

Sustainable Biosorption Using Plant Roots: From Mechanistic Insights To Practical Applications

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The increasing contamination of water bodies due to industrial effluents and chemical pollutants necessitates the development of sustainable and cost-effective remediation strategies. This study explores the potential of plant root biosorbents as a green and eco-friendly solution for the removal of pollutants from aqueous solutions. Various plant roots were investigated for their adsorption efficiency in sequestering contaminants such as heavy metals and organic dyes. Batch adsorption experiments were conducted to evaluate the effects of parameters like pH, contact time, adsorbent dosage, and initial pollutant concentration. The adsorption kinetics were analyzed using pseudo-first-order and pseudo-second-order models, while equilibrium data were fitted to Langmuir and Freundlich isotherms to understand the sorption mechanism. Results demonstrated that plant root biosorbents exhibit high adsorption capacities, rapid uptake rates, and favorable sorption characteristics, making them viable candidates for wastewater treatment. The study highlights the relevance of biosorption as a low-cost and sustainable approach to environmental pollution control, contributing to the advancement of green technologies in water purification.

Keywords: Green remediation, Adsorption efficiency, Heavy metal removal, Langmuir isotherm, Pseudo-first-order kinetics

Introduction

The increasing contamination of freshwater resources due to industrial discharge, agricultural runoff, and urban effluents has emerged as a major global concern, posing serious threats to both aquatic ecosystems and public health. Conventional wastewater treatment methods such as chemical precipitation, ion exchange, membrane filtration, and activated carbon adsorption are commonly employed for pollutant removal. However, these technologies are often cost-

prohibitive, energy-intensive, and may produce harmful secondary pollutants (Gupta & Suhas, 2009). As a result, there has been growing interest in alternative, sustainable, and cost-effective treatment methods that can address these challenges without further environmental burden.

Biosorption, the passive uptake of pollutants by biological materials, has gained wide recognition as an eco-friendly technique for water purification. Various natural materials—including algae, fungi, bacteria, and plant-based biomass—have been explored for their biosorption potential (Volesky, 2001). Among these, plant root biosorbents have drawn considerable attention due to their abundant availability, high surface area, and the presence of functional groups such as hydroxyl, carboxyl, and amine groups that enhance metal and dye binding (Mohapatra et al., 2009). For instance, Sharma and Bhattacharyya (2005) demonstrated the use of *Cassia fistula* root for the removal of cadmium and lead, showing remarkable adsorption capacities. Similarly, Garg et al. (2004) reported the effectiveness of *Eichhornia crassipes* root powder in the removal of methylene blue and crystal violet dyes from aqueous media.

In recent years, researchers have focused on evaluating the adsorption behavior of plant root biosorbents through equilibrium and kinetic studies. Isotherm models such as Langmuir and Freundlich are commonly used to describe adsorption capacity and surface interaction characteristics (Ho & McKay, 1999). Kinetic models, including pseudo-first-order and pseudo-second-order equations, help in understanding the rate-limiting steps involved in the biosorption process (Lagergren, 1898; Ho, 2006). Studies by Kumar and Bandyopadhyay (2006) and Sud et al. (2008) further support the high efficiency and reusability of plant-based biosorbents for a wide range of contaminants.

Given the growing need for environmentally sound and economically viable water treatment methods, this study aims to explore the potential of selected plant root biosorbents for the removal of pollutants from aqueous solutions. It evaluates their adsorption efficiency, investigates sorption kinetics using mathematical models, and analyzes equilibrium data with isotherm models. The findings are expected to enhance understanding of plant root biosorption mechanisms and contribute to the development of green and sustainable water remediation technologies.

