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CADMIUM INDUCED TOXICITY IN PLANTS: IMPACT ON GROWTH, DEVELOPMENT AND BIOCHEMICAL ATTRIBUTES.

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ABSTRACT

This review emphasises cadmium toxicity on plants with regards to ecological, physiological and biochemical aspects. Cadmium toxicity in plants and problems concerning tolerance and ecological performance are discussed briefly. Heavy metals are important environment pollutants and their toxicity is a problem of increasing significance for ecological, evolutionary, nutritional and environmental reasons. Plants possess homeostatic cellular mechanisms to regulate the concentration of metal ions inside the cell to minimize potential damage that could result from the exposure to non-essential metal ions.

Key words: cadmium toxicity, effects, plants, growth.

INTRODUCTION

The term heavy metal refers to any metallic chemical element that has a relatively high density and is toxic or poisonous at low concentrations. Examples of heavy metal include mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), thallium (Tl),

and lead (Pb). Heavy metals are natural components of the Earth's crust. They cannot be degraded or destroyed. Heavy metals are dangerous because they tend to bio accumulate. Bioaccumulation means an increase in the concentration of a chemical in a biological organism over time, compared to the chemical's concentration in the environment. Compounds accumulate in living things any time they are taken up and stored faster than they are broken down (metabolized) or excreted.

Cadmium (Cd) is a naturally occurring metal situated in the Periodic Table of the Elements between zinc (Zn) and mercury (Hg), with chemical behavior similar to Zn. It generally exists as a divalent cation, complexed with other elements (e.g., $CdCl_2$). Cd exists in the earth's crust at about 0.1 part per million, usually being found as an impurity in Zn or lead (Pb) deposits, and therefore being produced primarily as a byproduct of Zn or Pb smelting.

Cadmium is a heavy metal of considerable environmental and occupational concern. It is widely distributed in the earths' crust. The highest level of cadmium compounds in the environment is accumulated in sedimentary rocks, and marine phosphates. Effects of cadmium toxicity in plants are as follows:

- Cadmium decreases leaf conductance
- Cadmium affects CO_2 uptake
- Cadmium chloride induces stomatal closure in the nanomolar range of concentration
- Cadmium chloride induces stomatal closure via a calcium channel inhibitor sensitive pathway

Cadmium toxicity in crops has become in a serious problem, especially in developed countries. Cadmium accumulation in soils may come from different sources, including air pollutants and soil applications of commercial fertilizers, sewage sludge, manure and lime (McGrath et al., 1994). Also, industrial effluents may contain a wide variety of pollutants depending on the industries involved, and in many cases high concentrations of heavy metals have been reported (Iribar et al., 2000). In polluted soils, Cd is generally present as free ions or different soluble forms, and its mobility depends on pH and on the presence of chelating substances and other cations. Plants can accumulate Cd during plant growth, and the accumulation often occurs in edible parts, thus endangering crop yield and quality and becoming a potential hazard for human and animal health. Cadmium is suggested to cause damage even at very low concentrations, and healthy plants may contain Cd levels that are toxic for mammals (Chen et al., 2007). Moreover, it is widely recognized that Cd taken up by plants is the main source of Cd accumulation in food (Pinot et al., 2000). Most of the information available about Cd physiology in plants comes from studies with the Cd-hyperaccumulator *Thlapsi caerulescens* (Lombi et al., 2002) and Cd-tolerant plants such as *Arabidopsis halleri* (Weber et al., 2006), whereas less information is available in commercial crops such as tomato. It is commonly assumed that Cd, as well as other heavy metals, are taken up by transporters of essential elements, because of the lack of specificity of these proteins. There is evidence that metal transporters from different families such as ZIP and Nramp are able to transport several divalent cations, including Cd (Korshunova et al., 1999). Also, it has been described that a Ca transport pathway could be involved in Cd uptake (Clemens et al., 1998). Cadmium tolerance in plants is thought to involve internal metal detoxification processes, which may be achieved through both cellular and subcellular compartmentation (Küpper et al., 2007) and/or complications with cellular ligands such as phytochelatins, organic acids, cisteine and other low molecular weight thiols (Cobbett and Goldsbrough, 2002). Although long distance Cd transport also contributes to Cd distribution and accumulation throughout the plant (Chen et al., 2007), little is known about the chemical form(s) in which this heavy metal is present in xylem and phloem saps. Data available suggest that Cd may be associated in the xylem sap with small molecules such as organic acids. Physiological effects of Cd toxicity in plants include inhibition of seed germination, major reductions in growth rates, changes in photosynthetic efficiency, respiration and transpiration (Greger and Ögren, 1991) and alterations in nutrient homeostasis, including a Cd induced, Fe deficiency and changes in Mn, K, Mg and Ca uptake rates. At the cellular level, Cd toxicity is known to cause alterations such as membrane damage, disruption of electron transport, inhibition/activation of enzymes and interaction with nucleic acids (Chen et al., 2003a). Possible mechanisms by which these disorders are generated are induction of oxidative stress and replacement of elements such as Zn, Fe, and Mn, which are essential cofactors of many enzymes. Accordingly, there are several reports documenting oxidative stress following exposure to high concentrations of Cd (Smeets et al., 2005).

