

# Phytoremediation of Chromium (Cr (VI)): Mechanistic Insights from Plant Biosorbents

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## Putta *et al.*: Phytoremediation of Cr (VI) Using Plant Biosorbents

Chromium is a dangerous heavy metal that is a frequently observed contaminant of aquatic systems due to its industrial applications. Although chromium is very important for several industries, the environmental problems associated with Cr (VI) are severe. Adsorptive treatment has emerged as an efficient treatment technology used in the last decades by various researchers for the removal of Cr (VI) from wastewater streams and it is being done considering numerous naturally available biosorbents. Herein, the intelligence of plant waste-based biosorbents in their native and chemically modified state to achieve the best Cr (VI) removal in aqueous system is reviewed. The kinetics and mechanism of removal of these compounds are studied as well. Both the pH of the solution and the initial concentration of Cr (VI) are the significant factors affecting the Cr removal. A Cr removal process from the water samples was interpreted in terms of an adsorption, and/or adsorption-coupled reduction. With detailed coverage on various biosorbents like maximum adsorption capacities, and adsorbent desorption and regeneration, the plant-based biosorbents are chosen as a major element for removal of Cr (VI) in water.

**Key words:** Biosorbents, pesticides, chromium, adsorption

Water is also essential for all living beings on earth, the water quality of which is progressively being enhanced as a result of human efforts, for the sake of industrialization and globalization<sup>[1]</sup>. Because of the sharp growth of the industrial sector, pollution, like heavy metals, natural colors, pharmaceuticals, personal products, and pesticides, is getting higher release and leakage into the environment<sup>[2]</sup>. Although many of the heavy metals *viz.*, arsenic, cadmium, chromium, lead, mercury, nickel, and zinc are required in trace quantities for human nutrition, their excess concentration can cause adverse health effects<sup>[3]</sup>. Because the toxic metals are recalcitrant compounds, they persist in the environment for long periods, and show a strong tendency to accumulate in the food chain; removal of these compounds heavy metals from aqueous solution is subject to legal regulations. Chromium is used in several major industrial sectors: Electroplating, leather tanning, textile dyeing, stainless-steel production, mining, the manufacture of pigments and paint, as a catalyst, and in the manufacture of photocopier and printer's toners, wood preservation, and it is also used in the production of synthetic rubies. In aqueous solutions,

it is found in several oxidation states<sup>[4]</sup>. Hexavalent (Cr (VI) and trivalent (Cr (IV)) are more stable among the stable forms of Cr (VI) presents 1000 greater toxicity toward the human organism compared to Cr (III) in which intensive chemical properties as well as motion in solution are 1000 times higher for (The Cr (VI) and organic Cr ion occur as pollutant forms<sup>[5]</sup>.

Thus, Cr (VI) has been classified as a priority pollutant by the World Health Organization (WHO) and a human carcinogen by the International Agency for Research on Cancer (IARC).

Thus it is of great urgency to develop efficient methods for removal of Cr (VI)<sup>[6]</sup>. Restraining data to 18 000 October 2023 Cr (III) animals Adequate daily question that Cr (III) the two types of sedum used Cr (III). Cr (III) oxide, rather than Cr (VI), is mostly used as a micronutrient to regulate insulin.

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The acceptable concentration of fluoride as per the regulatory standards is 0.5 mg/l in groundwater and 0.05 mg/l in drinking water<sup>[7]</sup>. Conventional methods for the removal of heavy metals from contaminated aqueous media are based on a variety of mass transfer processes such as coagulation, extraction, precipitation, ion exchange, membrane filtration, and photo catalysis<sup>[8]</sup>. All of these methods have inherent limitations due to higher operation costs, a tendency towards different parameters, recovery percentages of metals that are very vary or zero, and especially the formation of secondary waste, requiring further treatment to be disposed off<sup>[9]</sup>. An excellent and feasible approach to address these issues is adsorption which has proven itself in the removal of heavy metal ions from aqueous effluent. In these studies, activated carbon has been traditionally used as the main adsorbent because of its large surface area reasonable pore volume, and its inertness to solutions<sup>[10]</sup>. However, high-temperature carbon activation is an expensive process, which means that its widespread application is restricted. The growing demand for a cost-effective and green approach to treatment, and biosorption has emerged as a perspective for treating heavy metal-containing effluents<sup>[11]</sup>. It involved the application of biological feedstocks, including, but not limited to, plant material and agricultural waste, as well as both living and non-living microorganisms, e.g., jackfruit bacteria, fungi, yeast, and algae. Biosorption is the adsorption of substances or adsorbates on the surfaces of homogeneous or heterogeneous biosorbents and thus efficiently removes pollutants from the solution<sup>[12]</sup>.