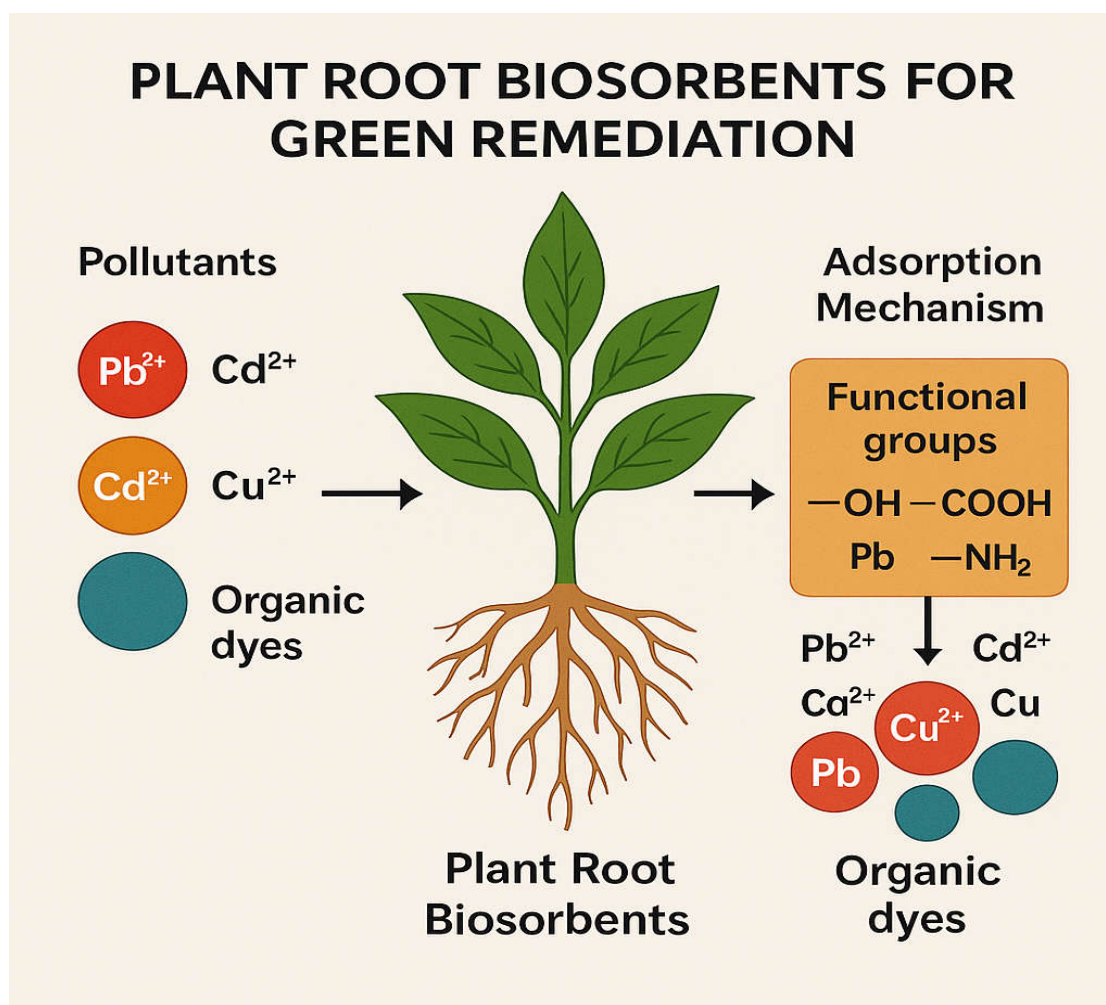


Figure 1: This diagram illustrates the role of plant root biosorbents in the eco-friendly removal of pollutants from aqueous solutions. It demonstrates how plant roots adsorb contaminants such as heavy metals (Pb^{2+} , Cd^{2+} , Cu^{2+}) and organic dyes through interactions with functional groups ($-OH$, $-COOH$, $-NH_2$) present on their surface. The image emphasizes the dual capability of plant root systems to bind both inorganic and organic pollutants, showcasing their potential as sustainable biosorbents in green remediation strategies for wastewater treatment.

Global Water Pollution: Causes and Consequences

Water pollution has emerged as one of the most pressing environmental challenges of the 21st century, primarily due to escalating industrialization, urbanization, and population growth. Numerous studies have highlighted that industrial effluents, which often contain heavy metals, dyes, organic solvents, and persistent hazardous substances, are frequently discharged into freshwater bodies without undergoing proper treatment (Gupta et al., 2020; Zhang & Zhou,

2019). This unregulated discharge contributes significantly to the degradation of water quality in rivers, lakes, and aquifers.

Agricultural runoff further intensifies the problem. The widespread use of synthetic fertilizers and pesticides leads to nutrient enrichment, particularly nitrogen and phosphorus, which causes eutrophication—a condition characterized by algal blooms, oxygen depletion, and disruption of aquatic ecosystems (Carpenter et al., 1998; Smith et al., 2017). These changes not only threaten biodiversity but also impair the ecosystem services provided by freshwater bodies.

Urban development and the poor management of municipal waste and sewage, especially in developing countries, exacerbate water pollution. According to WHO (2022), a significant portion of sewage in low-income regions is released untreated into water systems, introducing pathogens and organic waste that pose serious public health risks. Waterborne diseases such as cholera, typhoid, and dysentery remain prevalent in regions with inadequate sanitation (UNEP, 2021).

