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Review Article

Potential Role of Chitosan and Trichoderma in Remediating Cadmium Toxicity in Plants

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Abstract: Cadmium toxicity is one of the most serious environmental issues nowadays globally. Cd has high mobility and solubility in the water which enhances its uptake through cortical tissues of roots and hence reaches the xylem through apoplastic and symplastic pathways through ascent of sap and various transporters. The negative effects of cadmium stress on the plants include growth retardation, impaired photosynthesis, changed stomatal movements, enzymatic activities, metabolic activities and membrane functioning. Oxidative stress is primarily influenced through increased cadmium toxicity inside the plant. Microbial mediated remediation and application of biostimulators and elicitors like chitosan are also a promising way to enhance remediation process in plants in metal contaminated environment. The future of chitosan and Trichoderma-assisted bioremediation of cadmium toxicity is bright, especially as interest grows in sustainable and eco-friendly approaches to heavy metal contamination.

Keywords: Cadmium, Oxidative stress, Biostimulators, Chitosan, Trichoderma, Bioremediation. .

Introduction

Heavy metals are potent environmental pollutants which has become major concern in the ecosystem globally. Natural processes and increase in anthropogenic activities such as industrial waste, modern agricultural practices, sewage disposal has led to the accumulation of heavy metals like Cd in the soil [1]. Cd is a non-essential and extremely toxic heavy metal which consist of prolong biological half-life in the environment. It is commonly found in earth's crust along with zinc and released into the environment by zinc and copper industries, utilized in phosphatic fertilizers, urban compost, metal-based pesticides and thus gets accumulated globally [2]. The permissible level of cadmium intake in human dietary supplements is 60-70 µg day-1 while agricultural soil beyond 1ppm Cd concentration shows phytotoxic effects and decontamination methods must be practiced when its concentration reaches to 5-20 ppm in the agricultural land [3]. The phytotoxicity response occurs when critical Cd concentration in the soil reaches 8 mg kg^{-1} or in tissues 3-30 mg kg-1 or bioavailable Cd is > 0.001 mg kg^{-1} [4,5]. Plants uptake and absorb cadmium from soil and water through root cells and through atmosphere in minute amount. The extent of cadmium uptake and absorption by the plants is greatly dependent on its concentration in the soil system and bioavailability. Other factors that facilitate the uptake of cadmium include organic matter, pH, presence of other heavy metals or elements, redox reactions and temperature, organic acids in the rhizosphere. Additionally, the availability and accumulation of cadmium in the plant system is directly related to plant species and genotype, environmental conditions and presence of minerals [6]. The availability of cadmium usually differs at different pH. At acidic conditions, it exists as a free Cd^{2+} ions while at pH 6-7 cadmium exists in different forms such as CdCl-, $CdHCO^3$ and hydrated $CdCO^3$ [7] with cadmium complexes like $CdCl_n^{2-n}$ available to plants. Root secretions and exudates significantly affect Cd availability and toxicity in the plants by influencing rhizospheric pH, soil microbes and chelation capacity for Cd ions. The phenomenon of Cd accumulation in plant parts precisely depends upon the Cd entry through the roots and its sequestration within it along with translocation in the vascular tissues and dilution within the plant parts throughout its growth and development.

Cd has high mobility and solubility in the water which enhances its uptake through cortical tissues of roots and hence reaches the xylem through apoplastic and symplastic pathways through ascent of sap and various transporters. It is normally localized in the plant roots and very minute amount of Cd gets transported across different aboveground plant parts with the pattern roots > leaves > fruits > grains. The entry of cadmium into the root cells is governed by various factors such as cadmium concentration, plant species and minerals nutrient present in the soil. It enters into cells through various channels through several metal transporters including the ZIP family (ZRT- and IRT-like proteins) from yeast and IRT1 (iron-regulated transporter 1), Yellow stripe like transporters from oligopeptide transporter family [8,9]. Cadmium transport from roots to plant parts involves xylem loading, translocation in xylem and phloem and redistribution in phloem pathways. Cadmium gets accumulated in the vacuolar region of root cells and gets transported to tonoplast though several processes. Xylem mediates movement of cadmium to shoots via transpiration through leaves. It then gets sequestered either inside the vacuole or moved out through roots through membrane channels and pumps.

