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Removal of Heavy Metals from Wastewater Using Green Adsorbent

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Abstract: *Heavy metal poisoning in aquatic ecosystems creates a major health threat to worldwide populations and threatens the ecological balance of environments because these pollutants persist in their non-biodegradable state while they accumulate in living organisms. The conventional methods used for remediation face two major limitations which include high operational costs and the creation of additional waste materials. The research investigates how agricultural waste and microbial biomass and industrial by-products can function as green adsorbents to provide an environmentally friendly and economical wastewater treatment solution. We examine the essential mechanisms of biosorption which include three processes: ion exchange and surface complexation and electrostatic interactions. The study investigates how three main factors which include pH and temperature and initial concentration affect the efficiency of removal. Green adsorption creates an innovative solution for industrial environmental restoration by uniting waste management with water purification to support a circular economy model.*
Keywords: *Aquatic Ecosystems, Ecological Balance, Conventional Methods, Electrostatic Interactions, Green Adsorption etc.*

I. Introduction

The rapid rise of global industrial activity together with urban development and population growth has created an environmental emergency which results from widespread contamination of freshwater ecosystems. The aquatic environment faces serious risks because various contaminants include lead (Pb) cadmium (Cd) mercury (Hg) arsenic (As) and chromium (Cr) which pose dangers to both environmental preservation and human safety. Heavy metals exist in the environment as permanent materials which refuse to break down while organic pollutants become less dangerous through biological or chemical processes.

The primary sources of heavy metal pollution originate from industrial sectors which include electroplating and mining and textile production and battery manufacturing. The World Health Organization (WHO) and the Environmental Protection Agency (EPA) are implementing more severe restrictions which require metal ions to be removed from industrial wastewater, thereby creating an urgent demand for treatment solutions that are both effective and affordable and environmentally friendly.

The historical process for heavy metal removal required conventional methods which include chemical precipitation and ion exchange and membrane filtering and electrochemical treatment. The methods work well but they create major problems because they require high operating expenses and they use too much energy and they generate hazardous sludge which needs expensive disposal. The scientific community now studies Adsorption because it offers a straightforward solution which can be used to create various systems that effectively treat low concentration fluids [1].

The introduction of Green Adsorption brings about a fundamental change for environmental engineering. This system uses "green" adsorbents which are materials obtained from agricultural waste and forest by-products and industrial waste and microbial biomass to extract metal ions. The method uses waste materials such as rice husks and lemon peels and seaweed which convert a waste-management problem into an environmental resource that creates value according to Circular Economy principles [2]. The bio-based materials contain functional groups which include carboxyl and hydroxyl and amino groups that function as active sites for metal binding. The research study evaluates all aspects of these green alternatives by studying their operational processes and their effectiveness and their economic viability as substitutes for synthetic resins in large-scale wastewater treatment.

II. Origins and Toxicity of Heavy Metals

Aquatic ecosystems face heavy metal contamination from two sources which are natural geochemical weathering processes & human activities. Natural processes including volcanic eruptions, soil erosion, and the leaching of ore-bearing rocks create baseline metal concentrations but unregulated industrial discharge remains the primary cause of environmental harm [3]. Modern industrial production processes use heavy metals because these elements possess atomic densities that exceed 5\text{ g/cm}^3. The principal industrial sources of pollution include the electroplating sector which releases high quantities of copper (Cu) and nickel (Ni) and mining and smelting activities which emit lead (Pb) and arsenic (As) and the textile and leather tanning industries which send hexavalent chromium (Cr^{6+}) into the environment. The agricultural sector uses phosphate fertilizers extensively while people improperly discard electronic waste (e-waste) which together create significant cadmium (Cd) and mercury (Hg) pollution that reaches the groundwater table.

