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RESEARCH ARTICLE

TOXICITY OF CADMIUM IN PLANTS

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ABSTRACT

Cadmium are important environmental pollutants and their toxicity is a problem of increasing significance for ecological, evolutionary, nutritional, and environmental reasons. So, if high concentration of heavy metals is accumulated in the plants that adversely affect the absorption and transport of essential elements, disturb the metabolism and have an impact on growth and reproduction of the plant. Cadmium (Cd) is a heavy metal, recently which has attracted the more attention in plant nutrition due to its relative mobility in the soil plant system. Plant root is the main organ of water and nutrient entry to the plant body. It is also the main organ for uptake of pollutants including heavy metals like cadmium. This review summarizes the toxic effects of cadmium in plants (i.e. growth retardation, alterations of photosynthesis, stomatal movement, enzymatic activities, water relations, interferences with mineral uptake, protein metabolism, membrane functioning etc.) and also includes the mechanisms of cadmium uptake, translocation and deposition.

INTRODUCTION

Heavy metals are metallic elements having high density (greater than 4 g/cm^3) and are more toxic or poisonous even at their low concentration (Lenntech Water Treatment and Air Purification, 2004). Of the total 90 naturally occurring elements, 53 are considered heavy metals (Weast, 1984) and few are of biological importance. Heavy metal toxicity is one of the major abiotic stresses that cause hazardous effects in plants (Hossain *et al*., 2012). Cadmium (cd), a common and transitional metal and available in the environment which is one of highly dispersed metals by human activities (Morsy *et al*., 2011). Cadmium has acute and chronic effects on health and environment. Once cadmium is released into environment, it stay in circulation and is not degraded in nature (Nordic Council of Ministers Cadmium Review January, 2003). Cadmium is toxic to plant cells, so crop productivity was decreased due to cadmium contamination on agricultural land (Smith, 2009). Geochemically Cadmium is quite mobile in soil, water and thus freely taken up by plants. Excess concentration of Cd^{2+} could cause the decrease in plant growth development and yield even the accumulation in plants (Curguz *et al*., 2012, Chen *et al*., 2003, Benavides *et al*., 2005). On the topsoil, Cadmium is concentrated with organics (Tudoreanu *et al*., 2004). In soil higher cadmium concentrations can occur either naturally or through anthropogenic activities (Kirkby *et al*., 2008). Mostly the cadmium pollution in the environment has occurred through the mining, refining of metal ores, through the application of cadmium-containing phosphate fertilizers, sewage sludge and municipal composts to agricultural soils (Alexander *et al*., 2010). Cadmium used in the manufacture of various products, such as batteries, chipsets, pigments, televisions, and semiconductors also cause of cadmium pollution (Hashim *et al*., 2004).

Cadmium uptake, translation and deposition

Cadmium enters through roots into the plant body in a form of cadmium chelates with the help of zinc and iron regulated transporters like protein. Cadmium easily penetrates into the root system and through apoplastic and symplastic pathway it reaches to the tissues of aerial parts of plants (Verbruggen *et al*., 2009). Different metal ions have different mobilities and due to this metals content is generally greater in roots than in the above ground tissues (Ramas *et al*., 2002). Most cadmium ions are retained in the roots and only small amounts are transported to shoots. In general, the concentration of cadmium in plants decreases in the order: root > leaves > fruits > seeds. After uptake by the roots, cadmium is transferred to the shoots through the cells of vascular bundles. Movement of the trace metal is also regulated by vascular tissues (Conn *et al*., 2010). Cadmium uptake and accumulation by plant roots is generally inhibited by La^{3+}, Ca2+ Cu^{2+}, Fe^{2+}, Zn^{2+}or Mn^{2+} in the rhizosphere solution (Zhao *et al*., 2006). Xylem is the major route for root to shoot translocation. In phloem sap cadmium ions present in complex condition because of the presence of the abundance of organic ligands (organic acids, amino acids, sugars, peptides and proteins) and their alkaline pH (pH 7.0-8.0) that favour the stability of sulphydryl-containing ligands, which are likely to be carriers of Cd. It is presumed that phytochelatins and phytometallophores play a role in cadmium movement in phloem sap and in loading cadmium into seeds and grains. The compounds that bind cadmium in mature seeds during their development are not exactly known but Hsieh *et al*., (1996) reported that cadmium may bind to phytate (myo-inositol hexaphosphate) in globoid crystals within the protein bodies of developing seeds. After the uptake of the heavy metals by the plants these deposited/accumulated in plant tissue and cell compartments. Many factors influence the uptake of metals and include the growing environment, such as temperature, soil pH, soil aeration, Eh condition (particularly of aquatic environment) and fertilization, competition between the plant species, the type of plant, its size, the root system, the availability of the elements in the soil or foliar deposits, the type of leaves, soil moisture and plant energy supply to the roots and leaves (Alexander *et al*., 2010). As far as the growing environment is concerned the increase in pH, makes the environment becoming more alkaline, and decrease in Eh (redox potential), hence the environment becoming more reducing, result in decrease in availability of heavy metals, or metals in general to plants.

