Conservation of Agricultural Waste into Functional Carbon Materials for Sustainable Water Purification

Prof. Ashutosh Tripathi

Department of Chemistry
K S Saket PG College, Ayodhya

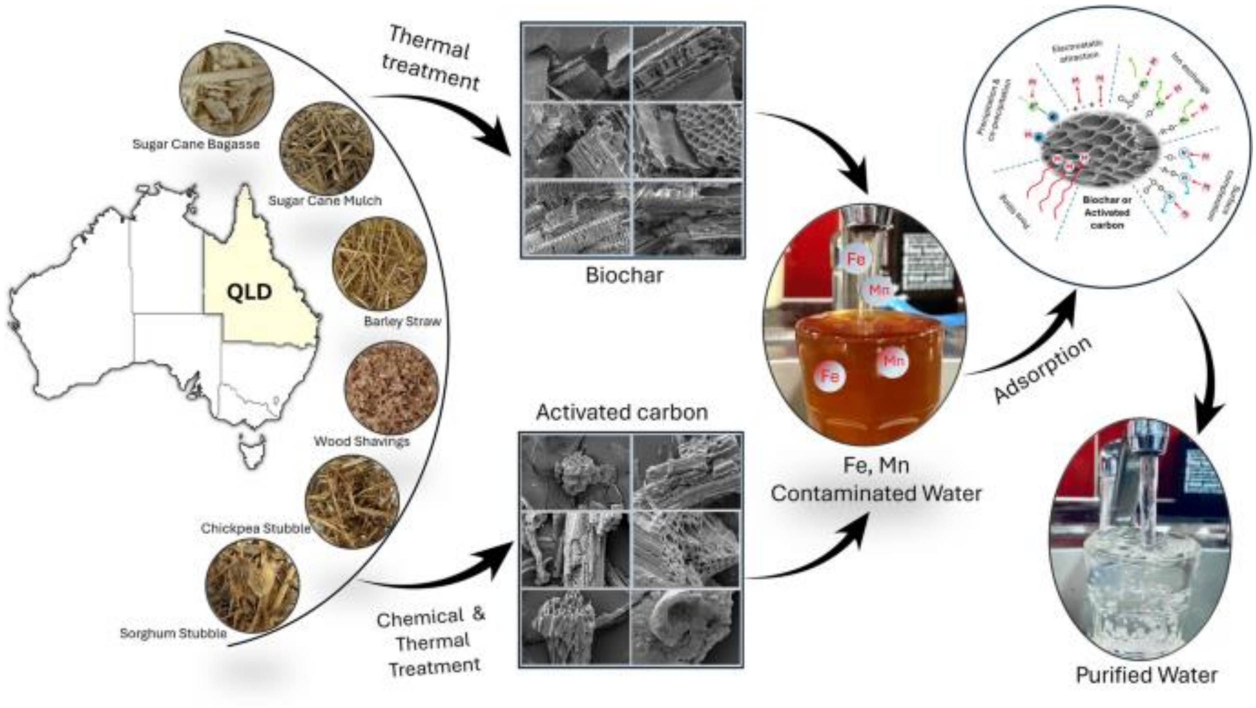
Abstract:
Converting agricultural waste into functional carbon materials offers a low-cost, eco-friendly solution for sustainable water purification and pollutant removal. [1] Conversion Process-Pretreatment: Biomass residues (such as corn cobs, husks, and shells) undergo cleaning and drying.Pyrolysis: The dried waste is heated at high temperatures (400°C–850°C) in an oxygen-free environment to carbonize the material.Activation: Physical or chemical activation (using agents like KOH or acids) increases the surface area and develops a porous structure.
Water Purification ApplicationsHeavy Metal Removal: Effectively captures toxic ions such as lead, cadmium, iron, and manganese.Nutrient and Microplastic Capture: Traps dissolved ammonia and micro/nanoplastics from contaminated water.Dye Eradication: Adsorbs hazardous organic dyes discharged from textile and industrial wastewater. [1]