Plant material, which falls in the category of lignocellulosic material, is also a very attractive option, as it is abundantly available and has a large adsorption capacity<sup>[13]</sup>. Studies to evaluate the efficiency of all classes of plant materials: Unmodified and chemically modified biosorbents; suggest that plant waste (lignocellulosic) offers many advantages: Economical, easy operation, biodegradability, etc.,<sup>[14]</sup>. Moreover, these plant extracts contain an enormous array of Phytochemicals, of which secondary metabolites; polyphenols, terpenoids, phytosterols, saponins, and alkaloids are considered to be the most important. That is, the groups consist of amino, carbonyl, Hydroxyl (-OH), Carboxyl (-COOH), sulfonate, phosphate, thiol, imidazole, and halide which can rapidly react with metal ions bearing opposite charge<sup>[15]</sup>. Biosorbents are effective for metal capture and their adsorption capacity

can be improved through physical or chemical modification. Consequently, plant waste which is generally considered an economically valueless material would make an effective and cost-effective approach for the removal of heavy metals through adsorption mechanisms<sup>[16]</sup>. The existing review includes the toxicology of Cr (VI) and refers to the multi-talented plant-based lignocellulosic bio-adsorbents being leaves, stems, barks, seeds, shells, husks, peels, and rinds used for the elimination of Cr (VI) as well as the raw forms and the modified forms<sup>[17]</sup>. Furthermore, the review highlights the factors influencing biosorption, removal mechanisms, desorption potentials of biosorbents, and their regenerating abilities also presents recent progress on biosorbents modification and features future research directions that may provide useful guidelines for the academic community about the biosorption potential of different plant materials.

## CHEMISTRY AND TOXICITY of Cr (VI):

Hexavalent chromium (Cr (VI)) is also considered one of the most toxic and highly environment-stable forms of chromium. It is widely used in several industries including electroplating, stainless steel production, leather tanning, textiles dyeing, and antimicrobial agent in pigment, which is used to fabricate wood treaters to avoid decay<sup>[18]</sup>. Cr (VI) occurs mainly in the form of Chromate ( $\text{CrO}_4^{2-}$ ), Dichromate ( $\text{Cr}_2\text{O}_7^{2-}$ ), and Hydrogen chromate ( $\text{HCrO}_4^-$ ) under various pH conditions<sup>[19]</sup>. They have a great affinity towards water, particularly under weak basic or neutral pH, resulting in increased environmental transport and biological accumulation.

The Cr (VI) compounds are strong oxidants and can traverse biological membranes by nonspecific anion carriers, due to similarity to sulphate and phosphate ions. However, Cr (VI) is also reduced intracellularly by reducing cascades to form lower oxidation states i.e., Cr (V), Cr (IV), and finally Cr (III)<sup>[20]</sup>. This reduction leads to a variety of reactions intermediates and Reactive Oxygen Species (ROS), which cause oxidative stress, lipid peroxidation, protein oxidation, and Deoxyribonucleic Acid (DNA) strand breakage and are involved in cellular toxicity. Even though Cr (III) is a much less toxic form; however, due to its stable binding to DNA and proteins, extensive data indicate that it can also induce mutagenesis and carcinogenesis<sup>[21]</sup>. Group 1 carcinogens by the IARC and its epidemiological and animal data reveal that occupational exposure leads to an increased risk of

lung, nasal, and sinus cancers<sup>[22]</sup>. In addition, dermal exposure to Cr (VI) can lead to allergic contact dermatitis, skin ulceration, and eczemas, and oral intake may cause gastric irritation, liver injury, and nephrotoxicity.

Cr (VI) has been lethally toxic to aquatic, and terrestrial organisms and thus environmental pollution with Cr (VI) is a major environmental concern as it is highly persistent. It can bio accumulate in food chains, interfere with enzymatic processes, and negatively affect reproductive and developmental functions in flora and fauna alike. In many parts of the world soil and groundwater contamination by industrial effluents and haphazard disposal of wastes has become a significant public health problem.

For that reason, Cr (VI) has strict regulatory limits in air, water, and occupational environments

established by regulatory agencies such as the United States Environmental Protection Agency (EPA), WHO, and the Occupational Safety and Health Administration (OSHA). Thus, in the case of, say, drinking water, the EPA MCL for total chromium is 0.1 mg/l, whereas OSHA maintains a PEL as an 8 h time-weighted average of 5 µg/m<sup>3</sup> for Cr (VI) compounds. Advanced remediation strategies (e.g., bioremediation, chemical reduction, membrane filtration, and adsorption with inexpensive natural materials) are being developed and implemented to remove Cr (VI) pollution. In the meantime, the simultaneous industrial emissions controlling and sustainable detoxification devices design remains one of the greatest challenges of such environmental and public health divisions in many countries (Table 1).

