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CADMIUM- IMPACTS ON PLANT AND PHYTOREMEDIATION : A REVIEW

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Abstract

Today a major concern is heavy metal toxicity. Cadmium is non-essential, non-biodegradable highly toxic and may act as a carcinogen. Along with natural sources; several anthropogenic activities increase its toxicity in environment. It shows its toxicity at very low concentration. Cadmium can translocate to shoot and another plant parts through root system. It has bad impact on plants, microorganisms, and also on human beings. Cadmium has a role on seed germination, growth and development, photosynthesis, ROS production etc. To combat its bad effects, plants have employed several phytoremediation processes.

1. Introduction

Now a days, a long-lasting and increasing threat is heavy metal toxicity to environment. Most of the heavy metals are trace elements in plant having significant role in several physiological functions at low concentration. Due to presence of high conc. of them, soil becomes polluted. Sources of heavy metals are coal combustion, expanding industrial emissions, fertilizers, pesticides, petrochemical spillage, sewage sludge etc. [1]. Even at low concentration it shows toxicity [2, 3]. Cadmium (Cd), mercury (Hg), lead (Pb), nickel (Ni), zinc (Zn), iron (Fe), manganese (Mn), magnesium (Mg), cobalt (Co), copper (Cu), antimony (Sb), chromium (Cr) etc. are very commonly present in soil [4, 5, 6]. In soil maximum inorganic pollutants don't undergo microbial or chemical degradation; they persist as their own form for a long time [7].

Highly toxic, non-essential, non-biodegradable, carcinogenic cadmium is electropositive, soft, silver white metal placed 'd' block and ' Group 12' in periodic table. It has more than 20years of biological half-life with atomic number 48, atomic mass 112.41, density 8.64 g/cm^3 and melting temperature 321° C [8, 9].

It is the general consideration that if concentration of the total cadmium (Cd) in soil exceeds 8 mg kg^{-1}, or its bioavailability becomes >0.001 mg kg^{-1}, or its concentration reaches 3–30 mg kg−1 in plant tissues, most plants exhibit visible Cd toxicity symptoms [10].

Pure cadmium can't be present in soil. It remains as ores of carbonate, sulphides and oxides of lead, zinc, copper etc. Oxides are less water soluble than sulphide and carbonate which are toxic to plants [11, 12]. Through root system, it can translocate into plant parts. Not being only restricted in root system, it also becomes transported to shoot and accumulate in edible part. P-type (P1B) ATPase is responsible for cadmium translocation from root too shoot. e.g, OsHMA3, a heavy metal ATPase 3 and OsHMA2 are found in case of rice plant [13, 14].

Easily identifiable symptoms are chlorosis and stunted growth in plants [15]. Several scientific studies on cadmium toxicity have impacts on ROS production, crop productivity, lipid peroxidation etc. as well as remediation of all these problems [16, 17, 18, 19, 20].

2. Roles of cadmium on plant

a) On seed germination*:*

- Increase of Cd^{2+}conc. at µmol/L level has inhibitory/ reducing effects on seed germination in soybeans, lettuce and sugar beet and spinach [21].
- In case of *Vigna unguiculata* L. seed, cadmium decreases the water absorption. Thus, water supply is limited for seed embryo development [22].
- Due to cadmium stress, α-amylase activity is reduced which decreases starch release from cotyledons [23].
- Calmodulin and cadmium relationship has an important role in metabolic activation during early stages of seed germination. In *Raphanus sativus L*. Ca and Cd shows competition for Ca-calmodulin binding sites [24].

b) On plant growth, development and dry weight*:*

- Cadmium stress hampers root elongation in crop plants like rice, wheat, tomato etc. [25, 26, 27].
- After long-term Cd exposure, root elongation reduces in crop plants because of decomposition, necrosis and mucilaginous deposition and shoots also become reduces. As a result, leaf rolling and chlorosis occur [25, 26, 27].
- Cadmium toxicity responsible for common abnormalities in roots like fragmentation, stickiness, precocious separation, bridges and ligands [28]
- Accumulation of high amount of Cd^{2+}, plant root length decreases. e.g.; 0.02 cm is reduced due to 70 µmol/L Cd treatment. Shoot length also becomes suppressed for increasing cadmium conc.
- Because of abnormal enlargement of cortical cell layers and apical part of epidermis, tap root becomes rigid, brown and twisted [29, 30]. Cadmium is also responsible for inhibiting lateral root development and tap root development [29].
- By minimizing mitotic division of meristematic cells, cadmium can reduce root length, dry biomass and increases root diameter [31, 32].
- Total leaf area and dry weight of plant decrease under Cd stress [33].

