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Hyperaccumulator plants for chromium phytoremediation: A review

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Abstract

Heavy metal contamination is the result of the expansion of industrialisation and urbanisation. Physical and chemical methods of eliminating heavy metals from a polluted environment are inefficient, expensive and unpopular. The use of plants to clean up a polluted environment is known as phytoremediation. This review aims to report tolerant and hyperaccumulator plants for chromium heavy metal detoxification. Hexavalent chromium makes up the majority of chromium, emitted into the environment. Recent studies have identified tolerant and hyperaccumulator plants for chromium detoxification. The studies on chromium absorption capacity of some aquatic macrophytes is reviewed. The review discusses chromium absorption of plants from various sources like simulated wastewater, sewage water from treatment plants, tannery effluent, artificial electroplating and nickel ore mining industry effluent and water samples from various lakes. Most of these researches have proved that chromium toxicity can be reduced in a lab condition, but the results are restricted due to the differences between lab and natural situations. It is necessary to examine the tolerance of native plants that are more adapted and can bioremediate chromium from chromium-contaminated environments.

Keywords: aquatic macrophytes, chromium, heavy metal, hyperaccumulator, phytoremediation

Introduction

The use of heavy metal elements has increased dramatically as a result of the industrialization and urbanisation of developing countries, as well as the increasing demands of people. Heavy metals, unlike organic pollutants, are non-degradable and can only be transformed into forms with altered toxicity or bioavailability (e.g., bacterial reduction of Hg^{2+} to elementary Hg^0, which is less toxic and can evaporate, or the reduction of arsenate to less toxic arsenite oxyanions) [1]. Heavy metal's elemental character is responsible for its persistence in soils, sediments, and water bodies [2]. Heavy metal pollution thus poses a long-term threat to the environment and human health, not just in industrial and post-industrial settings. Physical and chemical methods of removing heavy metals from a polluted environment are frequently ineffective at large scales, as well as being costly and unpopular with the public [3]. In contrast, bioremediation, or the use of live organisms or their parts for remediation, is a set of techniques that can be used in broad contaminated areas, particularly when heavy metal contamination is not a pressing concern. Phytoremediation, or the use of plants to decontaminate a polluted environment, was first described in the mid-1990s [4]. Since then, a plethora of studies has focused on the usage of diverse plant species to remove or stabilise both organic and inorganic contaminants [5–7].

In general, the most commonly used strategies for remediating a heavy metal polluted environment are based either on heavy metal stabilisation in situ, i.e., reducing heavy metal acute toxicity by decreasing their mobility and bioavailability, or on heavy metal removal. When it comes to plants, the former is known as phytostabilization, while the latter is known as phytoextraction, which is a clean-up technology that employs plants to extract heavy metals from soils and accumulate them in harvestable sections, which are then removed and processed [8]. Another subgroup of clean-up approaches is phytovolatilization, which involves the biological conversion of heavy metals/metalloids such as Hg, As, and Se into a volatile state and their release into the atmosphere [9]. Heavy metals commonly discharged in water include As, Pb, Hg, Cd, Cr, Cu, Ni, and Zn. [10].

Numerous research investigations have demonstrated that various plant species are capable of effectively extracting chromium (Cr) from contaminated areas, which could be valuable in the phytoremediation process [11]. Chromium hyperaccumulators and their associated microflora have been employed to remove excess harmful chromium as well as organic waste from industrial effluent sites. Because of its high efficacy, cheap cost, and eco-friendliness, plant-microbe interaction is also one of the most effective ways for chromium detoxification [12]. To develop tolerance in response to chromium toxicity, multiple mechanisms involved in chromium detoxification have been unraveled at the molecular level. Stress caused by chromium activates ROS signaling, antioxidant responses, defense proteins such as phytochelatins (PCs), metallothionine (MTs), and glutathione-S-transferases (GSTs), followed by phytosequestration and compartmentalization, all of which contribute to the plants' bioaccumulating ability. To enhance plant tolerance and accumulation rate, another approach could be to develop transgenic plants by upregulating genes involved in chromium absorption, transport, and sequestration [13].

Characteristics of chromium

Chromium (Cr) is a naturally occurring element that can be found in the earth's crust, with oxidation levels (or valence states) ranging from chromium bivalent [Cr (II)] to chromium hexavalent [Cr (VI)] forms. Chromium penetrates numerous environmental matrices such as air, water, and soil from several natural and anthropogenic sources, with industrial enterprises releasing the most. Metal processing, tannery facilities, chromate production, stainless steel welding, and ferrochrome and chrome pigment production are the industries that contribute the most to chromium release. The majority of chromium released into the environment as a result of the anthropogenic activity is in the hexavalent form [Cr (VI)]. Hexavalent chromium [Cr(VI)] is a harmful industrial pollutant that has been identified as a human carcinogen by several regulatory and non-regulatory organisations [14]. Chromium contamination of soil and water is a recent worry. Chromium exists naturally in bonded forms that make about 0.1 - 0.3 mg/kg of the Earth's crust. Based on health concerns, the maximum allowable content of chromium in drinking water of 0.05 mg/L (50 mg/ L) has been established. The toxicity of chromium to plants is determined by its valence state; Cr (VI) is very poisonous and mobile (it is generally found linked with oxygen as chromate (CrO_4^{2-}) or dichromate) ($Cr_2\ O_7^{2-}$). Cr (III) on the other hand is less mobile, less hazardous, and is mostly found attached to the organic matter in soil and aquatic habitats [15]. In India, chromium is a major source of water contamination [16].