The ecological consequences of water pollution are profound. Aquatic fauna are highly susceptible to toxic pollutants, leading to reduced species diversity, reproductive failures, and mortality (Rzymiski et al., 2015). Additionally, bioaccumulation of toxins in the food chain poses long-term health risks to humans, particularly in communities that rely heavily on fish and untreated water sources for their sustenance (Kumar & Puri, 2012).

From a socio-economic perspective, polluted water bodies hinder agriculture, reduce fishery yields, and strain public health infrastructure. The economic cost of water pollution in developing countries is significant, as it undermines sustainable development and increases healthcare expenditure (World Bank, 2019). Climate change and over-extraction of water resources further stress the availability of clean water, making pollution control an even more urgent priority.

To mitigate water pollution, there is a growing consensus on the need for integrated water resource management (IWRM), stricter industrial regulations, adoption of green technologies, and community-level interventions aimed at education and behavioral change (FAO, 2020; Khan et al., 2023). Addressing water pollution is not merely an environmental obligation but a prerequisite for global ecological balance and human well-being.

Table 1: Categorical Analysis of Water Pollution Sources and Their Environmental and Health Impacts

Category	Causes of Water Pollution	Consequences
Industrial Activities	Discharge of untreated effluents, heavy metals, and chemicals into rivers and lakes	Toxicity to aquatic life, bioaccumulation, and contamination of drinking water
Agricultural Runoff	Excessive use of fertilizers, pesticides, and animal waste washing into water bodies	Eutrophication, algal blooms, and depletion of oxygen in water bodies
Urbanization	Stormwater runoff, sewage overflows, and solid waste disposal	Spread of waterborne diseases, degradation of water quality
Mining Operations	Acid mine drainage, sediment runoff, and release of heavy metals	Habitat destruction, water acidification, and toxic contamination
Oil Spills	Accidental or illegal discharge of petroleum into oceans and rivers	Death of marine species, disruption of food chains, and long-term ecological harm
Plastic Pollution	Disposal of plastic waste and microplastics into waterways	Ingestion by aquatic organisms, blockages, and persistent pollution
Climate Change	Increased rainfall intensity, rising temperatures, and sea level rise	Altered water cycles, saline intrusion, and increased pollutant loads
Deforestation	Soil erosion and increased sedimentation in water bodies	Loss of aquatic habitats and increased turbidity
Lack of Sanitation	Open defecation, lack of wastewater treatment infrastructure	High incidence of diseases like cholera and dysentery
Marine	Disposal of industrial, medical, and	Contamination of marine ecosystems

Category	Causes of Water Pollution	Consequences
Dumping	household waste into the sea	and seafood toxicity

Conventional wastewater treatment technologies

Conventional wastewater treatment technologies such as chemical precipitation, ion exchange, membrane filtration, and activated carbon adsorption—have been widely adopted for the removal of pollutants from municipal and industrial effluents. While these methods are effective to a certain extent, especially for bulk removal of contaminants, they present significant limitations that hinder their long-term sustainability and adaptability to emerging water treatment challenges.

One major limitation is the high operational and maintenance costs associated with conventional techniques. These systems often require energy-intensive operations, costly reagents, and specialized equipment (Fu & Wang, 2011; Wang et al., 2020). For example, ion exchange and membrane systems demand constant energy input and regeneration chemicals, which make them economically unviable for widespread use in low-resource settings.

Another drawback is the generation of secondary waste, particularly sludge, which poses a further challenge in terms of handling, treatment, and safe disposal (Gupta et al., 2012). Chemical precipitation and activated carbon adsorption processes frequently produce residuals that can be hazardous and require additional disposal strategies, compounding the environmental footprint of treatment facilities (Bhatnagar & Sillanpää, 2010).

Limited efficiency in removing emerging contaminants such as pharmaceutical residues, endocrine-disrupting compounds (EDCs), and synthetic dyes has also been documented (Verlicchi et al., 2012; Luo et al., 2014). Conventional systems are not specifically designed to target micropollutants that exist in trace concentrations and complex chemical forms, making them inadequate in addressing modern wastewater challenges.

Membrane technologies, although advanced in separation efficiency, suffer from membrane fouling—a major operational bottleneck that decreases system performance and increases maintenance frequency (Meng et al., 2009). Fouling also limits membrane lifespan and necessitates the use of harsh cleaning agents, further contributing to operational costs and environmental risks.

The infrastructure and technical expertise required for these systems also limits their applicability in rural or economically disadvantaged regions (Ali et al., 2021). The complexity of installation, operation, and monitoring means that many communities cannot implement or sustain these technologies without external support.