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EFFECT OF CADMIUM ON PLANTS

a. Effects of cadmium on the growth of plants

Cadmium inhibited lateral root formation while the main root becomes brown, rigid, mucilaginous, twisted and it also cause reduction in root and shoot elongation and rolling of leaves (Rascio *et al*., 2011). Cadmium causes disordered division and abnormal enlargement of epiderma and cortical cell layers in the apical region and also causes changes in the leaf included alterations in chloroplast ultrastructure, low contents of chlorophylls, chlorosis and restricted activity of photosynthesis (Miyadate *et al*., 2011). In pea plants, the cadmium stress also caused disorders in root elongation and the mitotic process (Tuan *et al*., 2013). Cadmium cause reduction in the grain germination indices (FGP final germination percentage, MDG mean daily germination, GI germination index and CVG coefficient of velocity of germination), root anatomical traits as root diameter, central cylinder diameter, cortex thickness, cross section area of root and cross section area of central cylinder and leaf structures traits as thickness of midrib, upper epidermis and parenchyma and vascular bundle, in contrast they increased mean germination time (MGT) (Salah *et al*., 2013). Seedlings represent a more easily damaged stage of the life cycle. In crops such as rice and cotton (Qin *et al*., 2000) and vegetabsles such as spinach (*Spinaciaoleracea Linn*.) (Song et.al., 1996), *Brassica chinensis* L. and *Braseniaschreberi* L. (Yang *et al*., 2001), seedlings were easily injured and inhibited by the heavy metal pollution in a hydroponical exposure. The effects of heavy metals on plants are different in different growth stages of plants. Root vitality is reduced under heavy metal stress measured the root vitality of *Stylosanthesguianensis* in mine tailings, it was reduced by heavy metals (Pb, Zn, Cu and Cd) and the absorption of inorganic nutrients was prevented. Plants that grown in cadmium contaminated soil have less number of adventitious roots. The inhibition of root growth was probably caused by cadmium-induced depolymerization of microtubules of the cell cytoskeleton and chromosome aberrations, which resulted in lower mitotic activity of meristematic cells (Fusconi *et al*., 2006; Seth *et al*., 2008). Inhibition of root growth at high Cd concentration may affect nutrient and water uptake (Chen *et al*., 2003).

b. Effects of heavy metals on the cell division

Cadmium interferes directly with cell division in leaf (Tuan *et al*., 2013). Cadmium causes abnormal mitosis division in plant (Aery *et al*., 2012). Mo *et al*., (1992) studied effects of Cd on the cell division of root tips in beans. These results showed that the cell division was extended under a low concentration of 0.01, 1.0 and 10 ppm of Cd, Pb and Zn, respectively, while cell division was shortened but the cell cycle was extended by increasing the dose. Zhang (1997) investigated the effects of Cd, Hg and Pb on the cell division of barley (*Hordeum vulgate* Linn.) and also showed the trend of cell cycle extension under the 0.01 mol/L concentration treatment.

c. Effects on the form of chromosome

The genotoxicity of heavy metals in plants influences the synthesis, and the duplication of DNA and chromosomes both directly or indirectly, as well as inducing chromosomal aberration. Cadmium causes chromosomal aberrations of root tips (Tuan *et al*., 2013). The effects relate positively to heavy metal dosage. Zhang (1997) treated the barley with cadmium and showed that cadmium combined with nucleic acid and damaged the structure of the nucleolus, as well as causing chromosome fragmentation, aberration, conglutination and liquefaction. Exposed to cadmium, lead, mercury, the chromosomes of beans, garlic and onions were injured and revealed polyploid, C-karyokinesis, chromosomal bridges, chromosomal rings, and chromosome fragmentation, chromosome fusion, micro-nuclei and nuclear decomposition (Duan *et al*., 1995). The high concentration of heavy metals in medium, in which plants could not grow normally, affected the SCE (sister chromatid exchange) frequency in root tip cells of *Hordeumvulgare*. Cr203 or CdC12 could be detected by SeE tests even if there is a lower dose level.