**TABLE 1: COMPARISON OF CR (III) VS. CR (VI)**

Property	Cr (III)	Cr (VI)
Types	Trivalent chromium	Hexavalent chromium (e.g., CrO <sub>4</sub> <sup>2-</sup> , Cr <sub>2</sub> O <sub>7</sub> <sup>2-</sup> )
Solubility in water	Low	High
Membrane permeability	Poor	Easily crosses cell membranes
Characteristics	Poorly absorbed; essential trace element for glucose metabolism	Highly soluble, easily absorbed, strong oxidizing agent
Redox activity	Stable, not a strong oxidizer	Strong oxidizing agent
DNA/protein interaction	Binds after intracellular reduction	Causes DNA damage <i>via</i> ROS and direct action
Biological role	Essential trace element	No known beneficial role
Toxicity	Low	High
Regulatory status	Supplement form (e.g., Cr picolinate)	Carcinogenic (IARC Group 1)

## MECHANISMS OF Cr (VI) TOXICITY

Hexavalent chromium (Cr (VI)) is a toxicant that works through a complex toxicological mechanism that involves a multi-directional interplay of oxidative stress, genotoxicity, inflammation, and apoptosis. Cr (VI) can preferentially pass through cellular membrane non-specific anion channels and transporters, this is because of its structural similarity to sulphate and phosphate ions. This high permeability of cell membrane allows Cr (VI) to freely permeate different cell types (e.g. pulmonary epithelial cells, hepatocytes, renal tubular cells),

and immune cells. Once the Cr (VI) enters the cell, it undergoes a chain of reductions *via* the intermediate unstable Cr electron species, Cr (V) and Cr (IV) which ultimately forms a stable product of trivalent chromium (Cr (III)). This reduction is mediated by different intracellular reducing agents such as ascorbate, Glutathione (GSH), cysteine, and Nicotinamide Adenine Dinucleotide Phosphate (NADPH)-dependent enzymes. Cr (VI) toxins are predominantly due to the production of ROS by redox-conversions of Cr species. The ROS (oxygen radicals: Superoxide anion (O<sup>2-</sup>), Hydroxyl radicals

(•OH), and Hydrogen peroxide ( $H_2O_2$ ) could cause oxidative stress with damage to the essential biomolecules (DNA, protein, lipid, and cellular organelles) DNA damage can be composed of oxidative base alterations<sup>[23]</sup>, DNA-protein adducts, single and Double-Strand Breaks (DSBs), as well as of chromosomal damage. Cr (III), the end product of reduction, has a high affinity in DNA and nuclear proteins to form stable adducts that block DNA replication and repair processes, which can facilitate the development of mutations and carcinogenesis in cells. DNA binding capacity is an important factor in classifying Cr (VI) as a human carcinogen (Group 1; IARC).

Mitochondrial dysfunction represents another significant mechanism underlying Cr (VI) toxicity, wherein ROS induced by Cr (VI) disrupts mitochondrial membrane potential ( $\Delta\psi_m$ ), provokes cytochrome release, and activates the intrinsic apoptotic pathway involving caspases-3 and caspases-9. Furthermore, Cr (VI) diminishes intracellular antioxidant reserves, particularly GSH, thereby exacerbating oxidative injuries. In addition, Cr (VI) activates pro-inflammatory signalling pathways including Jun Kinase (JNK), Extracellular

Signal-Regulated Kinase (ERK), and p38 Mitogen-Activated Protein Kinases (MAPKs) signalling, and transcription factors including Nuclear Factor Kappa-B (NF- $\kappa$ B) and Activator Protein 1 (AP-1). This activation results in augmented production of proinflammatory cytokines (such as Interleukin (IL)-6, Tumor Necrosis Factor-Alpha (TNF- $\alpha$ )) and enzymes, such as inducible Nitric Oxide Synthase (iNOS) and Cyclooxygenase-2 (COX-2). Cr (VI) toxicity is also linked to epigenetic puzzles, with changes in DNA methylation, histone modifications, and the functioning of microRNAs that may unleash long-term deforming effects, and dysregulation of microRNAs, all of which may further contribute to long-term carcinogenic consequences. Moreover, prolonged exposure to Cr (VI) is linked to processes such as cellular senescence, immune suppression, and altered cell cycle progression (e.g., G1/S arrest), thereby amplifying its toxic potential. Collectively, the diverse mechanisms of Cr (VI) toxicity elucidate its capacity to induce both acute and chronic damage across multiple organ systems, particularly the lungs, liver, kidneys, and skin, depending on the exposure route and duration (Table 2)<sup>[24-28]</sup>.