Given these challenges, there is an urgent need to explore alternative, eco-friendly treatment methods that are low-cost, energy-efficient, and capable of addressing a wider range of pollutants. Among the promising alternatives is biosorption, a technology that utilizes biological materials (such as algae, bacteria, fungi, and agricultural waste) to remove heavy metals and organic pollutants effectively (Volesky, 2001; Babel & Kurniawan, 2003). Biosorption offers a sustainable and adaptable solution, especially suitable for decentralized treatment in areas lacking access to sophisticated infrastructure.

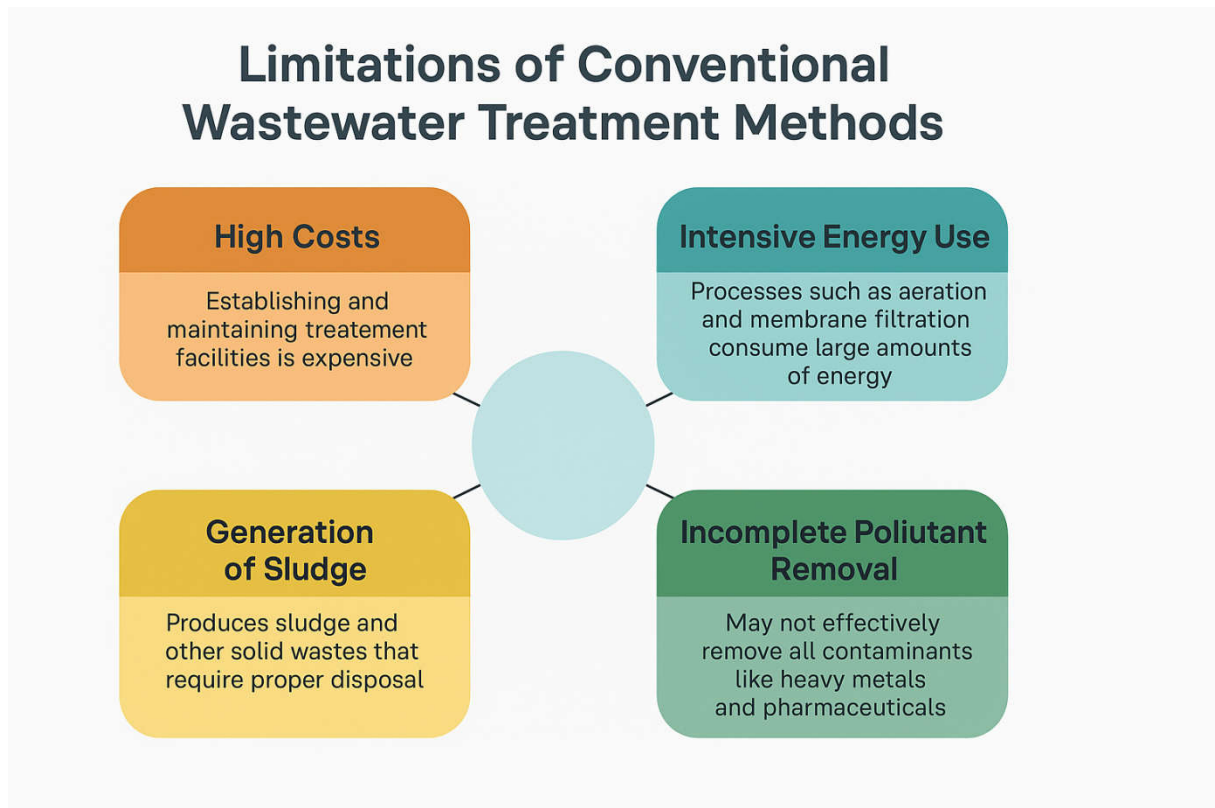


Figure 2: This infographic outlines the major challenges associated with traditional wastewater treatment systems. It highlights four key limitations: high operational and establishment costs, excessive energy consumption during processes like aeration and membrane filtration, generation of sludge and solid waste requiring careful disposal, and incomplete removal of pollutants such as heavy metals and pharmaceuticals. These factors emphasize the need for alternative, sustainable, and cost-effective treatment technologies to address growing environmental concerns and enhance treatment efficiency.

Emergence of Biosorption as a Green Alternative

In response to the increasing limitations and environmental concerns associated with conventional wastewater treatment technologies, **biosorption** has emerged as a sustainable and efficient alternative for the removal of various pollutants, particularly **heavy metals, dyes, and other hazardous contaminants** from aqueous environments. Biosorption is defined as the **passive binding of contaminants onto biological materials**, including algae, fungi, bacteria, and plant-based biomass (Volesky, 2001; Wang & Chen, 2009).