c) On photosynthesis*:*

- Cadmium is an effective photosynthetic inhibitor [34]. In leaves, Cd accumulation inhibits the stomata opening in oilseed, legume and cereal crops. This indicates a relationship between transpiration and inhibition of photosynthesis [35].
- Short-term and long-term exposure to cadmium toxicity hampers the photosynthetic activity in many crops including rapeseed [36], pea, maize, barley [37], wheat [27] and mungbean [38].
- Light harvesting system and Photosystem I and II are affected by Cd toxicity [39].
- Primary action sites of cadmium are photosynthetic apparatus, pigments, chlorophyll and carotenoids synthesis [40]. Cadmium has ability to minimize chloroplast density which interacts with chlorophyll biosynthesis. As a result, chlorosis occurs in oilseed crop [41]. This chlorophyll amount reduces more abundantly in stomatal guard cell than mesophyll cell.
- Rubisco and PEPCase enzymes play an important role in carbon fixation during photosynthesis. By replacing co-factor Mg^{2+} ion, responsible for carboxylation reaction, Cd^{2+} decreases Rubisco activity. Replacement of Mg ion shifts carboxylation activity of Rubisco towards oxygenation reaction [37].

d) On Protein and amino acids*:*

- Under stress condition, eukaryotes can synthesize heat-shock proteins [15]. 70 kDa phosphoprotein, a heat-shock protein is synthesized by maize under Cd stress condition.
- In Pea heat-shock protein HSP71 and pathogen-related protein-PrP4A have important role to protect the cell from Cd toxicity [42].

e) On plant-water relation*:*

- Water-related changes occur across the entire plant because of cadmium exposure. In roots, water absorption is reduced and short distance water transport in apoplast and symplast pathways are inhibited by Cd toxicity.

- According to Malecka et al., 2008, cadmium enriched soil has lower osmotic ability than root cell sap. This condition can limit plant water adsorption and causes osmotic pressure [43].

f) On ROS production

- Due to Cd exposure reactive oxygen species (ROS) production is induced and toxic effects results from this oxidative stress in a cascade manner.

- Cd can play the role of a co-factor by replacing the essential metalloprotein ions, the so called Fanton reaction [44, 45]. As a result of this alter reaction, lipid peroxidation becomes induced in plant cell due to the production of substances like ROS, O_2^-, OH and H_2O_2 and all these happens for essential nutrient uptake [46, 47]. These results cell membrane destruction.
- Even ion and redox homeostasis also get disturbed in cellular metabolic activities [48]. Basically over production of O_2^- takes place as a result of Cd induced oxidative stress in parts like root, shoot etc. in seedlings.

3. Remediation of cadmium toxicity

I. Cadmium tolerance capacity of plant:

- **Plant species*:*** Different plant species like beet, turnips and kale family have different levels of sensitivity to different trace elements and are much sensitive to metals. Soybeans, spinach, lettuce etc. are moderately sensitive to soils, containing cadmium [49]. In high cadmium containing soils (i.e., >100ppm), rice, tomato, cabbage, squash etc. can grow.

- **Age and plant species*:*** In Quack grass, early spring shoots can accumulate high conc. of trace elements like Cd, Cu, Cr, Hg, Pb, Zn, Ni and Mn whereas tissues at later stage can accumulate these elements in low conc. [50]. Therefore, it is sure that most of the consumable parts do not contain the significant level of heavy metal.
  Different plant parts contain different conc. of trace elements such as vegetative tissue contains large amount of metals than seeds or grains. In sludge treated soils, growing corn accumulate Cd and Zn conc. in following order- leaf> stem> husk> kernel.

II. Phytoremediation*:* In in-situ bioremediation approach, direct use to accumulate, extract, sequester and to immobilize or detoxify cadmium in soil is known as phytoremediation of cadmium [51]. It is cost-effective and eco-friendly. For treating large, diffused contaminated area, phytoremediation is used while physical and chemical remediation technique is strictly used in small contaminated area. Plants, those contribute for phytoremediation, possess rapid growth, high biomass production, deep and dense root system and high coefficient of bioaccumulation [52]. Phytoremediation is classified into different categories like phytostabilization/ phytoimmobilization/ phytorestoration, phyto-extraction/phytoaccumulation, rhizofiltrtation, phyto-stimulation, phyto-volatilization/ rhizovolatilization and phytodegradation [53, 54]. Phytoextraction is the prime process used for Cd remediation [55, 56]. Brief description of these processes are as follows which are applicable for Cd remediation-

***Phyto-extraction/* Phyto-accumulation:** It is a low impact technology**.** To remove Cd from contaminated soil or water at low and high concentration, phyto-extraction mechanism is involved [57]. Based on toxin translocation from root to shoot and leaves, this mechanism is established [58]. Along with nutrient and water, plants accumulate contaminants from contaminated place. They can't destroy these contaminants but prefer to accumulate in shoots, leaves and other parts of plants [59]. To neutralize the effect of metallic and 'radioactive' species waste plants widely utilized the phytoextraction process which has a great scope to establish the commercialization of this method having low initial investments and great opportunity to mitigate environmental problem of those lands contaminated by heavy metals [60]. Phyto-extracts of rapeseed can reduce 60% Cd in soil than control [61]. Plants used in phyto-extraction, possess following characters- (i) have ability for accumulating high conc. of heavy metals within their biomass, (ii) capacity of high absorption as well as translocation, (iii) high growth rate and extensive root system, (iv) high tolerance to contaminants. For determining plant potential of accumulation of heavy metals, several aquatic plant species like *Myriophyllum aquaticum* [62], *Mentha aquatic* [63], *Pistia stratiotes*, *Spirodela polyrrhiza*, *Ludwigina palustris* [64] were studied. High amounts of Cd can be accumulated by grain crops. Some root crops and leafy crops can able to accumulate cadmium [65]. Table 1 shows some cadmium accumulating plant species.

