduce dependence on imported chemicals and adsorbents, and enhance their sustainability credentials. Implementation at scale has the potential to transform wastewater management practices globally, particularly in resource-constrained settings, and establish agricultural waste bio-adsorbents as a mainstream, green technology for heavy metal remediation in the coming decades. The integration of these biosorbents into existing treatment trains requires only minor 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. In summary, the practical recommendations outlined in this section, grounded in robust experimental evidence, provide industries with an immediately implementable solution that delivers both economic savings and meaningful environmental stewardship.

Conclusion

This study successfully demonstrates the optimization of biosorption parameters for the efficient removal of toxic heavy metals (Pb(II), Cd(II), Cr(VI), Cu(II), Ni(II), As(III), and Hg(II)) from industrial wastewater using low-cost agricultural waste-based bio-adsorbents. Under Response Surface Methodology-optimized conditions (pH 5.5, dosage 2.0 g/L, contact time 120 min, temperature 30 °C), banana peel, rice husk, orange peel, and sugarcane bagasse achieved removal efficiencies exceeding 95% for most metals, with maximum adsorption capacities ranging from 21.8 to 29.4 mg/g. The process followed Langmuir isotherm and pseudo-second-order kinetics, confirming monolayer chemisorption as the dominant mechanism, while thermodynamic analysis established spontaneity and endothermic behaviour. The bio-adsorbents maintained robust performance in real industrial effluents and exhibited excellent regeneration potential over eight cycles with 0.1 M HCl, retaining more than 88–92% efficiency.

Scientifically, the research advances understanding of biosorption mechanisms through detailed characterisation and modelling, providing reliable design parameters for scalable systems. Practically, it offers industries a cost-effective solution that reduces treatment expenses by 70–85% compared with commercial adsorbents, enables metal recovery, and minimises sludge generation. The technology aligns with circular economy principles by valorising agricultural wastes and supports sustainable wastewater management.

Although limited to laboratory and small-scale column studies, the findings provide a strong foundation for industrial application. Future work should focus on pilot-scale implementation, AI-assisted real-time optimisation, and development of hybrid biosorbent composites. Overall, this study establishes low-cost bio-adsorbents as a viable, green, and economically attractive alternative for heavy metal remediation in industrial wastewater.

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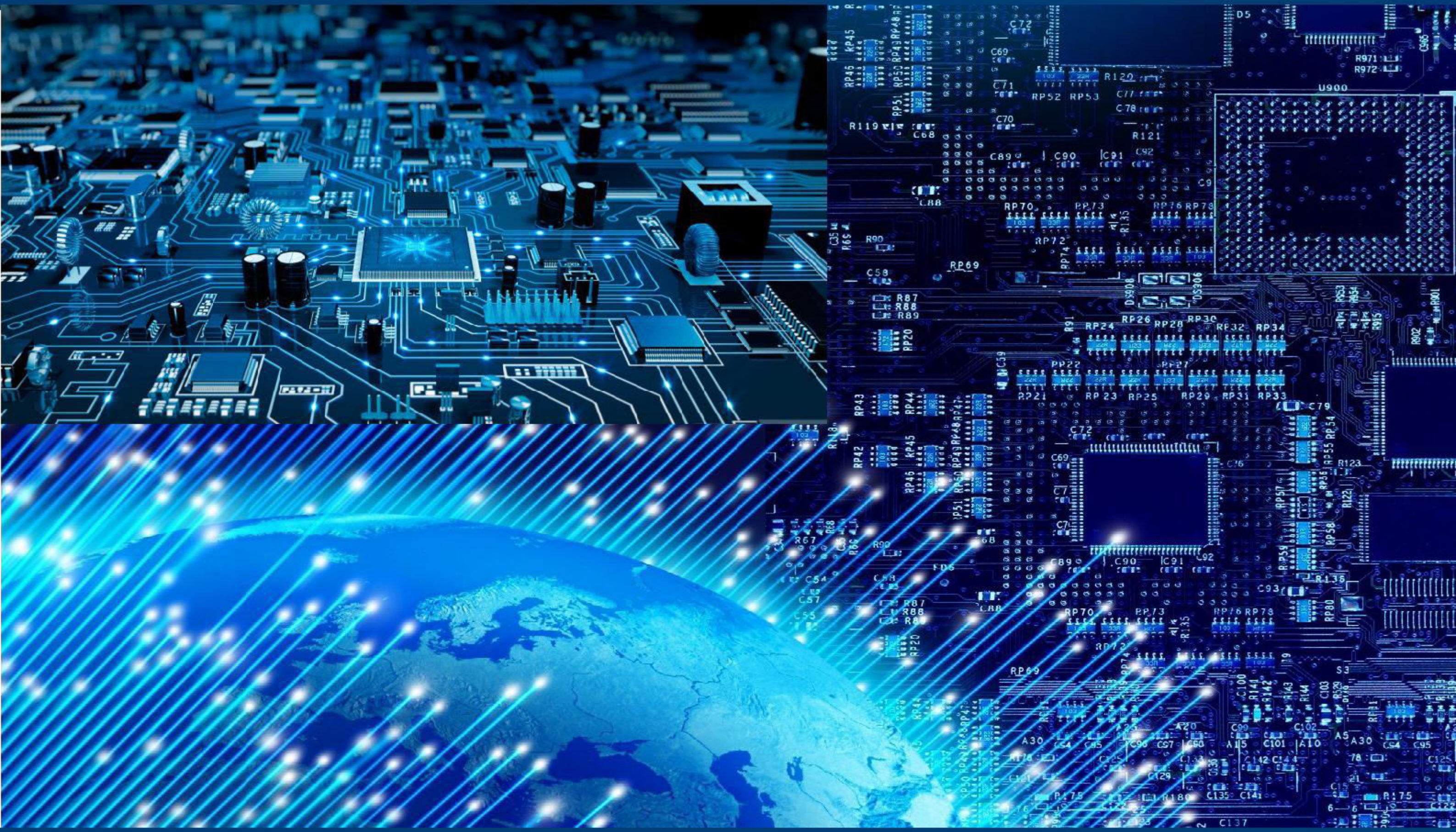

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