SOURCES OF CONTAMINATION

There are different sources of heavy metals in the environment such as: natural, agricultural, industrial, domestic effluents, atmospheric sources and other sources. Cadmium has been widely dispersed into the environment through the air by its mining and smelting as well as by other man-made routes:

- usage of phosphate fertilizers,
- presence in sewage sludge, and
- various industrial uses such as NiCd batteries, plating, pigments and plastics

The most important sources of airborne cadmium are smelters. Other sources of airborne cadmium include burning fossil fuels such as coal or oil and incineration of municipal waste such as plastics and nickel-cadmium batteries (which can be deposited as solid waste). Cadmium may also escape into the air from iron and steel production facilities.

Cadmium is used mainly:

- in metal plating,
- in producing pigments,
- in NiCd batteries,
- as stabilizers in plastics, and
- as a neutron absorbent in nuclear reactors.

When released into the atmosphere by smelting or mining or some other processes, cadmium compounds can be associated with respirable-sized airborne particles and can be carried long distances. It is deposited onto the earth below by rain or falling out of the air. Once on the ground, cadmium moves easily through soil layers and is taken up into the food chain by uptake by plants such as leafy vegetables, root crops, cereals and grains.

Cadmium concentrations in drinking water supplies are typically less than 1 microgram per litre (μg/L) or 1 part per billion (ppb). Groundwater seldom contains high levels of cadmium unless it is contaminated by mining or industrial wastewater, or seepage from hazardous waste sites. Soft or acidic water tends to dissolve cadmium and lead from water lines; cadmium levels are increased in water stagnating in household pipes. These sources have not been reported to cause clinical cadmium poisoning, but even low levels of contamination add to the body's accumulation of cadmium.

Cadmium oxide also exists as small particles in air (fume) which are the result of smelting, soldering, or other high-temperature industrial processes. A certain percentage of these particles are respirable. From the soil, certain plants (tobacco, rice, other cereal grains, potatoes, and other vegetables) take up cadmium more avidly than they do other heavy metals such as lead and mercury. Cadmium is also found in meat, especially sweetmeats such as liver and kidney. In certain areas, cadmium concentrations are elevated in shellfish and mushrooms.

Cadmium can also enter the food chain from water. In Japan, zinc mining operations contaminated the local water supplies with cadmium. Local farmers used that water for irrigation of their fields. The soil became contaminated with cadmium which led to the uptake of cadmium into their rice.