**TABLE 2: MECHANISMS OF CR (VI) TOXICITY**

Step	Description	References
Cellular uptake	Cr (VI) enters cells <i>via</i> non-specific anion channels (similar to sulphate and phosphate transporters).	[24]
Intracellular reduction	Cr (VI) is stepwise reduced to Cr (V) and Cr (IV) and ultimately to Cr (III) within the cell, producing ROS during each reduction.	[25]
ROS generation	Hydroxyl radicals (•OH) are the result of the formation of superoxide ( $O_2^-$ ) and $H_2O_2$ , which generate oxidative stress and DNA damage.	[21]
Cr (III) Binding	Cr (III) binds covalently to DNA, Ribonucleic Acid (RNA), and proteins, leading to mutations, DNA cross-linking, and impaired cellular function.	[26]
Genotoxicity and carcinogenicity	DNA strand breaks, chromosomal aberrations, and interference with DNA repair enzymes may lead to mutagenesis and cancer.	[27]
Inflammation and apoptosis	Cr (VI) can activate NF- $\kappa$ B and p53 pathways, resulting in apoptosis, inflammatory response, and cytotoxicity.	[28]



## POSSIBLE MECHANISMS OF Cr (VI) REMOVAL BY BIOSORBENTS

The removal of hexavalent chromium Cr (VI) utilizing biosorbents entails a combination of physicochemical interactions and, in certain instances, biological transformations that enhance the efficient detoxification of this highly toxic metal<sup>[29]</sup>. Biosorbents encompass a range of materials, including plant-derived substances (such as agricultural residues, fruit peels and sawdust), microbial biomass (including fungi, algae and bacteria), as well as biochar. These materials are characterized by a richness in surface functional groups, including -OH, -COOH, Phenolic, Amine (-NH<sub>2</sub>), Sulfhydryl (-SH), and Phosphate (-PO<sub>4</sub><sup>3-</sup>) groups<sup>[30]</sup>. These functional groups play a crucial role in the interaction with Cr (VI) species through various synergistic mechanisms. Electrostatic attraction serves as a predominant mechanism, particularly under low pH conditions (typically ranging from 2 to 4), where Cr (VI) predominantly exists as negatively charged oxyanions (HCrO<sub>4</sub><sup>-</sup>, Cr<sub>2</sub>O<sub>7</sub><sup>2-</sup>, CrO<sub>4</sub><sup>2-</sup>)<sup>[31]</sup>. In acidic environments, the surface of biosorbents becomes protonated, resulting in a positive surface charge that attracts Cr (VI) anions *via* coulombic forces. Ion exchange also significantly contributes to this process, whereby Cr (VI) anions displace original anions such as Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, or OH<sup>-</sup> that are present on the surface of the biosorbents, particularly in materials possessing exchangeable sites like cellulose, hemicellulose, and lignin matrices<sup>[32]</sup>.

Surface complexation represents another critical mechanism, wherein Cr (VI) or its reduced forms (Cr (III)) form covalent or coordinate bonds with electron-rich functional groups present on the biosorbents. This process encompasses interactions

with -COOH, amino, and phosphate groups, which serve as ligands to bind chromium ions strongly and selectively<sup>[33]</sup>. Notably, many biosorbents, especially those containing natural reducing agents such as phenolic compounds, flavonoids, or microbial enzymes (e.g., CrO<sub>4</sub><sup>2-</sup> reductase), facilitate the reduction of Cr (VI) to Cr (III). This reduction is advantageous not only due to the lower toxicity of Cr (III) but also because it enables further removal through adsorption or precipitation<sup>[34]</sup>. The reduction-coupled adsorption mechanism involves electron transfer reactions that convert soluble Cr (VI) to Cr (III), which may subsequently be chelated or precipitated as insoluble Cr (OH)<sub>3</sub>, particularly in near-neutral pH conditions<sup>[35]</sup>. Additionally, in biosorbents derived from living microorganisms, bioaccumulation and intracellular sequestration may occur, where Cr species are actively transported *via* metal transport systems and sequestered in vacuoles or bound to metallothionein-like proteins.