The toxicity of these metals occurs because they remain in the environment and they disrupt biological metabolic processes. Heavy metals differ from organic pollutants because they remain unchangeable while they undergo biomagnification which increases their concentration at each food web trophic level. The human body experiences severe poisoning effects from these metals. Lead (Pb) serves as a recognized neurotoxic agent because it disrupts calcium function in the brain which leads to cognitive impairments and developmental delays in children.

Methylated mercury (Hg) travels through the bloodstream to reach the brain and spinal cord because it has the ability to traverse the blood-brain barrier, which results in Minamata disease. The body accumulates cadmium (Cd) in the kidneys because this substance exhibits extreme toxicity to these organs. This condition leads to bone mineralization disorders which include Itai-itai disease [4]. The scientific community has established that hexavalent chromium induces human cancer through its ability to create DNA damage via reactive oxygen species. wastewater treatment requires engineers to remove hazardous chemicals because these substances pose health risks even at their lowest detectable concentrations which are measured in parts per billion.

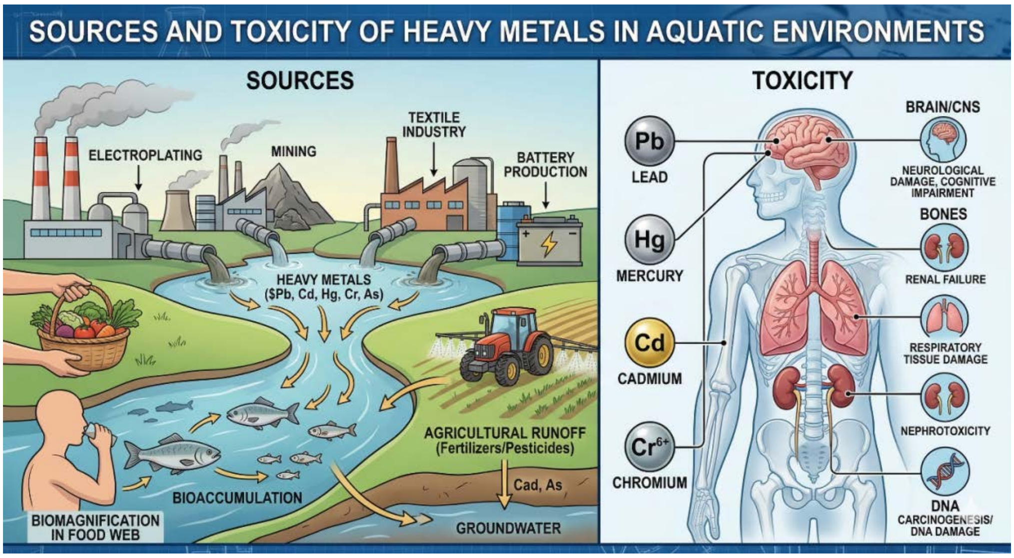

Figure 1: Heavy Metal Toxicity, Source: Author Finding

III. Mechanisms of Green Adsorption

Green adsorption here mostly depends on the essential processes of complexation & coordination. The process uses metal ions which act as Lewis acids and the adsorbent surface contain electron-rich functional groups which function as Lewis bases [5]. The interactions in this manner create coordination based most complexes which form permanent chemical bonds between metal ions & functional groups. Agricultural waste materials contain carboxyl groups that effectively bind divalent metal ions like Pb^{2+} and Cu^{2+}. The metal ion together with functional group donor atoms creates coordinate covalent links which securely attach metal ions to the adsorbent surface [6].

Ion exchange is a crucial mechanism as natural adsorbents often contain light metal ions (e.g., Ca^{2+}, Mg^{2+}, K^{2+}) or protons (H^+) in their functional groups in interaction with heavy metal-contaminated water, these adsorbents substitute the biomass's lighter ions with the solution's heavier metal ions. The exchange process maintains electrical charge balance within the system. A well-known example of this mechanism is alginate in algal biomass, were calcium ions exchange with wastewater heavy metal ions [7] [8].