d. Effects of heavy metals on cell membrane

The enzyme system is the interface and barrage between the cell and environment for substance and information exchange. The stabilization of this enzyme system is the basis for the physiological functions in the cell. Cadmium damages the enzyme system and increases the penetration of cell membrane (Li *et al.,* 1992) and there is a significant relationship between the penetration of cells and the concentration of cadmium. The absorption polypeptide compositions of the thylakoid membrane of the macrophyte Braseniaschreberi were degraded under cadmium stress. Under cadmium treatment, the accumulation of O_2, H_2O_2 and malondialdehyde (MDA) in wheat (*Triticumaestivum* L.) leaves were significantly enhanced, the content of SH group dropped and the electrolyte leakage out of the leaf cells was much higher, it indicated lipid peroxidation of cellular membrane was stimulated by endogenously active oxygen radicals (Luo, 1999).

e. Effect on photosynthetic system

Cadmium short and long term exposure affects photosynthesis. Cadmium induced decrease in pigment content was more powerful at the leaf surface (stomatal guard cells) than it was in the mesophyll. Cadmium might interfere directly with chloroplast replication in leaf (Tuan *et al*., 2013). Chlorophyll content can be reduced because of the destructive enzymes and chlorophyll decrease in carbon fixation is particularly high concentrations of cadmium contamination (Vassilev *et al*., 1997).

f. Effect on Enzymes

The value for nitrate reductase activity in leaves decreased due to accumulation of cadmium on leaves (Sharma *et al*., 2013). Superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) are important enzymes for plants adapted to environmental stress, they are called the plant protective enzymatic system. SOD, POD, CAT showed variation in their activities that depends on cadmium concentration (Tuan *et al*., 2013). Cadmium decreased the activity of carbonic anhydrase in plants.

g. Effect on proteins and amino acids

Protein synthesis was greatly affected by cadmium. The reduction in the amount of protein could be due to decrease in protein synthesis or an increase in the rate of protein degradation. In roots of soybean plants cadmium treatments 50 and 200 μM have caused an increase in the rates of protease activity. However in nodule, higher concentrations of cadmium (200 μM) decreased both protease activity and total protein content (Balestrasse *et al*., 2003). This reflects the toxic effects of supra cadmium concentrations on protein synthesis machinery which results in both a decrease in protease activity and the content of other proteins (Balestrasse *et al*., 2003). Under a lower stress with Cd (lower than 20 mg/L), the contents of proline increased little in wheat seedlings, but increased higher under concentrations of 50 and 100 mg/L. Cadmium cause production of reactive oxygene species (ROS) in plant and animal cells (Sobkowiak *et al*., 2004). The total protein and glutathione content of barley and maize roots declined with an increase in heavy metal concentration however, this decrease was more in the roots than in the shoots (Shanthala *et al*., 2006).

h. Effects on absorbtion of nutrients

Cd also affected the absorption of Mn and Zn by roots of *B. chinensis* seedlings (Qin et.al., 1994), inhibited the absorption of Fe, Mn, Cu, Zn, Ca and Mg by ryegrass (*Loliumperenne*), maize (Zea mays), shamrock (*Trifoliumrepens*) and cabbage (*B. oleracea* var. capitata) and increased the absorption of P (Yang et.al., 1998). These results show that Cd inhibited the absorption of N, K, Mg, Mn by plants. The effects on absorptions of P, S, Ca, Zn, Fe are more complicated are related to plant species and environmental stress, pH, elements.

i. Effect on water status

Increasing concentration of cadmium up to 150 mg/kg soil decreased significantly relative water content and water content of radish plant as compared to control (Farouk *et al*., 2011).

j. Effect on Sugar contents

The presence of cadmium in the soil had a negative effect on total sugars contents. Sugar content decreased significantly with increasing cadmium concentrations, compared to control plants (Farouk *et al*., 2011)

k. Effect on plant-water status

Heavy metals have an influence on plant-water status, causing a direct reduction in the absorption surface by inhibiting the formation of root hairs. The highest reduction in RWC was observed under high cadmium concentration. Decreased water content in different plant species growing in the presence of toxic levels of heavy metals was previously reported (Gouia *et al*., 2000). According to Barcelo *et al*., (1990), water uptake reduction may be mediated through the following effects of heavy metals: 1) decreased root elongation, 2) decreased rate of assimilates movement from shoots to roots, 3) decreased hydraulic permeability and conductivity, 4) loss of endodermis integrity, 5) increased root suberization and lignification, and 6) increased rate of root tip dieback.