Keywords: conservation, agriculture waste, sustainable, water purification, functional

Introduction

Iron (Fe) and manganese (Mn) are common drinking water contaminants, posing health risks and causing aesthetic issues. Conventional treatments are effective, but often too costly or impractical for remote areas. This study tested six biochars (BC) and six phosphoric acid-activated carbons (AC), from agricultural residues, as low-cost adsorbents for Fe and Mn removal in regional Queensland drinking water conditions. Batch adsorption experiments were conducted using 10 mg/L Fe and 10 mg/L Mn, with results interpreted through isotherm and kinetic modelling. Activated carbons demonstrated superior performance, with Fe removal efficiencies of 85–99% and Mn removal efficiencies of 85–98%. Maximum adsorption capacities (q_m) reached 8.01 mg/g for Fe and 4.67 mg/g for Mn. Adsorption followed Langmuir isotherms (R^2 up to 0.9954 for Fe and 0.9169 for Mn). Kinetic modelling showed that Fe adsorption followed a pseudo-second order (PSO) mechanism, whereas Mn adsorption adhered to pseudo-first order (PFO) kinetics. Biochar exhibited more variable performance, with Fe removal ranging from 48 to 99% and Mn removal from 31 to 97%, alongside lower q_m values (1.24–3.25 mg/g for Fe and 0.27–2.85 mg/g for Mn). Langmuir R^2 values for BCs ranged from 0.7182 to 0.9541 for Fe and 0.1998 to 0.8624 for Mn. Overall, ACs are recommended for centralised treatment systems due to their high performance, while biochar offer a promising, low-cost, and sustainable alternative for decentralised and rural applications. These findings highlight the potential of developing of waste-derived adsorbents as field-ready solutions to improve drinking water quality in underserved communities.[1,2,3]
Maintenance considerations such as clogging, biofouling, and exhaustion of sorption sites require regular monitoring and operational design (e.g., backwashing or layered media replacement) [93]. Scaling from

bench to field requires evaluation of performance alongside cost, reusability, system compatibility, and maintenance needs. A partnership with South Burnett Regional Council has been initiated to pilot-test these materials in real waters, where challenges such as variable chemistry, fouling, and regeneration must be addressed.



Discussion

Rapid population growth, urbanization, industrialization, and poor wastewater treatments are increasing heavy metal pollution and worsening global water scarcity. These problems posing serious threat to environmental sustainability, food safety, and human health. Globally, about 359 billion cubic meters of wastewater are generated annually, yet nearly 80% is discharged into ecosystems without proper treatment, lead to the accumulation of toxic metals in ecosystems and the food chain. Prolonged exposure to these metals can cause severe neurological, cardiovascular, and carcinogenic disorders. Although conventional wastewater treatment technologies are effective, but their large-scale application remains constrained by operational costs, energy demand, chemical consumption, complex processes, secondary pollution, and hazardous sludge generation. These limitations highlight the urgent need for sustainable, low-cost, and eco-friendly remediation approaches, particularly in resource-limited regions of world. This review critically examines the agro-waste derived bioadsorbents as green, sustainable, regenerable and cost-effective alternative for wastewater treatment within the framework of waste valorization and circular economy. Unlike previous studies that mainly focused on removal efficiency only, this review provide a comprehensive evaluation of agro-waste based biosorbent, including their preparation, characterization techniques, adsorption mechanisms, isotherm and kinetic models, influencing factors, and comparative assessment with conventional and emerging wastewater treatment technologies. A critical synthesis of studies published between 2001 and 2025 reported that raw biosorbents achieved 60–90% contaminant removal efficiency, whereas chemically modified and thermally activated biosorbent showed significantly higher removal efficiency of 90–97% and up to 99%, respectively. These findings confirm the strong practical potential of agro-waste-derived bioadsorbents for large-scale wastewater treatment. [4,5,6] The novelty of this review lies in its holistic perspective of their scientific performance along with sustainability, feasibility, and environmental benefits in line with waste-to-wealth paradigm and sustainable development goals (SDGs). Overall, agro-waste based bioadsorbent offer a promising and greener solution for wastewater treatment that can reduce environmental footprint and support global water security. Therefore, future research should be focused on hybrid treatment system, improved biosorbent modification, standardized testing protocols, techno-economic assessment and pilot-scale validation to support real-world implementation.