EFFECTS OF CADMIUM IN PLANTS

Cadmium is a non-essential element that negatively affects plant growth and development. It is released into the environment by power stations, heating systems, metal-working industries or urban traffic. It is widely used in electroplating, pigments, plastic stabilizers and nickel-cadmium batteries (Sanitá di Toppi and Gabrielli, 1999). It is recognized as an extremely significant pollutant due to its high toxicity and large solubility in water (Pinto et al., 2004). Genotoxicity and ecotoxicity of cadmium in animals have been also reported. Important sources of cadmium input to the marine environment include atmospheric deposition, domestic waste water and industrial discharges. Regarding its potential toxicity for soil organisms and soil microbial processes, Duxbury (1985) classified Cd as an element of “intermediate” toxicity. Although the toxic effects of cadmium on biological systems have been reported by several authors (Das et al., 1997; Sanitá di Toppi and Gabrielli, 1999), the mechanisms of Cd toxicity are not completely understood yet. Cadmium can alter the uptake of minerals by plants through its effects on the availability of minerals from the soil, or through a reduction in the population of soil microbes (Moreno et al., 1999). Stomatal opening, transpiration, and photosynthesis have been reported to be affected by cadmium in nutrient solutions, but the metal is taken up into plants more readily from nutrient solutions than from soil. (Sanitá di Toppi and Gabrielli, 1999). Chlorosis, leaf rolls and stunting are the main and easily visible symptoms of cadmium toxicity in plants. Chlorosis may appear to be Fe deficiency, phosphorous deficiency or reduce Mn transport. The inhibition of root Fe(III) reductase induced by Cd led to Fe(II) deficiency, and it seriously affected photosynthesis (Alcantara et al., 1994). In general, Cd has been shown to interfere with the uptake, transport and use of several elements (Ca, Mg, P and K) and water by plants. Cd also reduced the absorption of nitrate and its transport from roots to shoots, by inhibiting the nitrate reductase activity in the shoots (Hernandez et al., 1996). Appreciable inhibition of the nitrate reductase activity was also found in plants of *Silene cucubalus*. Nitrogen fixation and primary ammonia assimilation decreased in nodules of soybean plants during Cd treatments (Balestrasse et al., 2001). Metal toxicity can affect the plasma membrane permeability, causing a reduction in water content; in particular Cd 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 (Fodor et al., 1995), and disturbances in chloroplast metabolism by inhibiting chlorophyll biosynthesis and reducing the activity of enzymes involved in CO_2 fixation.

Cadmium homeostasis

The sensitivity of plants to heavy metals depends on an interrelated network of physiological and molecular mechanisms that includes uptake and accumulation of metals through binding to extracellular exudates and cell wall, complexation of ions inside the cell by various substances, for example, organic acids, amino acids, ferritins, phytochelatins, and metallothioneins; general biochemical stress defense responses such as the induction of antioxidative enzymes and activation or modification of plant metabolism to allow adequate functioning of metabolic pathways and rapid repair of damaged cell structures (Sanita di Toppi and Gabrielli, 1999; Hall, 2002).

Effect of Cd on growth and development

Cd toxicity causes inhibition and abnormalities of general growth in many plant species. After long-term exposure to Cd, roots are mucilaginous, browning, and decomposing; reduction of shoots and root elongation, rolling of leaves, and chlorosis can occur. Cd was found to inhibit lateral root formation while the main root became brown, rigid, and twisted (Krantev et al., 2008; Rascio and Navari-Izzo, 2011). The main reason indicated is disordered division and abnormal enlargement of epiderma and cortical cell layers in the apical region. The changes in the leaf included alterations in chloroplast ultra structure, low contents of chlorophylls, which caused chlorosis, and restricted activity of photosynthesis (He et al., 2008). In pea plants, the Cd stress also caused disorders in root elongation and the mitotic process and caused chromosomal aberrations of root tips. The observation showed that in these abnormalities as lagands, bridges, stickiness, precocious separation, and fragments were most common (Siddiqui et al., 2009). At high Cd concentration (250 µM), the disorder of mitosis of roots in pea happens rapidly, even after 24 h of treatment. An unusual number of nucleus populations in the differentiated roots were found

Effects of Cd on photosynthesis

In many species, such as oilseed rape (*Brassica napus*) (Baryla et al., 2001), sunflower (*Helianthus annuus*) (Di Cagno et al., 2001), *Thlaspi caerulescens* (Küpper et al., 2007), maize, pea, barley (Popova et al., 2009), mungbean (*Vigna radiate*) (Wahid et al., 2008), and wheat (Moussa and El-Gamal, 2010), the evidence showed that photosynthesis was inhibited after both long-term and short-term Cd exposure. A large number of studies have demonstrated that the primary sites of action of Cd are photosynthetic pigments, especially the biosynthesis of chlorophyll and carotenoids. According to Baryla et al. (2001), the observed chlorosis in oilseed rape was not due to a direct interaction of Cd with the chlorophyll biosynthesis pathway and most probably it was caused by decreasing of chloroplast density. the Cd-induced decrease in pigment content was more powerful at the leaf surface (stomatal guard cells) than it was in the mesophyll. In addition, the change of cell size, and the reducing of stomata density in the epidermis in Cd-treated leaves were observed. Thus, Cd might interfere directly with chloroplast replication and cell division in the leaf. This research also revealed that stomatal conductance was strongly reduced by Cd. Cd ions are known to affect the structure and function of chloroplasts in many plant species such as *Triticum aestivum* (Atal et al., 1991), *Beta vulgaris* (Greger and Ögren, 1991), *Vigna radiata* (Keshan and Mukherji, 1992), *Spinacea oleracea* (Sersen and Kral'ova, 2001), and *Phaseolus vulgaris*