Furthermore, pore diffusion and surface adsorption contribute to these mechanisms, particularly in porous materials such as activated carbon or biochar, wherein large surface areas and microspores facilitate metal ion capture through van der Waals forces and capillary condensation<sup>[36]</sup>. The efficiency of these mechanisms is influenced by several operational parameters, including pH, temperature, contact time, initial metal concentration, biosorbents dosage, particle size, and the presence of competing ions in solution<sup>[37]</sup>. In practical applications, the integration of multiple biosorption mechanisms fosters enhanced stability, reusability, and selectivity of biosorbents, rendering them promising candidates for industrial-scale remediation of Cr (VI) from aqueous environments (Table 3)<sup>[38-50]</sup>.

**TABLE 3: MECHANISMS OF CR (VI) REMOVAL BY PLANT BASED BIOSORBENTS**

Mechanism	Description	Typical functional groups	Cr species	Reference
Adsorption	Cr (VI) ions physically or chemically bind to the surface of biosorbents	-OH, -COOH, lignin, cellulose	Cr (VI)	[40,41]
Ion exchange	Exchange of native ions (e.g., H <sup>+</sup> , Na <sup>+</sup> ) on the biosorbent surface with Cr (VI) species	-COOH, -OH	Cr (VI)	[42,43]
Electrostatic attraction	Attraction of negatively charged Cr (VI) species to positively charged biosorbent surfaces	Protonated -NH <sub>2</sub> , -OH groups	Cr (VI)	[44,45]
Reduction (Cr (VI)-Cr (III))	Cr (VI) is reduced to Cr (III) by electron-donating groups (phenolic), often followed by Cr (III) binding.	Phenols, tannins, flavonoids	Cr (VI)	[46,47]
Chelation/ complexation	Formation of coordinate bonds between Cr ions and ligands present in the biosorbent	-COOH, -NH <sub>2</sub> , -OH	Cr (III)	[48,49]

Surface complexation	Covalent-like interaction of Cr (VI) with reactive surface sites	Modified -OH, -COOH	Cr (VI)	[43,47]
Micro precipitation	Formation of insoluble Cr(III) species (e.g., Cr (OH) <sub>3</sub> ) at or near the biosorbent surface	Local pH increase	Cr (III)	[46,48]
Hydrogen Bonding	Stabilizing secondary interactions between Cr species and biosorbent functional groups	-OH, -NH	Cr (VI)	[47,45]
Physical entrapment	Cr (VI) ions get trapped in the porous structure of the biosorbent	Porous structure	Cr (VI)	[42,50]

## PLANT BASED BIOSORBENTS AND THEIR MECHANISM OF DETOXICATION

In recent years, plant-based biosorbents have gained significant attention for their role as sustainable, cost-effective, and efficient materials in the extraction of toxic heavy metals, particularly hexavalent chromium Cr (VI) from aqueous environments<sup>[51]</sup>. These biosorbents are derived from a variety of agricultural residues, forest biomass, and industrial food processing wastes, providing an environmentally friendly alternative to traditional physicochemical treatment methods<sup>[52]</sup>. Common plant-derived biosorbents include sawdust, rice husk, coconut shell, wheat bran, peanut and walnut shells, banana peels, orange peels, sugarcane bagasse, corn cobs, tea waste, as well as the fibrous roots and leaves of plants such as drum stick, neem, water hyacinth, and Crown flower. The widespread availability and renewability of these materials, often treated as waste, contribute to their economic and environmental appeal for treating industrial effluents<sup>[53,51]</sup>.

The biosorption capacity of these materials primarily stems from their lignocellulosic composition, including cellulose, hemicellulose, and lignin-biopolymers rich in reactive functional groups, such as -OH, -COOH, C=O, (-NH<sub>2</sub>), Phenolic (Ar-OH), and Methoxyl (-OCH<sub>3</sub>) groups<sup>[54]</sup>. These functional groups are the active binding sites for Cr (VI) ions by various mechanisms like electrostatic attraction, ion exchange, complexation/chelation, hydrogen bonding, and physical adsorption. At low pH, the polymers in the plant biomass skeleton are protonated, thereby enhancing the electrostatic attraction for negatively charged species of Cr (VI), like HCrO<sub>4</sub><sup>-</sup> and Cr<sub>2</sub>O<sub>7</sub><sup>2-</sup><sup>[55]</sup>. A unique aspect of many adsorbents of plant origin is the capacity to promote *in situ* reduction of Cr (VI) to Cr (III), with this redox transition often being mediated by naturally occurring phenolic compounds (tannins, various

flavonoids, catechins, etc.) found within the plant matrix<sup>[56]</sup>. Upon reduction, the less toxic Cr (III) species can precipitate as Cr (OH)<sub>3</sub> at near-neutral pH or be further immobilized through complexation with surface groups. This reduction-coupled adsorption process is especially advantageous as it not only removes Cr (VI) but also detoxifies it in the process<sup>[57]</sup>. Moreover, certain biosorbents contain antioxidant enzymes and low molecular weight organic acids that augment redox activity.

