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RESEARCH ARTICLE

A SUSTAINABLE SOLUTION: HARNESSING MEDICINAL PLANT ADSORBENTS FOR ENVIRONMENTAL CLEANUP

Anandhi A [1], Nirmala B [2], Kiran Kumar S [3], Senthilkumar G P4* and Jenifer E[5]
[1]PERI Institute of Technology, Chennai - 48
[2]PERI College of Arts and Science, Chennai -48
[3]PERI College of Physiotherapy, Chennai -48
[4]PERI College of Pharmacy, Chennai -48
[5] PERI College of Nursing, Chennai -48

*Corresponding Author
Senthilkumar G P

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Abstract: Heavy metal contamination poses a severe threat to environmental and public health, necessitating the development of sustainable and cost-effective remediation approaches. Medicinal plants, rich in phytochemicals such as tannins, flavonoids, alkaloids, and saponins, provide promising biosorbent materials due to their metal-binding functional groups. This study reviews the biosorption potential of various medicinal plant biomasses for the removal of toxic metals such as Pb^{2+}, Cd^{2+}, Cr^{6+}, and Ni^{2+}, evaluating factors influencing adsorption efficiency, mechanisms of metal uptake, and recent technological advancements. The findings highlight the suitability of phytogenic adsorbents for low-cost wastewater treatment and propose future research directions for scale-up and optimization.

Keywords: Heavy metal remediation, biosorption, medicinal plants, phytogenic adsorbents, water purification, bioadsorbents, tannins, flavonoids, adsorption isotherms, wastewater treatment

INTRODUCTION

Industrialization, urbanization, and agricultural intensification have resulted in widespread heavy metal contamination of water bodies. Heavy metals such as lead, cadmium, chromium, and nickel are non-biodegradable and accumulate in the environment, posing risks to ecosystems, animals, and humans. Conventional remediation technologies—including ion exchange, membrane filtration, and chemical precipitation—are often expensive and generate secondary pollutants.Biosorption using plant-based materials has emerged as an eco-friendly, low-cost alternative. Medicinal plants in particular possess strong metal-binding phytochemicals, enabling high adsorption capacity. This study provides a comprehensive analysis of medicinal plant-derived adsorbents, focusing on their functional characteristics, biosorption mechanisms, and potential for practical application.

Fig 1: Green Adsorbents from Medicinal Plants

LITERATURE REVIEW

Heavy Metal Toxicity and Environmental Impact

Heavy metal accumulation disrupts soil health, microbial activity, and aquatic systems. Studies by Khan (2022) and Bai et al. (2020) established the role of heavy metals in oxidative stress, genotoxicity, and endocrine disruption. Pb^{2+} and Cd^{2+} are particularly harmful due to their high bioaccumulation and carcinogenic potential.

Medicinal Plants as Bioadsorbents

Medicinal plant biomass has diverse phytochemical profiles enabling efficient metal chelation. Harborne (1998), Trease & Evans (2002), and Sofowora (1993) documented rich concentrations of phenolics and alkaloids that bind metal ions. Research by Narayan & Rao (2019) demonstrated the nutrient-binding potential of plant residues, reinforcing their use as biosorbents.

Phytochemicals and Metal Binding Mechanisms

Phytochemicals—including flavonoids, tannins, alkaloids, and glycosides—contain hydroxyl, carbonyl, and amino groups that participate in metal complexation. Sharma (2017) and Pathak & Bhatnagar (2018) highlighted the involvement of humic-like substances in adsorption processes.

Adsorption Efficiency in Medicinal Plants

Studies show that neem, tulsi, moringa, aloe vera, and bael leaves exhibit promising biosorption capability. Mishra et al. (2020) reported enhanced microbial interaction aiding adsorption. Lal et al. (2021) supported the role of organic amendments in improving adsorption kinetics, Sindhuja A et al (2025), Vijay Krishanan et al (2025), Rubala Nancy J et al (2025), Ramya R et al (2025), Swetha, M et al (2025), Mahalakshmi, J et al (2025), Nafisa Farheen, S et al (2025) and Devasena, B et al (2025).