Chemical precipitation, particularly hydroxide and sulfide precipitation, is effective for treating wastewaters with high metal concentrations; however, it requires substantial reagent input, is highly pH-sensitive, and generates large volumes of metal laden sludge that may pose toxicity and disposal challenges (Kurniawan et al., 2006; Anotai et al., 2007; Al-Hemaidi and Elsheikh, 2012; Park et al., 2014). Ion exchange processes provide high selectivity and regenerability for a wide range of metal ions but are limited by high resin costs, fouling, sensitivity to competing ions, and reduced efficiency in complex effluents, which restrict their large-scale application (Daṃbrowski et al., 2004; Razzak et al., 2022). Coagulation–flocculation and flotation are effective for destabilizing and separating metal-bearing particulates; however, their applicability is often compromised by excessive sludge generation, chemical consumption, and reduced performance in dilute metal streams (Samrani et al., 2008; Duan et al., 2010; Tang et al., 2016). Enhanced ultrafiltration processes, including polymer-enhanced ultrafiltration (PEUF) and micellar-enhanced ultrafiltration (MEUF), significantly improve metal rejection but rely heavily on polymer or surfactant selection and are highly susceptible to fouling (Rahmati et al., 2019; Vidu et al., 2020). Nanofiltration and reverse osmosis systems achieve removal efficiencies often exceeding 95% for divalent and multivalent ions; however, their widespread adoption is limited by high operating pressures, substantial energy requirements, membrane fouling, and long-term material degradation (Fu and Wang, 2011; Qasem et al., 2021).[7,8,9]

Electrodialysis enables selective ion separation through applied electric fields, yet challenges related to membrane fouling, maintenance demands, and energy consumption constrain its practical implementation (Xiang et al., 2022). Electrochemical technologies including electrocoagulation, electroflotation, electro-oxidation, and electro-winning have gained attention for their ability to remove and recover metals without the addition of chemical reagents (Qasem et al., 2021; Liu et al., 2023). High removal efficiencies have been reported for metals such as Cd, Cu, Ni, and Pb (Michalak et al., 2014)nevertheless, these methods face challenges related to electrode passivation, energy consumption, sludge or by-product formation, and operational complexity, which limit their long-term economic viability and scalability (Fu and Wang, 2011; Liu et al., 2016).

Despite their effectiveness, conventional technologies have several limitations that restrict their sustainable large-scale application. Many chemical-based processes require precise operational control, involve hazardous reagents, and generate substantial quantities of secondary sludge, leading to increased treatment and disposal costs (Anotai et al., 2007; Tang et al., 2016). Membrane and polymer-assisted systems are highly sensitive to operating conditions and material selection, with fouling, frequent cleaning, and elevated energy consumption significantly increasing operational expenses (Fu and Wang, 2011; Malik et al., 2017; Qasem et al., 2021). Similarly, electrochemical methods demand strict process control and continuous energy input, further limiting their economic and environmental feasibility. These methods have some drawbacks or limitations such as limited specificity for particular metal concentrations, excessive generation of toxic sludge, high energy consumption, and substantial capital investment requirements

Results

Non-conventional treatment technologies have emerged as a sustainable, eco-friendly and greener approach for the removal of heavy metals from wastewater. This approach utilizes the renewable, low-cost, sustainable and economic accessible agricultural waste based biosorbent that bind metal ions through surface functional groups and reducing metal mobility and toxicity (Wang and Chen, 2009; Kanamarlapudi et al., 2018). Compared to conventional treatment technology, biosorption using agricultural waste biomass provide one of the most promising environmental friendly approaches due to their abundance, renewability, low cost, and strong metal-binding affinity, minimal sludge generation, no requirement for additional nutrients, that promote waste minimization through a “treating waste by waste” strategy, thereby reducing environmental footprint (Huang et al., 2017).[10,11,12]