Effects of Cadmium on Plants

Cadmium is a nonessential and toxic element which imparts negative effects on plant species. Cadmium toxicity in the plants inhibits germination, suppresses plant growth and development and alters seedling physiological processes. It inhibits germination in wheat [10], barley [11], pea [12]. It negatively affects DNA formation in root cells. The common symptoms of cadmium stress include chlorosis, necrosis, stunted growth and dessication among plants [13,14]. Also it decreases chlorophyll content, retard photosynthesis and decrease plant growth. It hampers redox potential of the cell and induces the production of reactive oxygen species (ROS) ultimately causing oxidative burst inside cell and damages the biomolecules. The other negative effects of cadmium stress on the plants include growth retardation, impaired photosynthesis, changed stomatal movements, enzymatic activities, metabolic activities and membrane functioning. Additionally, cadmium uptake and absorption effects phytochemicals activity, mineral nutrition of plants and alters water balance inside plant system. affecting photosynthetic enzymes and carbohydrate metabolism further changes antioxidant which subsequently effects plant growth and development. Oxidative stress is primarily influenced through increased cadmium toxicity inside the plant. Increase in concentration of cadmium is directly related to excessive production of ROS like H_2O_2, O_2, and OH- in the plant cells. Mineral nutrients are essential for plant growth and development and cadmium uptake leads to disturbance in their absorption and translocation within plant systems. Besides this, it also imparts negative effect on crop growth, grain yield and yield related attributes [15]. Cd also altered molecular mechanism inside plant cells by impairing gene expression which initiated certain cellular responses for various stress related factors.

Chitosan Mediated Remediation of Cadmium Toxicity in the Plants

Application of biostimulators and elicitors may be a promising way to increase crop growth and yield without affecting soil health and environment and to cope up with the changes in environmental stresses. Recently chitosan has gained special attention in its role in plant tolerance to several abiotic stresses which is evident through comprehensive reports and reviewed thoroughly. Chitosan is produced from chitin, an important component of crustacean shells, such as crab, shrimp and crawfish, and is mainly made up of (1–4)-2-amino-2-deoxy-β-D-glucan. Chitin is synthesized as polymer of mol. wt. 30– 3000 kDa with DA greater than 90%. Chitosan mediated soil contaminated with heavy metals like cadmium involves either removal of metals through contaminated soils by active method or immobilization of metals. Chitosan can be used as soil amendments for metal contaminated soils and enhances metal sorption by the plants by forming water soluble metal-chitosan complexes [16]. Besides bioremediation strategy, chitosan also functions as plant growth promoter in many plant species. Recent findings suggested that chitosan has evolved as promising elicitors in the field of agriculture. Chitosan was first characterized as an elicitor in plant. It was reported to improve soil fertility and enhance nutrient uptake by plant, increased yield and quality of crops. Chitosan plays important role in enhancing growth of shoots, roots and flowering. It stimulates plant growth processes by enhancing plant physiological and biochemical attributes namely nutrient uptake, cell division and elongation, enzymatic activities and protein synthesis which eventually results in yield enhancement.

Trichoderma Mediated Remediation of Cadmium Toxicity in the Plants

Metal contaminated soils are unsuitable for agricultural purposes, hence remediation of these soils are requisite. Heavy metals like Cd are non-essential and extremely toxic to plants and soil, thus a sustainable eco-friendly strategy is imperative for its remediation and to prevent its bioaccumulation in the food chain. The knowledge that micro-organisms play an important role in plant production and environmental sustainability has been understood since ages [17]. Plant-microbe interaction has gained much attention in heavy metal stress tolerance as microbes have potential role in remediation and bioaccumulation of heavy metals like cadmium. Microbes like fungi, bacteria, algae are potential players in heavy metal stress tolerance due to their ability to produce great biomass, growing rapidly in the environment and flexibility to the existing environment. They have immense ability to confer the remediation of environmental contaminants and removal of pollutants from the natural environment. They are key and efficient players in bioremediation strategies for Cd contaminated environment. The technique of remediation of pollutants through fungi is known as myco-remediation. Myco-remediation imparts the potential utilization of fungal biomass, extracellular enzymes and fugal metabolism to alleviate the pollutants from the environment and agricultural land. Fungi are multi-cellular, heterotrophic and eukaryotic organisms that are potential decomposers and degraders of environmental contaminants and pollutants. Fungi are ubiquitous, diverse and dominant species on the planet, hence myco-remediation approach is feasible over conventional methods. They are known to remediate many heavy metals like As, Pb including Cd and mediate their accumulation in fruiting bodies and mycelia.

The ability of microorganisms to remediate heavy metal toxicity in the environment is mediated through certain processes. They can change the ionic state of metals that influences its solubility, bioavailability and movement through the soil and surroundings. Microbial remediation encompasses mobilization and immobilization of metal and metal complexes, further mediated by oxido-reduction, chelation and modification of metallic complexes in the environment. Moreover, the microbial communities utilize the processes of biosorption, bioaccumulation, biotransformation, and bioleaching to survive in metal contaminated environment. Furthermore, the fungal biome possesses certain degradative enzymes for removal of contaminant from the surrounding.