Enhancing the performance of plant-based biosorbents can be achieved through pre-treatment and modification processes. Physical treatments (e.g., size reduction, drying, carbonization), chemical modifications (e.g., acid/base treatment, oxidation with H<sub>2</sub>O<sub>2</sub>, grafting with -NH<sub>2</sub> or thiols), and thermal activation can result in increased porosity, surface area, and enhanced density of functional groups<sup>[58]</sup>. For instance, acid-treated orange peel and alkali-modified sawdust have shown improved Cr (VI) sorption capacities compared to their unmodified forms. Furthermore, biochar produced from paralyzed plant biomass features a highly porous structure and considerable surface area, making it a superior material for heavy metal adsorption. Research indicates a broad range of maximum Cr (VI) adsorption capacities for various plant-based biosorbents, typically from 20 to over 200 mg/g, influenced by factors such as source material, treatment method, and operating conditions (e.g., pH, contact time, temperature, initial Cr (VI) concentration)<sup>[59]</sup>. Optimal removal is generally achieved at a pH of 2-4, where Cr (VI) species are more soluble and the biosorbents surface is favourably charged. Kinetic studies often reveal pseudo-second-order behaviour, indicating that chemisorption is a dominant mechanism, while isotherm models such as Langmuir and Freundlich are employed to characterize monolayer and multilayer adsorption processes (Table 4)<sup>[60]</sup>.

**TABLE 4: PLANT-BASED BIOSORBENTS FOR CHROMIUM REMOVAL**

Biosorbent	Source	Target Cr species	Functional groups	Optimal pH	Adsorption capacity (mg/g)	Mechanism	Contact time (min)	Reference
<i>Lemna minor</i>	Aquatic plant	Cr (VI)	Carboxyl, hydroxyl	5	~22.4	Reduction, electrostatic attraction, adsorption	60	[44]
<i>Chlorella vulgaris</i>	Green microalgae	Cr (VI)	Carboxyl, phosphate, -NH <sub>2</sub>	2	~45.6	Biosorption, electrostatic attraction, chelation	90	[45]
<i>Azolla pinnata</i>	Aquatic fern	Cr (VI)	Phosphate, hydroxyl	6	~18.3	Reduction, complexation, adsorption	60	[46]
Banana peel powder	Fruit peel waste	Cr (VI)	Carboxyl, hydroxyl	2.5	~30.5	Adsorption, Ion exchange, surface complexation	60	[41]
Tea waste	Tea industry waste	Cr (VI)	Polyphenols, hydroxyl	4	~23.1	Reduction, adsorption, hydrogen bonding	60	[47]
Rice husk ash	Agricultural waste	Cr (VI)	Silanol, carboxyl	2	~15.7	Physical adsorption, Ion exchange	120	[42]
<i>Moringa oleifera</i> Pods	Agro waste	Cr (VI)	Carboxyl, amino	4	~33.8	Chelation, adsorption, complexation	80	[48]
Coconut shell-activated carbon	Biomass waste	Cr (VI)	Hydroxyl, carboxyl	2	~48.3	Physical adsorption, surface complexation	90	[43]
Sawdust ( <i>Acacia nilotica</i> )	Wood industry by-product	Cr (VI)	Cellulose, lignin	2.0-4.0	~26.1	Adsorption, ion exchange, chelation	60-90	[40]
<i>Eichhornia crassipes</i>	Water hyacinth	Cr (VI)	Hydroxyl, phosphate	5.5	~19.4	Biosorption, electrostatic attraction, reduction	75	[50]
Coriander Seeds	Spice	Cr (III)	Carboxyl, hydroxyl	6	~11.2	chelation, adsorption, complexation (for Cr (III))	120	[49]

The study revealed that the efficient reduction of Cr (VI) from water and wastewater is highly dependent on the pH of the solution, shaking time, adsorbent type, initial concentration, and temperature<sup>[61]</sup>. Several studies indicate that the maximum removal efficiency of Cr (VI) using the various low-cost adsorbents ranged from 50.0-100.0 % with optimum pH and contact time ranging from 2.0-6.0 and 30.0-180.0 min, respectively at room temperature (25.0°)<sup>[62]</sup>.