A wide range of agro-waste such as rice husk (Hegazi, 2013; Shi et al., 2019; Zafar et al., 2020), wheat bran (Basu et al., 2017; Kumar et al., 2017), sugarcane bagasse (Ezeonuegbu et al., 2021; Yogeshwaran and Priya, 2021), sawdust, peanut shell (Liu et al., 2010; Banerjee et al., 2019), coir pith (Parab and Inbaraj, 2006; Namasivayam and Sangeetha, 2006), lentil husk (Kumar et al., 2017), pine cone (Amar et al., 2021), pine needles (Gulati et al., 2018), onion peel (Molaudzi and Ambushe, 2022), and biochar, have been extensively investigated and successfully applied in wastewater treatment

Real industrial wastewaters present complex conditions that challenge the performance of agro-waste-derived biosorbents (Kamsonlian et al., 2012a,b). Competing cations like Ca2, Mg2, and Na+ occupy binding sites and screen negatively charged functional groups, reduces the electrostatic attraction that draws heavy metals to the biosorbent (Park et al., 2010). Dissolved organic matter, including humic acids and surfactants, further complicates treatment by blocking pores and forming soluble complexes with metal ions, which alters their chemical form and prevents adsorption (Chen et al., 2018). These effects become more problematic in multi-metal waste stream. For example, in electroplating wastewater containing Cu^{2+}, Ni^{2+}, and Zn^{2+}, biosorbents selectively follows the order $Cu^{2+} > Zn^{2+} > Ni^{2+}$, because Cu^{2+} smaller hydrated radius and higher electronegativity allow it to outcompete the others for functional groups (Ahmad et al., 2019). Similarly, in tannery wastewater containing a mixture of Cr^{6+}, Pb^{2+}, and Cd^{2+} along with high salinity and organic load, individual metal removal has been reported to decrease by 15–25% compared to single-metal systems, due to combined ionic competition and organic interference (Garg et al., 2017). Beyond competitive effects, fouling from organic and inorganic constituents can mask active sites and impose mass transfer limitations over repeated cycles, while regeneration through chemical desorption often leads to gradual capacity loss due to irreversible binding, structural degradation, or functional group depletion (Vijayaraghavan and Balasubramanian, 2015). Therefore, realizing the full potential of these materials requires rigorous testing under realistic conditions and targeted strategies to enhance selectivity, mitigate fouling, and enhance long-term regenerability.[13,14,15]

Similarly, the initial metal ion concentration provides the primary driving force for mass transfer, with higher concentrations enhance adsorption rates up to the point at which biosorbent sites become fully occupied, due to increased concentration gradients, however beyond this removal efficiency declines despite increased adsorption capacity per gram due to saturation effects (Ozer and Ozer, 2003; Taha et al., 2011; Okafor et al., 2012). Temperature influences both adsorption kinetics and thermodynamics processes. Moderate temperature increases generally enhance metal uptake by improving diffusion rates and active site accessibility, whereas excessive temperatures may induce desorption, disrupt biosorbent structure, or reduce binding stability (Argun and Dursun, 2008; Kumar et al., 2012). For endothermic adsorption processes, uptake capacity may increase with temperature due to enhanced interaction between metal ions and active sites. In contrast, exothermic adsorption may show decreased capacity at elevated temperatures, as higher thermal energy weakens sorbate-sorbent interactions and can promote partial desorption (Khaskheli et al., 2011; Ezeonuegbu et al., 2021).