Defence mechanism against cadmium in plants

Plant tolerance mechanisms include accumulation and storing of cadmium by binding it to amino acids, proteins and peptides (Pal *et al*., 2006). Other mechanisms that plants have developed to cope with damage caused by cadmium are related to some stress signalling molecules, such as salicylic acid, jasmonic acid, nitric oxide, and ethylene. All these compounds were induced by cadmium treatment, which suggests that they are involved in cell response to cadmium toxicity (Popova *et al*., 2012). Many plants survive, grow and develop in cadmium-polluted soils even in high concentrations of cadmium. Investigations showed that some of these plants exhibit a hypertolerant capacity of their organelles and tissues. Strategies to cope with cadmium toxicity involve the uptake and the distribution of cadmium, defined as "hyperaccumulation". On the other hand, some plants increased cleaning up of the reactive oxygen species (ROS) by antioxidants to protect cells and tissues from destruction. Thus, the mechanism of cadmium tolerance in plants can include both antioxidant defence and hyperaccumulation defence (Rascio *et al*., 2011).

Other effects

Nitrogen fixation and primary ammonia assimilation decreased in nodules of soybean plants during cadmium treatments (Balestrasse *et al*., 2003). Metal toxicity can affect the plasma membrane permeability, causing a reduction in water content; in particular, cadmium has been reported to interact with the water balance. Cadmium treatments have been shown to reduce ATPase activity of the plasma membrane fraction of wheat and sunflower roots. Cadmium produces alterations in the functionality of membranes by inducing lipid peroxidation and disturbances in chloroplast metabolism by inhibiting chlorophyll biosynthesis and reducing the activity of enzymes involved in CO_2 fixation. The development of endodermis under the effect of cadmium is accelerated and casparian bands and suberin lamellae are developed closer to the root apex (Martinka *et al*., 2004). Cadmium disturbs cellular redox environment of the root causing oxidative stress (Puertas *et al*., 2004). Various parts of root metabolism are affected as a consequence of cadmium, including water and nutrient uptake and inhibition of several enzyme activities. Heavy metal accumulation in plants has multiple direct and indirect effects on plant growth and alters many physiological functions by forming complexes with Oxygen, Nitrogen and Sulphur ligands. Heavy metals interfere with mineral uptake (Zhang *et al*., 2002; Kim *et al*., 2003; Shukla *et al*., 2003; Drazic *et al*., 2004; Adhikari *et al*., 2006) protein metabolism.

Conclusion and Discussion

In the recent years, cadmium toxicity in higher plants as well as in the soil-plant system has increased but there are still many gaps in our knowledge about the basic mechanisms that control cadmium movement and its accumulation in plants. Cadmium affects plants growth, metabolism in many ways like damage to roots, chromosomal abbreviations, activities of enzymes, rate of photosynthesis, chlorophyll contents, nitrogen fixation and protein metabolism. Certainly more research is needed to understand the cadmium uptake by the root, translocation and its deposition within plants so that we can minimize its toxic effect on plants. Plants have well organized defence system to tolerate the toxic effects of heavy metals upto a certain concentration but plants cannot tolerate high concentration of heavy metal. A genetic approach as opposed to physiological or biochemical investigations may assist in understanding the mechanism of metal tolerance.

Future prospects

There is a growing interest in problems concerning heavy metals contamination of cultivated land. It is very necessary to make some strategies for minimizing cadmium toxicities. Proper plant nutrition is a good strategy to alleviate the damaging effects of cadmium. Crop rotation and the use of other organic and inorganic amendments are some other approaches being used to remediate cadmium contaminated soil, but these approaches are time consuming and require extra resources. Therefore, to remediate or to utilize the cadmium polluted land we need to develop genetically modified plant species which can tolerate high concentration of heavy metals.

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