This review investigates hyperaccumulator plants for chromium phytoremediation.

Chromium Detoxification Using Phytoremediation

Phytoremediation is a green technique that uses plants to treat environmental contaminants. Plants can accumulate contaminants such as heavy metals by phytoextraction, phytostabilization, rhizo-degradation, phytotransformation, phytodegradation, and phytovolatilization processes. Plants' ability to absorb and remove heavy metals in high concentrations is vital in phytoremediation methods [17]. In response to heavy metal stress in the environment, plants create chelators and organic acids that bond with harmful metal ions. The complex formed by metal and chelator was sequestered by the cell, resulting in metal ion inactivation via compartmentalization in cellular parts of the plants [18].

In the last few decades, researchers have identified some tolerant and hyperaccumulator plants and studied their mechanism and use in the phytoremediation process. Nearly 500 plant species from 45 different families have been discovered thus far. When exposed to harmful metals, many of the tolerant hyper-accumulator plants converted them into less dangerous and immobile forms [19]. For the most part, the process behind chromium hyper-accumulators involves the function of high-affinity molecules such as amino acids, peptides, and organic acids, which bind metal ions and sequester them inside the vacuole. Increased rhizospheric metal mobilisation by organic acids; absorption using a variety of transporters and then translocating it into the shoot via xylem loading; and finally detoxification via chelation and compartmentalization within the vacuoles are all important factors governing the hyper-accumulation of chromium and other heavy metals [20].

Chromium Phytoremediation by Hyperaccumulator Plants

Phytoremediation, an environmentally sustainable method of rehabilitating contaminated soil and wastewater, can be a very efficient and cost-effective solution for combating chromium toxicity. Various research investigations have shown that many plant species can successfully remove chromium from contaminated areas, which could be important in the phytoremediation process (Table 1). The locally available macrophytes *Phragmites karka*, *Vetiveria nigritana*, and *Cana lilies* can be efficiently employed for metal removal, especially chromium, according to a study conducted to investigate the effectiveness of a Vegetated Submerged Bed Constructed Wetland (VSBCW) for removal of heavy metals from industrial wastewater in a steel manufacturing company [21]. The effects of reductants on Cr (VI) phytoremediation by *Ipomea aquatica* was examined in a study. Chromium concentrations in plant roots and shoots were impacted by the reductants utilised and their dosage levels [22]. During 15 days of phytoextraction experiments, the aquatic macrophyte *Potamogeton pusillus* was evaluated for the removal of Cu^{2+} and Cr^{+6} from aqueous solutions. The results showed enhanced Cr^{+6} phytoextraction in the presence of Cu^{2+} and bioaccumulation of these heavy metals by *Potamogeton pusillus* [23]. Based on chromium, cadmium and copper accumulation patterns in different plant organs, the bioaccumulation potential of six *Monochoria vaginalis* ecotypes was investigated. Heavy metal and plant organs being metal-specific by accumulating chromium and copper in aboveground parts and cadmium in belowground parts, implying genotypic roles in determining heavy metal and plant organs being metal-specific [24].

Table 1: Efficacy of chromium removal in various plants

Plant	Condition	Chromium concentration	Duration	Chromium removal efficiency	References
Spirogyra, Eichhornia crassipes Pistia stratiotes	Simulated wastewater	1, 3, and 5mg/l	15 days	*Spirogyra* 86% *Eichhornia crassipes* 92% *Pistia stratiotes* 99%	[25]
Azolla filiculoids	Sewage water	27.2 mg/kg	28 days	126%	[26]
Ipomoea aquatica	Microcosm Mesocosm experiment synthetic wastewater	Microcosm 0.01, 0.1, 0.9, and 4.4 mg/L Mesocosm 10 mg/L	4 days	82.8 % in microcosm 90.4% mesocosm	[27]
Eichhornia crassipes *Pistia stratiotes*	4 % Batik wastewater	596mg/l	15 days	*E.crassipes* 63.76 % *P.stratiotes.* 83.39 %	[28]
Chrysopogon zizanoides	Artificial electroplating wastewater	Different levels chromium concentration	28 days	61.10%	[29]
Azolla pinnata *Salvinia molesta*	Hoagland's nutrient solution with different concentrations of chromium	0.07, 0.09, 0.11 and 0.13mg/l along with control (untreated)	15 days	*Azolla pinnata* 72.86 - 97.69 % *Salvinia molesta* 75.71 - 90 %	[30]
Brachiaria mutica, Canna indica, Cyperus laevigatus, Leptochloa fusca, Typha domingensis	Tannery effluent in vertical subsurface flow CWs	Cr^{6+} (mg/L) 0.48 ± 0.15 Cr^{3+} (mg/L) 133 ± 1.4	42 days	*Leptochloa fusca* 55% *T.domingensis* 48% *B.mutica* 35%	[31]