Particle size and surface area further affect biosorption efficiency; smaller particles generally enhance uptake due to high surface area though more accessible binding sites and reduced diffusion path length (Nguyen et al., 2013). However, excessively fine particles may cause pore blockage, hinder solid–liquid separation, or increase pressure drop in column systems. Finally, agitation speed enhances biosorption by reducing boundary layer resistance and improving contact between metal ions and biosorbent surfaces, thereby enhancing external mass transfer. However, insufficient mixing or excessively high agitation rates may promote attrition of biomass particles and structural damage, or reduce sorption efficiency, particularly in mechanically fragile agricultural residues (Marín et al., 2010; Lim et al., 2014). Overall, effective biosorption requires careful optimization of these interdependent factors, as their combined effects determines adsorption capacity, equilibrium behavior, kinetic performance, and the practical applicability of biosorption processes for heavy metal remediation.[16,17,18]

Conclusion

Heavy metal contamination remains a major global threat to water quality, ecosystem, biodiversity, and human health due to its persistence and accumulation in soil, water and food chains. The growing demand for sustainable water treatment has rapidly increased interest in green and low-cost technologies. This review explores the agro-waste-derived bioadsorbents as sustainable, low-cost, and eco-friendly solution for wastewater treatment, particularly in resource-limited regions. Converting agro-waste into bioadsorbents support waste-to-wealth approach, circular economy principle, and contributes to the United Nations Sustainable Development Goals (SDGs), especially SDG 3 (Good Health and Wellbeing) and SDG 6 (Clean Water and Sanitation).

The performance of biosorption is depend on multiple adsorption mechanisms and physicochemical factors. Chemical and thermal modifications significantly improve the adsorption capacity, stability, and overall treatment efficiency. A synthesis of published studies showed that raw biosorbent achieved contaminant removal efficiencies of 60–90%, whereas chemically modified and thermally activated biosorbent showed significantly higher removal efficiency of 90–97% and up to 99%, respectively. These findings confirm the strong potential of biosorption as an effective and environmentally sustainable wastewater treatment technology.[19]

Despite these advances, several challenges still limit large-scale application, this review identified the critical gap between laboratory research and industrial implementation and outlines a roadmap for future research. To bridge this gap, future research should focus on improving biosorbent regeneration, reuse, and safe disposal to reduce operational costs and prevent secondary pollution. The application of techno-economic analysis (TEA) and life cycle assessment (LCA) is also essential to evaluate cost, energy demand, and environmental impact compared with conventional treatment methods. Moreover, integrating biosorbents with hybrid treatment systems such as membrane filtration, advanced oxidation, and biological treatment can further improve the removal of complex industrial pollutants. Overall, biosorption offer a practical, sustainable and greener pathway for cleaner water, minimizing environmental footprint, and long-term water security.[20]

REFERENCES:

1 Abdel HalimA.El-EzabyK. H.ElgammalM. (2019). Removal of Fe2+ and Pb2+ ions from wastewater using rice husks-based adsorbents. J. Egyptian Acad. Soc. Environ. Dev. D Environ. Stud.20, 47–60. doi: 10.21608/jades.2019.67694

2 AbdelfattahI.IsmailA. A.Al SayedF.AlmedolabA.AboelghaitK. (2016). Biosorption of heavy metals ions in real industrial wastewater using peanut husk as efficient and cost effective adsorbent. Environ. Nanotechnol. Monit. Manag.6, 176–183. doi: 10.1016/j.enmm.2016.10.007

3 AbdullahN.YusofN.LauW. J.JaafarJ.IsmailA. F. (2019). Recent trends of heavy metal removal from water/wastewater by membrane technologies. J. Ind. Eng. Chem.76, 17–38. doi: 10.1016/j.jiec.2019.03.029

4 AdenugaA. A.AmosO. D.OyedeleJ. A. O.UmukoroE. H. (2019). Adsorption performance and mechanism of a low-cost biosorbent from spent seedcake of Calophyllum inophyllum in simultaneous cleanup of potentially toxic metals from industrial wastewater. J. Environ. Chem. Eng.7:103317. doi: 10.1016/j.jece.2019.103317