Electrostatic interaction is very important in adsorption which depends on the solution pH level. The surface charge of the adsorbent material varies according to the functional groups which change their protonation and deprotonation states at different pH levels [9]. The solution pH level reaches beyond the adsorbent material's point of zero charge (pH□zc) because functional groups like carboxyls deprotonate which creates negatively charged sites that include $–COO^-$. The negatively charged sites establish electrostatic attractions which draw positively charged metal ions (M^{n+}) to create better adsorption results. The presence of electrostatic repulsion causes difficulties in cationic metal ion adsorption for positively charged surfaces which exist in environments with acidic conditions.

Microprecipitation provides another method for heavy metal elimination from wastewater. Insoluble metal compounds develop when metal ions react with biomass anions or when local circumstances near the adsorbent surface favor this. The adsorbent surface allows metal ions to precipitate as hydroxides carbonates or phosphates which become insoluble. Chemical conditions create specific environments where microprecipitation enhances adsorption performance.

Multiple mechanisms control heavy metal adsorption onto green adsorbents. The biomass and metal ion and solution physicochemical conditions determine how each pathway operates. The understanding of these principles needs to be established for three purposes which include optimization of the adsorption process and advancement of biomass-based adsorbent design and creation of sustainable wastewater treatment system regeneration methods [10].

Metal Ion	**Target Functional Group(s)**	**Predominant Adsorption Mechanism(s)**	**Examples of Green Adsorbents**	**References**
Lead (Pb^{2+})	Carboxyl (–COOH), Hydroxyl (–OH)	Complexation, Ion Exchange	Coconut shell, Rice husk, Orange peel	[1,2,5]
Cadmium (Cd^{2+})	Carboxyl (–COOH), Phosphate ($–PO_4$)	Ion Exchange, Complexation	Microbial biomass (Bacillus sp.), Algae	[3,4]
Chromium (Cr^{6+})	Amino ($–NH_2$), Hydroxyl (–OH)	Electrostatic attraction (as $HCrO_4$ by reduction to Cr^{3+}	Biochar, Chitosan, Sawdust	[6,7]
Copper (Cu^{2+})	Amino ($–NH_2$), Carboxyl (–COOH)	Complexation, Coordination	Modified agricultural waste, Fungal biomass	[2,8]
Mercury (Hg^{2+})	Sulfhydryl (–SH), Amino ($–NH_2$)	Complexation (high affinity according to HSAB theory)	Algae, Thiol-modified adsorbents	—

Table 1: Dominant Adsorption Mechanisms for Selected Heavy Metals on Green Adsorbents, Source: Author Generated

IV. Categories of Eco-Friendly Adsorbents

The classification of environmentally friendly adsorbents depends primarily on their natural origins and the techniques used to enhance their capacity to attract heavy metal ions. The materials are divided into three categories which include agricultural residues and microbial biomass and industrial by-products that each deliver distinct structural advantages for treating wastewater. The main type of green adsorbents used in this study comes from agricultural waste materials which include rice husks and wheat straw and coconut shells and citrus peels [11]. The materials create a strong fibrous structure which consists of cellulose and hemicellulose and lignin. The matrix contains pectin and polyphenolic chemicals which produce a high level of oxygen-containing functional groups that include carboxyl and hydroxyl moieties. Citrus peels contain high levels of methylated pectic compounds which can undergo conversion to polygalacturonase acid through basic chemical treatment that functions as a binding agent for divalent cations including lead and cadmium. The complex design of these plant-based materials provides a large surface area which enables them to absorb metal ions through their porous structures.