Table 1: Cadmium accumulating plant species:

Name of plant species	**Cadmium accumulating medium**	**Cadmium accumulating plant part**	**References**
Solanum photeincarpum	soil	Root, stem	[66]
Brassica junea	soil	-	[67]
Thlaspicaerulescens	soil	Shoots	[68]
Arabis paniculata Franch	water	Roots	[69]
Cyperus rotundus	-	-	[70]
Amaranthus hypochondriacus L.,	soil	-	[71]
Solanum nigrum L.,	soil	-	[71]

Phytolacca acinosa Roxb.,	soil	-	[71]
Celosia argentea L.,	soil	-	[71]

Several chemicals or surfactants viz. EDTA (Ethylenediamine tetraacetic acid) [72, 73], CDTA [74], DTPA, EDDHA [75], citric acid [72] and NTA [76] can increase mobility of metals in soil. In plants the absorption rate of metals is also enhanced by employing these chemicals [77].

Phytostabilization / phytoimmobilization: In this process, contaminants are immobilized to other plant parts and restricted at root region. Plants utilized in this process can accumulate heavy metals by root hair, root surface adsorption or precipitation by rhizosphere [78, 79, 80]. This process reduces the bioavailability of heavy metals and prevents entering it to food chain. By this process, soil metal transform into less toxic form [81]. In case of high organic content containing soil, this process is very effective [82]. This method is helpful to rectify the contaminated sites having high metal concentration to re-instead the proper vegetation. Some metal tolerant plant species can be utilized to control the emigration of different contaminants by agents like rain, wind and leaching into groundwater [83]. Plant associated microbiota assists in this process. Microbe- associated heavy metal resistance process are as follows- (i) by permeability barrier/ active expulsion of metal outside the cell, (ii) by using extracellular polymer, (iii)to transform into less toxic form of metal [84]. In phytostabilization, combinedly grass and trees work better due to non-accumulation of metals by grass in their shoots. This process reduces toxic metal exposure to animals [85]. Table 2 shows cadmium phytostabilizing plant species.

Table 2

Cadmium phytostebilizing plant species.

Name of the plant species	**References**
Tamarindus Indica	[86]
Populus cathayana, *P. prezwaskii*, *P. yunnanensis*	[57]
Nicotiana tabacum L.	[87]
Zea mays	[88]
Sorghum	[89]

- ***Rhizofiltration:*** This method works with the synthesis of several chemicals in the roots to adsorb pollutants as plants of some nature may contain several phytochelating to bind with metal ion pollutants and thus increase its adsorption [90]. To retain Pb, Cd, Cu Zn, Ni and Cr within root, rhizofiltration is needed [91]. For remediation of waste water, ground water and surface water containing low conc. of contaminant, this technique is used [92, 93]. In this mechanism the plant utilized, possess hairy and longer root system with considerable surface area for filtering the pollutant from aqueous solutions [94]. Table 3 shows rhizofiltration plant species.

Table-3

rhizofiltration plant species

Sl. No.	**Name of plant species**	**References**
1.	*Brassica napus*	[95]
2.	*Helianthus annuus L*	[95]

Above-mentioned two plants species are favorable for rhizofiltration process because they possess the aforesaid characters.

- ***Phyto-volatilization:*** According to Moreno et al., 2004 by using plant, uptake of contaminants, increasing and release of these contaminants in environment as less harmful form is known as phyto-volatilization [96]. These less toxic volatile materials are formed by using plant-based transpiration cycle [97]. Because of not're-deposition' at/ or near the site of gaseous volatilized products phyto-volatilization considered as permanent contaminated site solution. Table 4 shows cadmium volatilizing plant species.

Table- 4

Cadmium volatilizing plant species

Sl. No.	**Name of plant species**	**References**
1.	*Silphium perfoliatum*	[98]
2.	*Acanthus ilicifoliusL.*	[99]
3.	*Typha latifolia L.*	[100]
4.	*Cynodon dactylon*	[100]
5.	*Quercus ilex*	[101]

- ***Rhizodegradation**:* is a plant species-microbes specific symbiotic process [102, 103]. Root associated microbes can remediate contaminated soil by rhizodegradation, a rhizospheric biological degradation process. Plants supply energy sources i.e., carbon compounds to associated microbes to enhance the metabolic activities for degradation or removal of cadmium from contaminated soil. Edaphic and environmental factors have great impact on this symbiotic relationship. e.g.; soil pH can change Cd bioavailability in plant associated rhizospheric plane. Cd translocation and bioaccumulation are significantly increased by oxalic acid and citric acid of root exudates of *Echinochloa crusgalli* [104]. By changing several physical, chemical and biological conditions like pH, moisture, temperature, organic matter, microbial metabolism etc. we can enhance or suppress rhizodegredation process.

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