5 AfrozeS.SenT. K.AngH. M. (2016). Adsorption removal of zinc (II) from aqueous phase by raw and base modified Eucalyptus sheathiana bark: kinetics, mechanism and equilibrium study. Process. Saf. Environ. Prot.102, 336–352. doi: 10.1016/j.psep.2016.04.009

6 AhluwaliaS. S.GoyalD. (2005). Removal of heavy metals by waste tea leaves from aqueous solution. Eng. Life Sci.5, 158–162. doi: 10.1002/elsc.200420066

7 AhmadZ.GaoB.MosaA.YuH.YinX.BashirA.et al. (2019). Removal of Cu2+, Zn2+, and Ni2+ from aqueous solution by biochar derived from microwave pyrolysis of rice husk. Environ. Sci. Pollut. Res. Int.26, 21662–21675. doi: 10.5772/intechopen.94175

8 AhmadA.RafatullahM.SulaimanO.IbrahimM. H.HashimR.ChiiY. Y. (2012). Removal of cu(II) and Pb(II) ions from aqueous solutions by adsorption on sawdust of Meranti wood. J. Hazard. Mater.170, 969–977. doi: 10.1016/j.jhazmat.2009.05.066

9 AhmadM.RajapakshaA. U.LimJ. E.ZhangM.BolanN.MohanD.et al. (2014). Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere99, 19–33. doi: 10.1016/j.chemosphere.2013.10.071,

10 AhmadF.ZaidiS. (2020). Potential Use of Agro/Food Wastes as biosorbents in the Removal of Heavy Metals. Emerg: Contam

11 AhmadA.ZaidiN. A. H. M. (2020). Removal of heavy metals from aqueous solution using agricultural wastes as biosorbents: a review. Environ. Technol. Rev.9, 1–22.

12 AhmedM. A.AminS.MohamedA. A. (2024). Current and emerging trends of inorganic, organic and eco-friendly corrosion inhibitors. RSC Adv.14, 31877–31920. doi: 10.1039/D4RA05662K,

13 AjmalM.RaoR. A. K.AnwarS.AhamadJ.AhmadR. (2003). Adsorption studies on rice husk: removal and recovery of Cd2+ from wastewater. Bioresour. Technol.86, 147–149. doi: 10.1016/S0960-8524(02)00159-1

14 Al HasanN. H. J.AlaradiH. J.Al MansorZ. A. K.Al ShadoodA. H. J. (2019). The dual effect of stem extract of Brahmi (Bacopa monnieri) and henna as a green corrosion inhibitor for low carbon steel in 0.5 M NaOH solution. Case Stud. Constr. Mater.11:e00300. doi: 10.1016/j.cscm.2019.e00300

15 Al HemaidiW.Al ZuhairS. (2024). Ion exchange mechanisms and selectivity in heavy metal remediation. Inorg. Chem. Front.11, 4499–4527. doi: 10.1039/d4qj00326h

16 AlalwanH.KadhomM.AlminshidA. H. (2020). Removal of heavy metals from wastewater using agricultural byproducts. J. Water Supply Res. Technol. AQUA69, 99–112. doi: 10.2166/aqua.2020.133

17 AlamA.HassanA.SultanaZ.DasN. (2025). Natural polymer-based bioadsorbents for wastewater treatment. RSC Sustainability3, 5027–5050. doi: 10.1039/D5SU00369E

18 Al-HemaidiW. K.ElsheikhM. A. (2012). Approach in choosing suitable technology for industrial wastewater treatment. J. Civil Environ. Eng.2, 1–6. doi: 10.4172/2165-784X.1000123

19 AmarM. B.WalhaK.SalvadóV. (2021). Valorisation of pine cone as an efficient biosorbent for the removal of Pb(II), cd(II), cu(II), and Cr(VI). Adsorpt. Sci. Technol.2021:6678530. doi: 10.1155/2021/6678530

20 AmarasingheB. M. W. P. K.WilliamsR. A. (2007). Tea waste as a low cost adsorbent for the removal of cu and Pb from wastewater. Chem. Eng. J.132, 299–309. doi: 10.1016/j.cej.2007.01.016