Comparison with Conventional Methods

Compared to synthetic adsorbents, plant-based materials offer advantages such as biodegradability, cost-effectiveness, regeneration potential, and minimal environmental impact.

MATERIALS AND METHODS

Sample Collection and Preparation

Medicinal plant leaves were collected, washed, dried, powdered, and sieved. Sequential solvent extraction was performed using methanol, ethanol, and aqueous solvents.

Phytochemical Screening

Qualitative tests (Harborne, 1998; Kokate, 2001) were applied to identify tannins, alkaloids, phenols, flavonoids, saponins, and terpenoids.

Heavy Metal Solutions Preparation

Standard solutions of Pb^{2+}, Cd^{2+}, Cr^{6+}, and Ni^{2+} were prepared using analytical-grade chemical salts.

Batch Adsorption Experiments

Key parameters analyzed:

- Contact time
- Adsorbent dosage
- pH levels
- Initial metal concentration
- Temperature

Adsorption Isotherms and Kinetics

Langmuir and Freundlich models were applied to evaluate surface adsorption characteristics.

RESULTS AND DISCUSSIONS:

Phytochemical Composition

Medicinal plants exhibited rich phytochemical diversity, with high presence of tannins and flavonoids contributing to adsorption.

Table 1: Adsorption Capacity

Metal	Adsorption Capacity (mg/g)	Most Efficient Plant Biomass
Pb^{2+}	78.4	Neem leaf powder
Cd^{2+}	64.1	Tulsi leaf extract
Cr^{6+}	52.6	Moringa seed coat
Ni^{2+}	49.8	Bael leaf powder

Effect of pH

Maximum adsorption occurred between pH 5–7 due to reduced metal ion competition.

Mechanism of Adsorption

The adsorption followed chemisorption involving:

- Complexation
- Ion exchange
- Electrostatic attraction
- Microbial-assisted binding (Mishra et al., 2020)

CONCLUSION

Medicinal plant-based bioadsorbents provide an efficient, green, and economical strategy for heavy metal removal. Their phytochemical composition makes them suitable for large-scale application, although optimization and industrial trials are needed. These biosorbents offer high affinity toward toxic metals due to the presence of functional groups such as hydroxyl, carboxyl, amino, and phenolic moieties. They also exhibit rapid adsorption kinetics, minimal sludge production, and complete biodegradability, making them superior to conventional chemical adsorbents. Furthermore, medicinal plants are widely available, renewable, and can be processed into adsorbent material with minimal cost. Their use supports circular bioeconomy models by valorizing agricultural and herbal residues. Additionally, plant-derived bioadsorbents demonstrate strong performance across varying pH levels, allow regeneration through simple desorption methods, and show potential for integration into filtration systems, adsorption columns, and decentralized wastewater treatment units.

FUTURE SCOPE

Future research should focus on the development of modified and activated bioadsorbents, particularly through chemical activation, thermal treatment, and surface functionalization to enhance adsorption capacity and selectivity. The incorporation of nanoparticle-functionalized plant adsorbents, such as metal oxide nanocomposites or carbon-based nanosystems, can further improve surface reactivity, kinetics, and regeneration potential. In addition, column-scale continuous-flow adsorption studies are essential to bridge the gap between laboratory-scale batch experiments and real-world industrial applications. Validation using real wastewater matrices, which often contain mixed pollutants, competing ions, and fluctuating environmental conditions, will help determine operational feasibility and long-term stability of plant-based biosorbents. Advanced phytochemical–metal interaction modeling, supported by spectroscopy, density functional theory (DFT), and molecular docking tools, can provide deeper insights into binding mechanisms and adsorption thermodynamics. Moreover, future studies should consider life cycle assessments (LCA) to evaluate environmental sustainability, scale-up cost modeling, and regeneration–reuse efficiency of the adsorbents for multiple cycles. The integration of biosorbents into hybrid treatment systems—combining phytoremediation, membrane filtration, or biochar technologies—also offers promising potential for high-performance, eco-friendly metal remediation.

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