Among the various biosorbents explored, plant-derived materials, especially root biomass, have garnered considerable attention due to their natural abundance, low cost, renewability, and eco-friendly characteristics (Babel & Kurniawan, 2003; Bhatnagar & Sillanpää, 2010). Unlike conventional techniques such as chemical precipitation or membrane filtration, biosorption does not require energy-intensive operations or harmful chemical additives, making it particularly advantageous for decentralized applications in rural and low-income regions (Ali et al., 2021).

The efficiency of plant-based biosorbents is attributed to the presence of various functional groups, such as hydroxyl, carboxyl, and amino groups, which facilitate strong electrostatic and chemical interactions with metal ions and dye molecules (Demirbas, 2008; Bhatti et al., 2007). These natural binding sites allow for high sorption capacity across a wide range of contaminants and environmental conditions.

An additional benefit of biosorption is the minimal production of toxic sludge compared to conventional methods, as well as the potential for biosorbent regeneration and reuse, which aligns well with circular economy principles (Barakat, 2011). This makes biosorption not only effective but also more sustainable and adaptable to evolving environmental regulations and societal expectations.

Recent advancements in biosorption research have focused on kinetic, isotherm, and thermodynamic modeling, which help elucidate the underlying mechanisms of pollutant uptake and optimize operational parameters for maximum efficiency (Crini & Badot, 2008; Kumar et al., 2011). Such models have improved the understanding of biosorbent–contaminant interactions, paving the way for the development of scalable and tailored biosorption systems for real-world wastewater treatment applications.

As global priorities shift toward low-impact, eco-innovative solutions biosorption continues to play a vital role in green engineering and environmental pollution control. With continued

research and technological refinement, plant-based biosorption is poised to become a key component of next-generation water purification strategies.



Figure 3: This illustration emphasizes the role of biosorption in eco-friendly wastewater remediation. The image symbolically represents biosorption using a plant rooted in soil, highlighting nature-based solutions. The presence of laboratory glassware suggests the scientific foundation behind this process, while the arrow and cloud imply environmental regeneration and cleaner ecosystems. Biosorption uses biological materials such as algae, fungi, and agricultural waste to effectively remove heavy metals and pollutants from water, offering a sustainable, low-cost, and efficient alternative to conventional chemical-based treatment methods.

Advantages of Plant Root Biosorbents

Plant root biosorbents have gained increasing attention as effective and eco-friendly materials for wastewater treatment, owing to their natural abundance, biodegradability, and renewable nature. Derived often from agricultural by-products or waste biomass, plant roots present a

cost-effective and sustainable solution for large-scale environmental remediation, particularly in low-resource settings (Babel & Kurniawan, 2003; Bhatnagar & Sillanpää, 2010).

The structural characteristics of plant roots, including their fibrous morphology and high surface area, play a crucial role in facilitating the adsorption of a wide range of contaminants. In particular, the presence of functional groups such as hydroxyl (-OH), carboxyl (-COOH), and phenolic groups enables strong interactions with heavy metals, synthetic dyes, and various organic pollutants (Demirbas, 2008; Bhatti et al., 2007). These active sites promote ion exchange, complexation, and electrostatic attraction, contributing to high sorption capacity and efficiency.

Unlike synthetic sorbents, plant root biosorbents are non-toxic and do not generate secondary pollutants, which is critical for maintaining environmental safety throughout the treatment process (Barakat, 2011; Crini & Badot, 2008). Moreover, modification techniques such as acid or base treatment, functionalization, and thermal activation have been shown to significantly enhance their adsorption performance without compromising biodegradability (Kumar et al., 2011; Wang & Chen, 2009).

In addition to chemical properties, mechanical strength and structural stability of certain plant roots allow for repeated use and facile handling during operation, making them suitable for batch and column treatment systems (Ali et al., 2021). Their compatibility with low-tech purification setups further supports their application in rural or decentralized water treatment scenarios, where sophisticated infrastructure may not be feasible (Volesky, 2001).

Importantly, the use of plant root biosorbents aligns with the principles of green chemistry and the circular economy, promoting waste valorization, energy conservation, and reduced reliance on synthetic chemicals (Gupta et al., 2012). This eco-centric approach not only addresses water pollution effectively but also supports sustainable development goals by integrating environmental responsibility with practical engineering solutions.

Evaluation of Adsorption Efficiency: Kinetics and Isotherms

Adsorption kinetics explores the rate at which contaminants are removed from aqueous solutions and is essential for understanding whether the process is governed by physical adsorption, chemisorption, or diffusion-based mechanisms (Ho & McKay, 1999). The most widely employed kinetic models include the pseudo-first-order and pseudo-second-order models. The pseudo-first-order model, based on Lagergren's equation, assumes a rate proportional to the number of unoccupied sites, while the pseudo-second-order model suggests that the adsorption process is dependent on the availability of both the adsorbate and biosorbent functional groups, implying chemisorption as the dominant mechanism (Hameed et al., 2008; Azizian, 2004).