Trichoderma is a genus of soil inhabiting, teleomorph bearing filamentous fungi belonging to Hypocreales order of the Ascomycota division. Trichoderma species are known to tolerate and detoxify heavy metals and have been isolated from contaminated soils. Trichoderma asperellum has been used in phytoremediation process of lead and cadmium in Arabidopsis thaliana [18]. However, compared with physicochemical remediation, bioremediation is considered as the most feasible remedial technology for decontamination of polluted soils because it is more cost effective, environment compatible, sustainable, and associated with less secondary pollution. They employ metal stress tolerance by stimulating production of root metabolites, reducing oxidative stress in the plants, increased nutrient availability and acquisition inside plant tissues and hyperaccumulation of metal ions inside plant tissues. The remediation strategy of heavy metals like cadmium through Trichoderma includes bioaccumulation, biosorption, biovolatilization, and phytobial remediation. Besides this, Trichoderma plays crucial role in plant growth and development. The plant interaction with Trichoderma shows enhanced plant growth and crop yield along with enhanced nutrient uptake and transport within the plants. It stimulates root growth and enhanced root biomass in many plant species. They upregulate photosynthetic system, nitrogen use efficiency, carbohydrate metabolism, abiotic and biotic stress modulation in many crop species like Arabidopsis, wheat, tomato, potato and Poplar [19]. Hence, Trichoderma is a potential species that enhance growth and development in many plant species with sustainability. The effectiveness of remediating cadmium toxicity depends on crop species and mode of application. Chitosan can be used as a biosorbent for removing cadmium from contaminated water or soil, while Trichoderma can help mitigate the toxic effects of cadmium on plants and soil microorganisms. This synergistic approach can lead to more effective and holistic remediation of cadmium toxicity.

Conclusion and Future Prospects

Plants growing in metal contaminated soil contains a significant group of microorganisms that have capability to tolerate high concentration of metals and also provide benefit to both soil system and plants. Other than microbial mediated remediation, application of biostimulators and elicitors are also a promising way to enhance remediation process in plants in metal contaminated environment. The future of chitosan and Trichoderma-assisted bioremediation of cadmium toxicity is bright, especially as interest grows in sustainable and eco-friendly approaches to heavy metal contamination. Their complementary mechanisms provide a powerful strategy for tackling cadmium pollution in both soil and water. With continued research, optimization, and field testing, these natural bioremediation techniques could become key components in addressing cadmium toxicity on a global scale, offering an environmentally safe, cost-effective, and sustainable solution.

By using chitosan as a physical sorbent and Trichoderma as a biological agent, this approach could address multiple stages of cadmium contamination, from the initial contamination phase (removal from water or soil) to long-term remediation (improving plant tolerance and microbial health). Combining these natural methods could lead to a more sustainable, cost-effective, and environmentally friendly solution to cadmium pollution. Both chitosan and Trichoderma are biodegradable and non-toxic, making them suitable for large-scale, eco-friendly remediation projects. Despite the promising potential, there are still several challenges to overcome in the development of these technologies. The efficiency of chitosan and Trichoderma in real-world, complex contaminated environments (e.g., highly polluted soils or waters with varying pH and salinity) needs further optimization and research. Scaling up the production of chitosan-based materials and cultivating Trichoderma fungi for large-scale applications may present cost challenges. Future research could focus on making these processes more cost-effective. The stability of chitosan and the effectiveness of Trichoderma in remediating cadmium over extended periods need to be better understood to ensure the long-term sustainability of these techniques. The future prospects of chitosan and Trichoderma-assisted remediation of cadmium toxicity are highly promising, especially when combined for a multi-faceted approach. As research advances in areas like chitosan modification, Trichoderma's genetic manipulation, and optimization of remediation conditions, these methods are likely to become increasingly effective, environmentally friendly, and economically viable solutions for addressing heavy metal pollution in the future.

Future research will focus on developing more efficient chitosan-based materials, such as chitosan nanomaterials or chitosan composites, to improve cadmium uptake and regeneration capacity. There is a growing interest in field-based studies to assess the effectiveness of chitosan in large-scale remediation efforts, including wastewater treatment, soil detoxification, and phytoremediation support. The scalability of chitosan production from natural resources, such as crustacean shells, needs to be optimized for large-scale applications. Cost-effective and sustainable production methods will be key to the future widespread use of chitosan in bioremediation. Trichoderma can be genetically modified to enhance its resistance to cadmium and its ability to degrade or transform heavy metals. This could lead to the development of superior strains capable of handling higher levels of contamination and exhibiting more efficient detoxification pathways. Further research into the specific mechanisms by which Trichoderma enhances plant resistance to cadmium is needed. Understanding these interactions at a molecular level will enable the development of more efficient plant-fungus systems for bioremediation.

The use of Trichoderma in large-scale bioremediation, especially in soil-based phytoremediation projects, will require further validation and optimization. Trichoderma's impact on soil health and microbial diversity must be studied to ensure that its application is beneficial in the long term. Researchers may develop integrated bioremediation systems that combine chitosan adsorption, Trichoderma detoxification, and phytoremediation, making them more effective in treating large areas with cadmium contamination. This could be a highly efficient, low-cost, and environmentally friendly alternative to current methods. Developing specific formulations of chitosan and Trichoderma for particular environmental conditions (e.g., soil pH, moisture content, and contamination levels) will be a key focus. Such formulations could ensure that the remediation process is optimized for a variety of contaminated environments.

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