Preclinical and clinical studies are essential for advancing plant-based biosorbents from experimental stages to real-world applications for chromium detoxification. They also help assess the safety and efficacy of these biosorbents and guide their incorporation into public health approaches<sup>[63]</sup>. Biosorbents are preliminary studies conducted on animal models that provide vital information regarding mechanisms of action and toxicity profiles.

Veterinary studies help identify an optimal dosage, determine the duration of exposure, and the most effective way to administer it so that chromium is detoxified from the body before human trials can begin<sup>[64]</sup>. They also evaluate the possible side effects or harmful effects due to long-term usage of plant-based biosorbents. Natural products derived from plant sources such as *Moringa oleifera*, *Azadirachta indica*, and *Phyllanthus emblica* have shown protective action on chromium-induced renal, hepatic, and pulmonary toxicity in animal models<sup>[65]</sup>. The preclinical observations provide essential safety data on the clinical use of plant biosorbents. Moreover, preclinical investigations uncover the cellular and molecular-level interactions of these materials on chromium. Understanding this assists researchers in identifying whether chelation, adsorption, or reduction acts as the main detoxification mechanism in chromium<sup>[66]</sup>.

In addition to assessing safety and efficacy, preclinical research is critical to comprehending the biokinetics of chromium when paired with plant biosorbents. These are the factors that affect chromium's Absorption, Distribution, Metabolism, and Elimination (ADME) in the body<sup>[67]</sup>. To evaluate whether these materials could prevent chromium accumulation and toxicity, researchers must study chromium's bioavailability and retention in biological tissues (e.g. liver or kidneys) in response to exposure to plant biosorbents<sup>[18]</sup>. Furthermore, the maximum uptake parameters can be useful in determining the optimal physicochemical characteristics of the biosorbents including surface area, functional groups, and porosity for effective chromium uptake and to limit undesirable interactions with other components of the cells<sup>[68]</sup>. As another step towards clinical studies, these trials give real evidence of the safety, efficacy, and long-term effects of plant-based biosorbents on humans. Animal models are not enough for human subjects, and clear evidence needs to be established for what has been observed in preclinical studies<sup>[69]</sup>. Although human exposure to chromium is most frequently a result of environmental contaminants and industrial occupation, this metal family also appears which be dangerous to human health, especially in areas of soil or groundwater high in contamination<sup>[70]</sup>. The chromium-related health risks (cancer, cardiovascular disease, neurological disease, and kidney failure) decreased with *Moringa*/Amla extracts, and these plant-based biosorbents are undergoing studies for clinical testing<sup>[71]</sup>. These studies highlight the protective roles such as showing the protective role of biosorbents against injury by analysing biomarkers including serum creatinine, Blood Urea Nitrogen (BUN), hepatic enzymes, and malondialdehyde (a marker of oxidative stress).

Furthermore, clinical studies elucidate the possible delivery of these biosorbents either as functional foods, dietary supplements, or *via* phytotherapy, thus providing easily applicable measures for potentially

huge populations exposed to chromium<sup>[72]</sup>. The importance of clinical trials goes beyond efficacy; they are necessary for regulatory approval of or standardization of plant-based biosorbents. Comprehensive clinical trials are designed to provide enough data for regulatory authorities like the Food and Drug Administration (FDA) and European Medicines Agency (EMA) to establish guidelines for safe and effective use<sup>[73]</sup>. Clinical trials of longer duration will be critical to assess the potential for these biosorbents to provide chronic protection for individuals with regular exposure to chromium including workers in industries like tanning, plating, and welding where exposure to Cr (VI) is routine<sup>[74]</sup>. Also, human studies play a major role in studying the interaction of chromium with plant-based biosorbent materials. Mass spectrometry, chromatography, Nuclear Magnetic Resonance (NMR) spectroscopy, etc. can allow for the monitoring of metabolic pathways for chromium and show how native compounds from plants (e.g., polyphenols, flavonoids, terpenoids, etc.) reduce the toxicity of chromium<sup>[75]</sup>. Moreover, studies show that certain bioactive substances in plant biosorbents can prevent chromium from being absorbed within the gastrointestinal tract, thereby preventing systemic dissemination.

Looking ahead, the success of plant-based biosorbents for chromium detoxification hinges on translating these preclinical and clinical insights into accessible, cost-effective solutions for global health<sup>[51]</sup>. As clinical trials yield more consistent data on the safety and efficacy of plant biosorbents, large-scale applications for environmental remediation and healthcare could become increasingly viable. For instance, integrating plant-based biosorbents into functional foods targeting chromium detoxification for at-risk groups may be possible<sup>[76]</sup>. Moreover, combining these biosorbents with traditional treatments could enhance chronic chromium exposure management further (Table 5)<sup>[77-83]</sup>.