In parallel, adsorption isotherms describe the equilibrium relationship between the concentration of the adsorbate in solution and the amount adsorbed onto the biosorbent. Among the most commonly used models, the Langmuir isotherm assumes monolayer adsorption on a homogenous surface with finite adsorption sites, whereas the Freundlich isotherm accounts for heterogeneous surface energies and multilayer adsorption phenomena (Langmuir, 1918; Freundlich, 1906). These models are critical in estimating the maximum adsorption capacity (q_{max}) and the intensity of the adsorption process, offering insight into biosorbent efficiency under real-world conditions.

Studies applying these models to plant-based biosorbents have demonstrated their utility in identifying optimal dosage, contact time, and pollutant concentration ranges for maximum removal efficiency (Kumar et al., 2011; Bhatti et al., 2007). For example, root-derived biosorbents such as those from *Moringa oleifera*, *Brassica juncea*, and *Casuarina equisetifolia* have shown high affinity for heavy metals like Pb^{2+} , Cd^{2+} , and Cu^{2+} , with isotherm modeling confirming monolayer adsorption and kinetic modeling indicating chemisorption dominance (Demirbas, 2008; Barakat, 2011).

Moreover, the integration of kinetic and isotherm analyses supports comparative evaluation across different biosorbent materials, enabling data-driven selection and design of cost-effective, scalable water treatment systems (Wang & Chen, 2009). This approach is especially

beneficial in the context of low-cost technologies for rural or decentralized wastewater treatment, where precise control of operating parameters is essential for consistent performance.

In conclusion, the combined application of kinetic and isotherm modeling not only enhances the scientific understanding of biosorption mechanisms but also plays a pivotal role in guiding engineering design and field implementation of plant root-based biosorption technologies for sustainable water purification.