Microbial biomass, which consists of bacteria and fungi and yeast and algae, serves as a specialized category of green adsorbents that people refer to as biosorbents. Bacteria use their cell walls to capture heavy metals because their walls contain complex polysaccharide structures and protein materials and lipid substances. The peptidoglycan layer and teichoic acids of Bacillus subtilis bacteria show multiple anionic sites which capture cationic metal ions. Fungal biomass contains high levels of chitin and chitosan which include nitrogen-containing amino groups that show strong coordination affinity toward transition metals including copper and nickel [12]. Algae especially brown seaweeds are valued for their alginate content. Alginates function here as natural polymers which create "egg-box" structures that specifically bind more than heavy metal ions through combined binding & ion exchange processes. The use of microbial biomass provides substantial most advantages because it can be obtained as a byproduct prospect from large-scale fermentation operations or it can be easily grown using low-cost nutrient sources here.

Biochar and altered industrial by-products function as advanced green adsorbents which scientists developed through engineered design. Biochar results from the thermochemical reduction process which transforms organic waste into biochar through pyrolysis in an oxygen-limited environment. The method produces a material which exhibits exceptional stability and high carbon content and features a complete microporous structure together with multiple surface functional groups. The aromaticity of biochar creates stronger cation-\pi bonding because it establishes a second binding mechanism which works independently from ion exchange. The industrial by-products which serve as adsorbent materials include fly ash and blast furnace slag and food processing waste that contains eggshells and bone meal. The materials contain high concentrations of calcium carbonate and phosphates which enable heavy metals to be removed through surface precipitation and complexation processes. Researchers develop waste management systems which reduce environmental harm from traditional industrial operations by implementing water treatment methods which incorporate biological and industrial waste materials for toxic metal elimination [13].

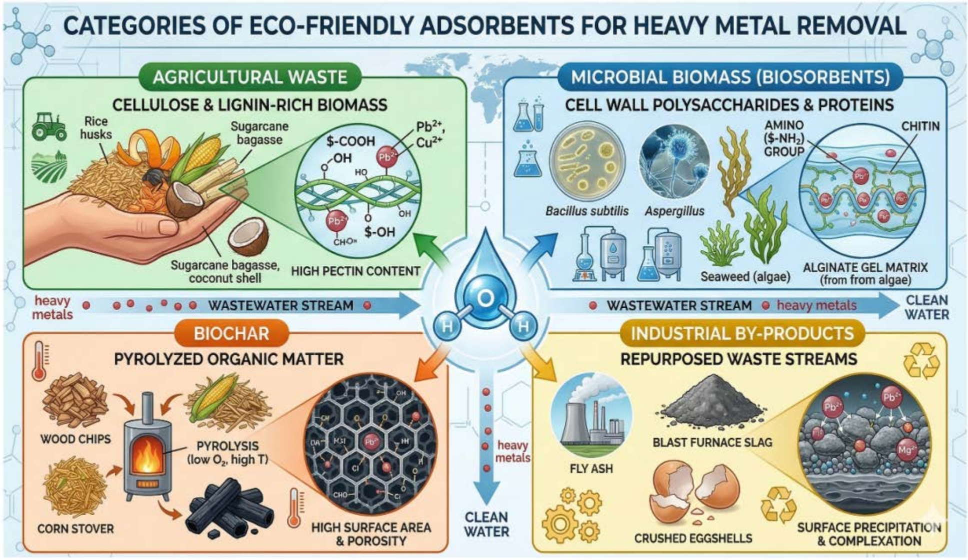

Figure 2: Ecofriendly Category, Source: Author Generated

V. Determinants of Adsorption Efficiency

The effectiveness of green adsorbents depends on multiple physicochemical factors which determine how metals interact with biomass materials. The pH of the aqueous solution is likely the most crucial variable. The parameter controls both the operational status of adsorbent surface functional groups and the metallic ion distribution in the aqueous solution. At low pH levels, a high concentration of hydrogen ions (H^+) competes with metal cations for accessible binding sites, resulting in less adsorption. The functional groups such as carboxyl and phosphate groups remain in a state where they have positive charges or no charge at all which results in metal cation repulsion through electrostatic forces [14]. The pH value reaches the point of zero charge (pH_{pzc}) because these functional groups lose their protons which creates a surface that attracts negative charges and enables complexation through electrostatic forces. Researchers must avoid using excessively high pH levels because they lead to metal precipitation as hydroxides which creates confusion about the true adsorption process.