**TABLE 5: PRECLINICAL AND CLINICAL STUDIES ON PLANT-BASED BIOSORBENTS FOR CHROMIUM DETOXIFICATION**

Study type	Plant/extract	Experimental model	Outcome/findings	Reference
Preclinical	<i>Azadirachta indica</i> (Neem)	Wistar rats exposed to Cr (VI)	Reduced oxidative stress, restored liver/kidney markers	[77]
Preclinical	<i>Moringa oleifera</i> leaf extract (Drum Stick)	<i>In vitro</i> +rats with K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> intoxication	Antioxidant protection, improved hematological profile	[78]
Preclinical	<i>Camellia sinensis</i> (Green tea)	Albino rats with chronic Cr (VI) exposure	Improved antioxidant enzyme levels, reduced lipid peroxidation	[79]



Preclinical	<i>Phyllanthus emblica</i> (Amla)	<i>In vitro+in vivo</i> (Cr-induced liver damage)	Reduced serum Cr levels, protection of hepatic tissue	[80]
Preclinical	<i>Curcuma longa</i> (Turmeric)	Rats+K <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub> injection	Reduced genotoxicity, DNA fragmentation, oxidative markers	[81]
Clinical (limited)	<i>Spirulina platensis</i>	Human volunteers in heavy metal-contaminated areas	Improved antioxidant markers, reduced heavy metal burden (non-specific to Cr only)	[82]
Clinical (pilot)	Polyherbal formulation (with <i>Moringa</i> , <i>Triphala</i> )	30 patients occupationally exposed to metals	Improvement in renal biomarkers, antioxidant levels (not chromium-specific)	[83]

## RECENT ADVANCES AND FUTURE PROSPECTIVE

Recent advancements in chromium detoxification utilizing plant-based biosorbents have focused on enhancing their efficiency, scalability, and real-world applicability in environmental and health contexts. Significant innovations have occurred in the functionalization and modification of plant-derived materials to improve their adsorption capacity, selectivity, and reusability<sup>[51]</sup>. Researchers have explored the Nano-structuring of biosorbents, wherein plant materials are engineered at the nanoscale to increase surface area, generate mesoporous structures, and improve metal binding sites<sup>[84]</sup>. For example, biochar and activated carbon derived from agricultural residues have exhibited significant improvements in Cr (VI) removal due to their increased porosity and surface area, achieved through modifications such as chemical activation (with phosphoric acid or potassium hydroxide) or thermal treatment<sup>[85]</sup>. These approaches demonstrate enhanced sorption kinetics and regeneration potential, making them increasingly suitable for continuous-flow systems and industrial applications.

Furthermore, the development of composite biosorbents that combine plant biomass with other materials, including clays, Metal-Organic Frameworks (MOFs), and polymeric matrices, has augmented the removal efficiency and stability of Cr (VI) in complex aqueous environments<sup>[86]</sup>. These composite materials leverage the complementary properties of both plant-based and synthetic components, allowing for improvements in mechanical strength, chemical resistance, and adsorption capacity. Hybrid biosorbents integrating plant materials with nanoparticles (such as silver, iron, or silica nanoparticles) have also shown enhanced adsorption properties, contributing additional catalytic or reductive effects in the Cr (VI) reduction process<sup>[87]</sup>.

On the biological front, genetically engineered plants and microorganisms have emerged as effective tools for the bioremediation of chromium. For instance, genetically modified plants that overexpress specific metal-binding proteins or enzymes capable of reducing Cr (VI) to Cr (III) have displayed improved detoxification capabilities<sup>[88]</sup>.

Looking forward, the future of plant-based biosorbents in chromium detoxification lies in the integration of multifunctional materials, combining plant-based biosorption with advanced oxidation technologies, membrane filtration, or biodegradable polymer systems to achieve more effective chromium recovery and treatment regeneration<sup>[89]</sup>. Additionally, green synthesis techniques for producing biosorbents from plant materials are expected to become more widespread, enhancing cost-effectiveness, environmental sustainability, and scalability. Addressing the challenge of translating laboratory successes into practical applications for wastewater treatment, industrial effluent clean up, and health-related interventions remains critical<sup>[90]</sup>. As our understanding of plant-metal interactions enhances and we develop more robust, bio-based materials, plant-based biosorbents are likely to play a crucial role in sustainable solutions for environmental remediation and the protection of human health from chromium toxicity.

## Conflict of interests

The authors declared no conflict of interests.

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