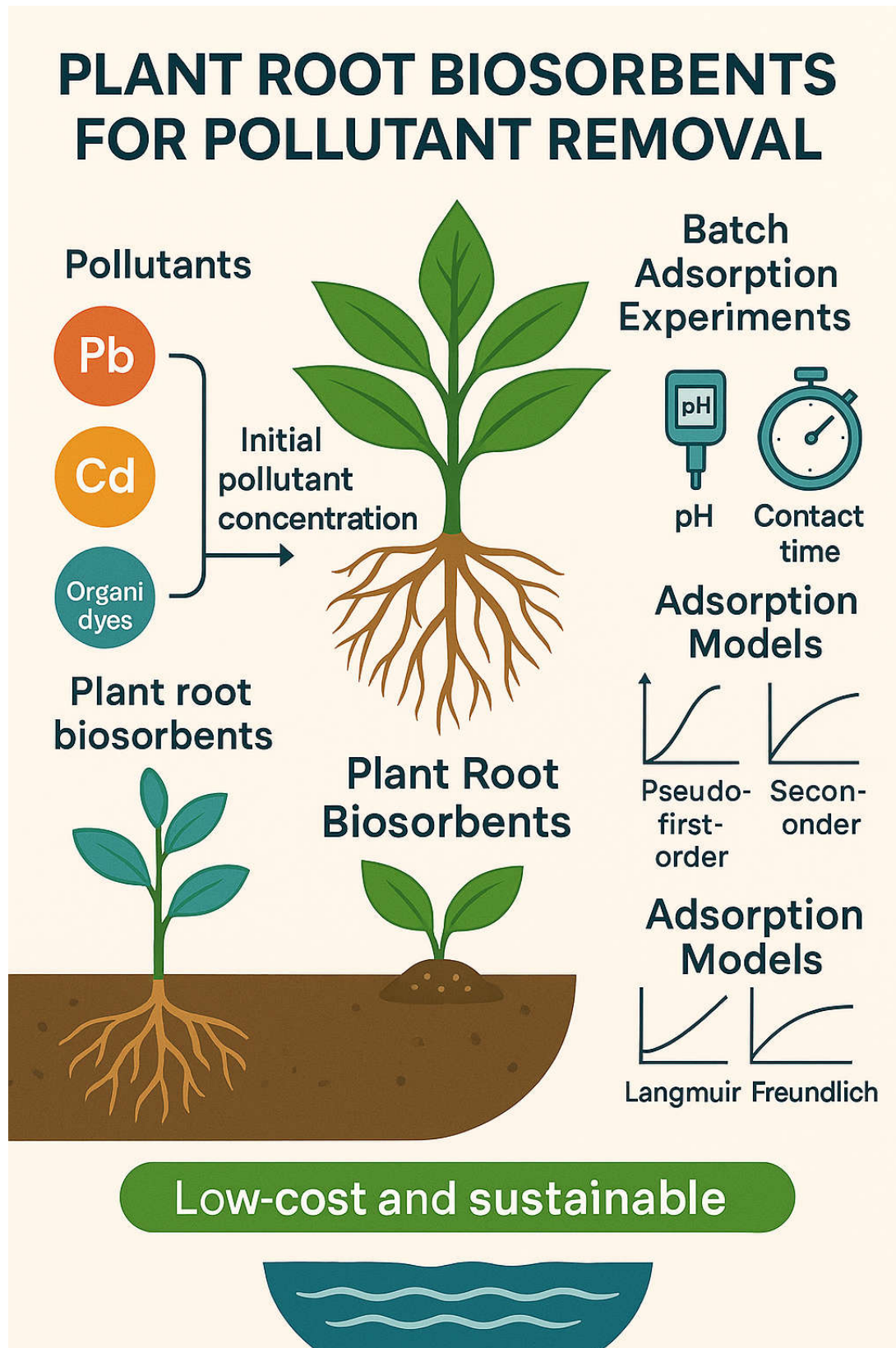


Figure 4: This figure illustrates the effect of varying carbon to nitrogen (C:N) ratios on microbial performance, specifically in terms of biomass accumulation and metabolite production. The left graph shows a steady increase in biomass concentration (g/L) as the C:N

ratio increases from 10:1 to 50:1, indicating that higher carbon availability promotes microbial growth. Similarly, the right graph demonstrates a positive correlation between increasing C:N ratios and metabolite production, with the highest output at a 50:1 ratio. These trends highlight the critical role of nutrient balance in microbial fermentation processes, where optimizing the C:N ratio can significantly enhance both growth and product yield. Such insights are essential for designing efficient bioprocessing strategies in industrial biotechnology.

Research Scope and Objectives

The increasing contamination of aquatic environments by industrial effluents, agricultural runoff, and domestic discharges has necessitated the development of eco-friendly, cost-effective, and sustainable water treatment technologies. In this context, biosorption—the passive uptake of pollutants by biological materials—has emerged as a promising solution for the remediation of contaminated water sources (Volesky, 2001; Wang & Chen, 2009). Among the various biosorbents investigated, plant root biomass has gained significant attention due to its renewability, natural abundance, and functional surface chemistry conducive to adsorption processes (Babel & Kurniawan, 2003; Demirbas, 2008).

This research is focused on exploring the potential of plant root biosorbents as green alternatives for removing common water pollutants, particularly heavy metals and synthetic dyes, which are among the most persistent and toxic constituents in wastewater (Barakat, 2011; Crini & Badot, 2008). The study involves the selection, preparation, and physicochemical characterization of various plant root materials, with an emphasis on understanding their surface morphology, functional group distribution, and textural properties relevant to adsorption.

A major objective of this research is to systematically evaluate the adsorption performance of selected plant root biosorbents under varying experimental conditions, including pH, contact time, initial pollutant concentration, and biosorbent dosage. To elucidate the adsorption mechanisms and rate-controlling steps, kinetic models such as the pseudo-first-order and pseudo-second-order equations will be employed (Ho & McKay, 1999; Hameed et al., 2008). These models are instrumental in determining whether adsorption is governed primarily by physical interaction, chemisorption, or intraparticle diffusion.

In addition, the equilibrium data obtained will be fitted to isotherm models, primarily Langmuir and Freundlich, to assess the monolayer adsorption capacity, adsorption intensity, and surface heterogeneity of the biosorbents (Langmuir, 1918; Freundlich, 1906). These insights will facilitate the comparison and optimization of different plant root biosorbents in terms of efficiency and scalability.

The overarching goal of the study is to identify high-performance plant-based biosorbents and optimize operational parameters to achieve maximum pollutant removal efficiency. Ultimately, this research aims to support the development of low-cost, environmentally benign, and nature-based treatment technologies that are particularly well-suited for resource-constrained settings and decentralized water purification systems.