The process efficiency depends on two factors which are metal ion initial concentration and adsorbent application rate. The presence of higher initial metal concentration establishes needed force which enables to overcome mass transfer barriers between solids and liquids which results in greater specific adsorption capacity (q_e) than before. The binding sites become full which leads to lower metal removal rates because of high concentration levels [15]. The overall removal percentage increases when adsorbent dosage rises because of two factors: expanded surface area and active site availability; however, the amount of metal adsorbed per unit mass decreases because active sites which are not being used create "screening effects".

The process becomes feasible through temperature and contact duration which also determine its operational speed. Most green adsorption techniques operate through endothermic processes because higher temperatures lead to better metal ion movement and greater biomass pore size which results in improved operational performance. Contact duration establishes the time needed to reach equilibrium; initial adsorption occurs quickly because external surface sites are available but the process slows down when ions start to enter the internal micropores. The understanding of these essential properties enables the development of green adsorption technology from laboratory experiments to industrial-scale wastewater treatment systems which require government approval.

Metal Ion	**Green Adsorbent Type**	**Optimal pH Range**	**Max Adsorption Capacity (mg/g)**	**Mechanism Change at High pH**
Lead (Pb^{2+})	Rice Husk / Fruit Peels	5.0 – 6.0	45.0 – 120.0	Precipitation as $Pb(OH)_2$
Cadmium (Cd^{2+})	Algal Biomass	6.0 – 7.0	30.0 – 80.0	Formation of $Cd(OH)^+$
Copper (Cu^{2+})	Sugarcane Bagasse	5.0 – 5.5	20.0 – 65.0	High competition with H^+ below pH 3
Chromium (Cr^{6+}	Biochar / Sawdust	2.0 – 3.0	15.0 – 40.0	Speciation shift to CrO_4

				(repulsion)
Zinc (Zn^{2+})	Coconut Coir	6.0 – 6.5	25.0 – 55.0	Minimal adsorption in acidic conditions

Table 2: Adsorption Characteristics of Heavy Metals Using Green Adsorbents, Source: Author Generated

VI. Restoration and Sustainability

Eco-friendly adsorbents must demonstrate substantial reusability and a favorable life-cycle assessment to be considered a suitable substitute for conventional ion-exchange resins. Regeneration is usually accomplished through desorption which involves treating the used adsorbent with a stripping agent that typically consists of either dilute mineral acids (HCl HNO_3) or chelating agents such as EDTA. These agents displace the bound metal ions through their ability to decrease pH levels or to increase binding power which results in effective "cleansing" of the adsorbent surface that prepares it for upcoming cycles [16].

Sustainability in this context includes two dimensions: the diversion of organic waste from landfills & the potential for resource recovery. The concentrated cantered metal solution obtained after desorption can be processed here to recover high-purity metals which aligns mostly with the principles of the circular economy in this nature [17]. The "cradle-to-cradle" methodology guarantees that the remediation process will not generate any secondary waste which establishes green adsorption as an essential element of sustainable industrial water management.

VII. Conclusion and Prospective Outlook

The use of eco-friendly adsorbents which come from bacterial and agricultural and industrial waste represents a scientifically valid and economical method for removing heavy metals from wastewater. The study demonstrates that biomass materials contain multiple functional groups which enable metal extraction through three methods that match the performance of expensive synthetic materials. The current research field faces its greatest challenge when researchers attempt to develop laboratory testing methods which can function in actual production environments.

Future research needs to conduct competitive adsorption tests which involve multiple metal systems and actual industrial wastewater because competing ions together with organic substances create major impacts on system performance. The development of continuous-flow column reactors together with the advancement of large-scale milling techniques for powdered biomass represents two crucial developments needed for successful implementation of this initiative. Green adsorption technology will become a new solution for global water challenges which will help restore natural ecosystems through its combination of advanced surface modification techniques and economical waste materials.