Effect of Cd on mineral nutrition

It has been reported that uptake, transport, and subsequent distribution of nutrient elements by the plants can be affected by the presence of Cd ions. In general, Cd has been shown to interfere with the uptake, transport, and use of several elements (Ca, Mg, P, and K) and water by plants. In sugar beet, deficiency of Fe in roots induced by Cd was observed (Chang et al., 2003). In pea plants, the uptake of P, K, S, Ca, Zn, Mn, and B was inhibited strongly after Cd exposure (Metwally et al., 2005). Treatment of barley plants with 1.0 µM Cd decreased the concentrations of P, K, Ca, Mg, Cu, Fe, Mn, Zn, Mo, and B in roots, whereas the concentrations of these elements in shoots were not decreased in comparison with the control (Guo et al., 2007). A decrease in uptake of Ca and K by Cd has been found in a Cd-hyperaccumulator, *Atriplex halimus* subsp. schweinfurthii (Nedjimi and Daoud, 2009). Cd also reduced the absorption of nitrate and its transport from roots to shoots, by inhibiting nitrate reductase activity in the shoots (Hernandez et al., 1996). Appreciable inhibition of the nitrate reductase activity was also found in plants of *Silene cucubalus*. Nitrogen fixation and primary ammonia assimilation decreased in nodules of soybean plants during Cd treatments (Karina et al., 2003). The observation of Cd-treated soybean seedlings showed that there was an increase in laccase activity (laccases are responsible for lignin biosynthesis), during the early stage of Cd treatment, whereby Cd induced the lignin synthesis in early stage of root growth and as a result might cause inhibition of root elongation (Yang et al., 2007).

Defence mechanisms against Cd in plants:

The mechanisms leading to heavy metal tolerance can be divided into avoidance strategies and tolerance strategies. Avoidance leads to limitation of Cd uptake. Plant tolerance mechanisms include accumulation and storing of Cd by binding it to amino acids, proteins, and peptides. Other mechanisms that plants have developed to cope with damage caused by Cd are related to some stress signalling molecules, such as salicylic acid, jasmonic acid, nitric oxide, and ethylene. All these compounds were induced by Cd treatment, which suggests that they are involved in cell response to Cd toxicity (Rodríguez Serrano et al., 2009). Many plants survive, grow, and develop in Cd-polluted soils even in high concentrations of Cd. Investigations showed that some of these plants exhibit a hypertolerant capacity of their organelles and tissues. Strategies to cope with Cd toxicity involve the uptake and the distribution of Cd, defined as "hyperaccumulation". On the other hand, some plants increased cleaning up of the ROS by antioxidants to protect cells and tissues from destruction. Thus, the mechanism of Cd tolerance in plants can include both antioxidant defence and/or hyperaccumulation defence (Rascio and Navari-Izzo, 2011).

CONCLUSION

In conclusion, Cd affects photosynthesis either directly or indirectly thus decreasing the crop yield. We reviewed its inhibitory effect on pigments, lipids, photosystems proteins and chloroplasts. Summing up all we investigated net loss in photosynthesis. It can be said that much has been known about Cd toxicity to plants but numerous mechanisms remains debatable about its interaction with photosynthetic proteins i.e. D1 and D2 and oxygen evolving complexes. In particular, we should extend our knowledge towards PSI measurements to get an intricate knowledge on effect of Cd on photosynthesis. Strategies must be evolved on understanding the mechanism of Cd hyperaccumulation to uphold various phytoremediation strategies.

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