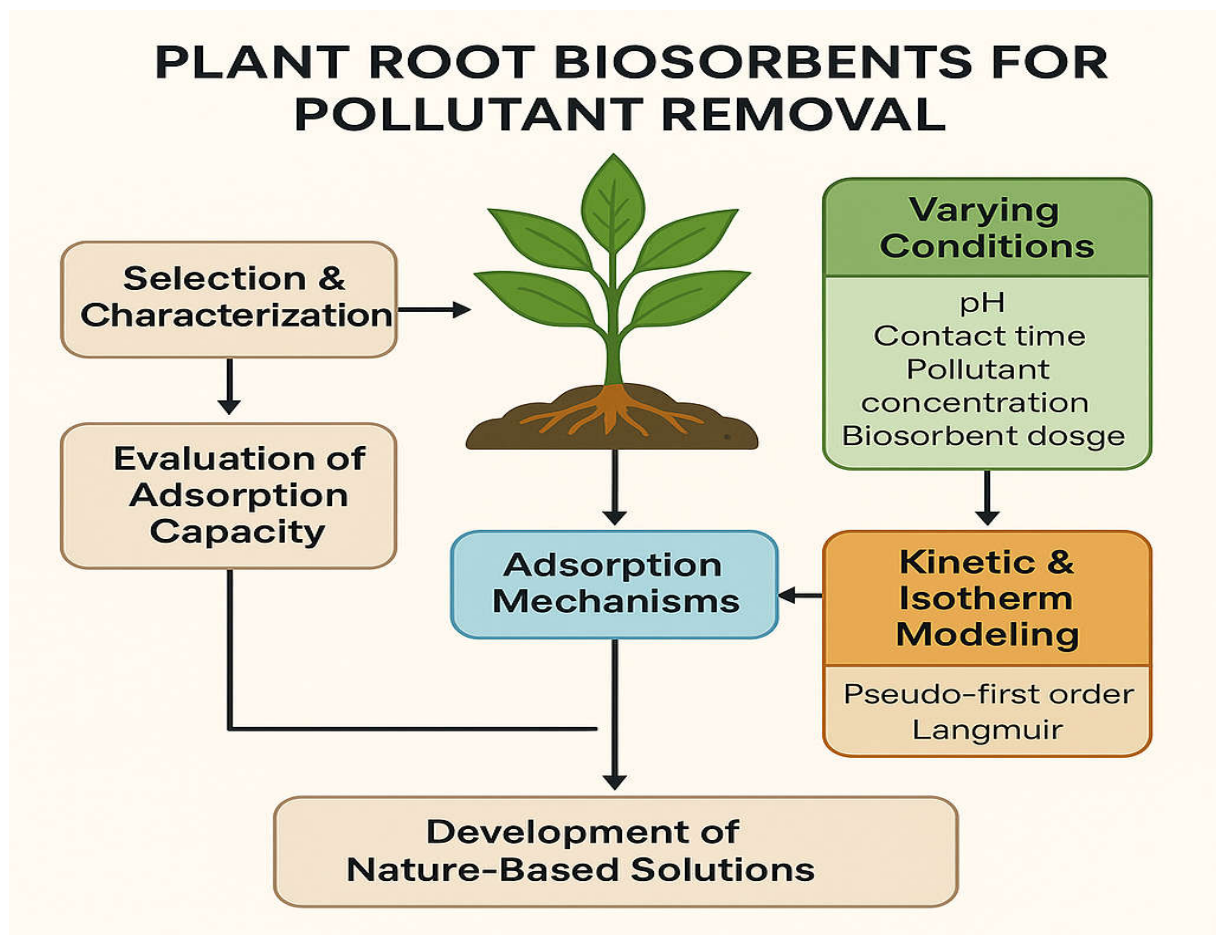


Figure 5: This diagram illustrates the role of plant-based biosorbents, particularly plant roots, as a green alternative for water purification. It emphasizes the eco-friendly nature of

biosorption technology, where plant roots absorb and remove pollutants such as heavy metals and dyes from contaminated water. The integration of natural biosorbents in wastewater treatment presents a sustainable and cost-effective approach, reducing dependency on chemical-intensive methods. The image symbolically connects laboratory research with environmental restoration, highlighting the synergy between biotechnology and nature for clean water solutions.

Conclusion

The present study highlights the promising role of plant root biosorbents as a green and sustainable alternative for the remediation of polluted aqueous environments. With their natural abundance, low cost, and environmentally friendly properties, plant roots offer significant advantages over conventional treatment methods, particularly in terms of biosorption efficiency and compatibility with eco-conscious wastewater management practices. The evaluation of adsorption kinetics and isotherms provides a comprehensive understanding of the mechanisms involved and helps in optimizing treatment conditions for enhanced pollutant removal. This approach not only supports the principles of green chemistry and circular economy but also contributes to the development of low-tech, scalable solutions suitable for rural and industrial settings alike. Overall, plant root biosorbents represent a viable strategy for addressing the global challenge of water pollution while minimizing environmental impact, encouraging further research and application in the field of sustainable environmental engineering.

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