Chrysopogon zizanioides	Laboratory condition	2L Cr (VI) to 5, 10, 30 and 70 ppm	49 days	87 % reduction in Cr (VI) 5 ppm container 51 % in 10 ppm container.	[32]
Salvinia molesta *Lemna gibba*	Wastewater from treatment plant	1.58±0.08 mg/l	7 days	*S.molesta* 81.66% *L.gibba* 86.99%	[33]
Pistia stratiotes Eichhornia crassipes	Prepared metal solutions of different concentrations	2, 4, 6 and 8 mg/L	30 days	*Pistia stratiotes* 77.3% *Eichhornia crassipes* 80.9% r	[34]
Pistia stratiotes	Synhetic waste water of nickel ore mining industry	0.5, 1, 2, 5 and 7 ppm	20 days	89%	[35]

A study of the remediation potential of *Eichhornia crassipes* (water hyacinth) for the removal of chromium (Cr), zinc (Zn), and nickel (Ni) found that the bioconcentration factor (BCF) for Zn, Ni, and Cr were 14.6, 12.5 and 10.2 respectively, indicating that *Eichorrnia crassipes* is a moderate accumulator of heavy metals, and thus the ubiquitous weed could be used to clean aquatic bodies threatened with pollutants [36]. In a study for enhanced treatment of wastewater from an electroplating industry, a constructed wetland with a vertical–horizontal subsurface flow with *Phragmites australis*, *Lythrum salicaria*, *Acorus calamus* and *Typha minima* was used. According to the findings, the combined model has a substantial elimination efficiency. The processing took 35 days, with removal efficiencies of 70–80 %for Zn^{2+}, Cu^{2+}, Mn^{2+}, and Cr^{6+} and a 60 % chemical oxygen demand (COD) [37]. A study was done to see how heavy metals including Cr, Mn, Cu, and Pb move from the Qalyasan stream's wastewater to roots and from roots to shoots in the macrophytes *Typha angustifolia* and *Phragmites australis,* using the bioaccumulation factor (BAF), enrichment factor (EF), and translocation factor (TF). The findings demonstrated that metal concentrations in macrophyte root and shoot tissues were significantly higher than in wastewater samples from the Qalyasan stream. Both species had bioaccumulation and enrichment factor values greater than 1. The wide range of values suggests that these plants could be regarded as trace metal accumulators, with the potential for both phytostabilization and phytoextraction [38]. Copper (Cu), Chromium (Cr), Iron (Fe), Manganese (Mn), Lead (Pb), and Zinc (Zn) concentrations in the aquatic ecosystem of the Bundelkhand region of Madhya Pradesh and Uttar Pradesh have been estimated. Four aquatic macrophytes *Eichornia crassipes, Pistia stratiotes, Lemna minor* and *Vallisneria spiralis* were chosen for phytoremediation study based on their abundance in selected study areas and *E. crassipes* and *Pistia stratiotes* were found to be promising plant species for remediation of polluted water bodies from a phytoremediation perspective [39]. The potential of *Potamogeton crispus* for heavy metal phytoremediation (Cu, Cr, Pb, As and Cd) in the Anzali wetland was assessed in a study and the results revealed that *P. crispus* accumulates significant amounts of Cu, Cr, Pb, As, and Cd based on their tested concentrations [40]. The hydroponic culture method was used to study chromium accumulation in *Ipomea cornea*, *Jetropha gasifolia* and *Heliotropium curassavicum,* and Cr^{+6} concentrations were found to be higher in *Heliotropium curassavicum* than in *Jatropha gasifolia* and *Ipomoea carnea,* indicating that *Ipomea cornea* and *Heliotropium curassavicum* have better chromium remediation capacity [41].

Conclusion and Future prospects

A number of phytoremediation studies are conducted in controlled hydroponic environments with varying amounts of chromium on a lab scale. Toxic chromium concentrations were significantly reduced and removed in these studies, but the results are limited since the conditions in the lab are so different from those found in nature. As a result, native plants that are better adapted and can bioremediate chromium from chromium contaminated areas need to be tested for toleration. Far more research is needed to determine the various transporters for chromium absorption and translocation within the plant so that the entire metabolic machinery can be comprehended. To date, only a few research have looked at molecular pathways and signals to see if they can help plants develop tolerance to chromium toxicity. There is a need to study the synergistic effect of rhizospheric microorganisms on phytoremediation systems to promote heavy metal removal in the phytoremediation process. In the future, genetically engineered aquatic plants may prove to be a beneficial tool for phytoremediation. The handling of post-remediation biomass is another issue that needs to be addressed.

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