Reference

[1]. Volesky, B. (2001). Detoxification of metal-bearing effluents: Biosorption for the next century. Hydrometallurgy, 59(2-3), 203–216. https://doi.org/10.1016/S0304-386X(00)00160-2

[2]. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. Molecular, Clinical and Environmental Toxicology, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6

[3]. Fu, F., & Wang, Q. (2011). Removal of heavy metal ions from wastewaters: A review. Journal of Environmental Management, 92(3), 407–418. https://doi.org/10.1016/j.jenvman.2010.11.011

[4]. Crini, G. (2006). Non-conventional low-cost adsorbents for dye removal: A review. Bioresource Technology, 97(9), 1061–1085. https://doi.org/10.1016/j.biortech.2005.05.001

[5]. Michalak, I., Chojnacka, K., & Witek-Krowiak, A. (2013). State of the art for the biosorption process—a review. Applied Biochemistry and Biotechnology, 170(6), 1389–1416. https://doi.org/10.1007/s12010-013-0269-0

[6]. Gadd, G. M. (2009). Biosorption: Critical review based on thermodynamics and kinetics. Journal of Chemical Technology & Biotechnology, 84(1), 13–28. https://doi.org/10.1002/jctb.1999

[7]. Sud, D., Mahajan, G., & Kaur, M. P. (2008). Agricultural waste material as potential adsorbent for sequestering heavy metal ions from aqueous solutions – A review. Bioresource Technology, 99(14), 6017–6027. https://doi.org/10.1016/j.biortech.2007.11.090

[8]. Feng, N., Guo, X., Liang, S., Zhu, Y., & Liu, J. (2011). Adsorption of heavy metals from aqueous solutions by chemically modified orange peel. Journal of Hazardous Materials, 185(1), 49–54. https://doi.org/10.1016/j.jhazmat.2010.08.114

[9]. Wan Ngah, W. S., & Hanafiah, M. A. K. M. (2008). Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: A review. Bioresource Technology, 99(10), 3935–3948. https://doi.org/10.1016/j.biortech.2007.06.011

[10]. Davis, T. A., Volesky, B., & Mucci, A. (2003). A review of the biochemistry of heavy metal biosorption by brown algae. Water Research, 37(18), 4311–4330. https://doi.org/10.1016/S0043-1354(03)00293-8

[11]. Vijayaraghavan, K., & Yun, Y. S. (2008). Bacterial biosorption and biosorption technology for the removal of heavy metals. Biotechnology Advances, 26(3), 266–291. https://doi.org/10.1016/j.biotechadv.2008.02.002

[12]. Mohan, D., Pittman, C. U., & Steele, P. H. (2006). Single, binary and multi-component adsorption of copper and cadmium from aqueous solutions on lignocellulosic materials (common wood and bark). Journal of Colloid and Interface Science, 297(2), 489–504. https://doi.org/10.1016/j.jcis.2005.11.023

[13]. Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S. S., & Ok, Y. S. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere, 99, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

[14]. Ahmaruzzaman, M. (2011). Industrial wastes as low-cost adsorbents for the removal of Cu(II) from wastewater. Advances in Colloid and Interface Science, 166(1-2), 36–59. https://doi.org/10.1016/j.cis.2011.04.005

[15]. Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. Process Biochemistry, 34(5), 451–465. https://doi.org/10.1016/S0032-9592(98)00112-5

[16]. Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. Journal of the American Chemical Society, 40(9), 1361–1403. https://doi.org/10.1021/ja02242a004

[17]. Gupta, V. K., & Rastogi, A. (2008). Biosorption of lead from aqueous solutions by green algae Spirogyra species: Kinetics and equilibrium studies. Journal of Hazardous Materials, 152(1), 407–414. https://doi.org/10.1016/j.jhazmat.2007.06.114