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Detoxification Mechanisms of Mercury Toxicity in Plants: A Review

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Detoxification Mechanisms of Mercury Toxicity in Plants: A Review

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Abstract
Mercury is one of the most toxic heavy metals present in the earth's crust. It has been considered as environmental pollutant because of its potent toxicity to plants and humans. In this review, we discuss mercury toxicity responses on plant metabolism and its detoxification mechanism by phytochelatins and antioxidant enzymes. Some light is also shed on selenium antagonistic study with mercury. Due to its potential toxicity, it has attracted attention in fields of soil science and plant nutrition. Mercury has harmful toxic effects on the molecular and physiobiochemical behavior of plants. Mostly research work has been done on seed germination, and shoot, root, and leaf morphology. Enzyme responses with respect to mercury as a result Hg accumulated in food chain is also reviewed here. Hence, this review may provide a compiled data for other researches in this direction, to provide a better mechanism or details about mercury's noxious effect in the ecosystem.

Keywords: Mercury; Phytochelatins; Ecosystem; Physiobiochemical behavior; Selenium; Toxicity; Plants.

1. INTRODUCTION

The rapid industrial and technological advancement by man has become a menace for himself. Heavy metals are emitted into the environment by both natural and anthropogenic causes. The major causes of emission are the anthropogenic sources, specifically mining operations (Hutton and Symon, 1986; Battarbee *et al.*, 1988; Nriagu, 1989). The biotoxic effects of heavy metals refer to the harmful effects of heavy metals to the body when consumed above the bio-recommended limits. Heavy metals are present in soils as natural components or as a result of human activity. Metal-rich mine tailings, metal smelting, electroplating, gas exhausts, energy and fuel production, downwash from power lines, intensive agriculture, and sludge dumping are the most important human activities that contaminate soils and aqueous streams with large quantities of toxic metals (Seaward and Richardson, 1990).

Heavy metals occur as natural constituents of the earth crust. They are persistent environmental contaminants since they cannot be degraded or destroyed. Metalloids enter the body system through food, air, and water and bioaccumulate over a period of time (Lenntech, 2004; UNEP/GPA, 2004).

Genomic protection of our biota from environmental or global pollution is the key for conservation of earth's biodiversity. Metals constitute one of the major groups of genotoxic environmental pollutants, posing serious threat to human as well as environmental well-being (Nriagu, 1990; Panda and Panda, 2002).

2. MERCURY

Mercury poisoning has become a problem of current interest as a result of environmental pollution on a global scale. Mercury is a strong phytotoxic as well as genotoxic metal (Fridovich, 1986; Suszeynsky & Shann, 1995). It is ubiquitous in the environment and is inevitable for both humans and animals to avoid its exposure in some form or forms on a regular basis. Mercury occurs widely in the biosphere (Clarkson, 1987).

Mercury occurs naturally in the environment. It is considered as one of the most toxic elements for human health and environment (Tuzen and Soylak, 2005; Ghaedi, 2006; Meucci *et al.*, 2009; Niazi *et al.*, 2009). Mercury pollution is one of the most serious environmental problems in the world (Pilon-Smits and Pilon, 2000). Its exposure in both organic and inorganic forms is the second-most common cause of toxic metal poisoning (Storelli *et al.*, 2000). Moreover, it exhibits biomagnifications in aquatic food chains among pollutants (Ribeiro *et al.*, 1996). The reported mercury content of food is rather low, about 0.02 pg/g, but there is a high variability in the content depending on the kind of product, its geographic origin, and the agricultural and industrial techniques of the area taken into account (Hugunin & Bradley, 1975).

3. CONSEQUENCES ON PLANTS

Mercury is not essential to living cells and performs no known biological function. It has a strong affinity for sulfur, and mercury's primary mode of toxic action in living organisms is thought to be the interference of enzyme function

and protein synthesis by binding to sulfhydryl (SH) groups (Sharma, 1985; Garcia and Reyes, 2001; Patra *et al*., 2004). Maximum work has been carried out on seed germination and seedling growth of different plant species in fields exposed to mercury (Sharma, 1985; Bonifacio and Montano, 1998; Al-Yemeni, 2001; Umadevi *et al*., 2009).

Mercury accumulation in plants has been studied in several plant species: pea (*Pisum sativum* L.), ryegrass (*Lolium perenne*), spearmint (*Mentha spicata* L.), Norway spruce (*Picea abies* L.), spinach (*Spinacia oleracea*), rice (Oryza sativa L.), and willow (*Salix*) (Beauford *et al*., 1977; Al-Attar *et al*., 1988; Godbold and Huettermann, 1988; Chunilall *et al*., 2004; Wang and Greger, 2004; Du *et al*., 2005).

Toxic effects of mercury in plants include abscission of older leaves, growth reduction, decreased, vigor inhibition of root and leaf development, and decreased chlorophyll content and nitrate reductase activity (Vyas and Puranik, 1993). Other adverse effects caused by excessive mercury accumulation include membrane structure's integrity disruption (Ma, 1998), mineral nutrient uptake reduction (Cho and Park, 2000; Patra and Sharma, 2000), and photosynthesis and transpiration reduction (Krupa and Baszynski, 1995). Higher concentrations (>1–2 mg/l) of mercury decreased the growth of pea (Beauford *et al*., 1977), tobacco (Suszeynsky and Shann, 1995), tomato (Cho and Park, 2000), and alfalfa (Zhou, 2007). Mercury also inhibited water uptake through aqua porins in plasma membranes of wheat (Zhang and Tyerman, 1999). Inhibition of enzymes of different metabolic pathways has also been reported because of mercury toxicity (Basak *et al*., 2001; Lenti *et al*., 2002; Morch *et al*., 2002; Shaw and Rout, 2002).

Considerable amounts of mercury may be added to agricultural land with fertilizers, lime, and manures. The most important sources of contamination of agricultural soils have been the use of organic forms of mercury as a seed-coat dressing to prevent fungal diseases in seeds. The absorption of organic and inorganic mercury from soil by plants is low, and there is a barrier to mercury translocation from plant roots to shoots. Thus, large increase in mercury levels in soil produce only modest increase in mercury levels in plants by direct uptake from soil (Patra and Sharma, 2000). Higher plants receive inorganic nitrogen mostly in the form of nitrate. The nitrate in plant tissues is reduced to ammonium via nitrite by the sequential action of enzymes.

4. CONSEQUENCES ON ENZYMES

The enzymes glutamine synthetase (GS), glutamate synthase (GOGAT), glutamate dehydrogenase (GDH), and nitrate reductase (NR) are responsible for the biosynthesis of nitrogen-carrying amino acids (Lam, 1996).

Nitrate reductase (NR, EC 1.6.6.1) is a complex enzyme characterized as a SH containing molybdoflavohemoprotein (Hewitt and Nottan, 1979). Nitrate is currently one of the most hazardous pollutants (Awasthi and Rai, 2005). NR is substrate inducible and involves de novo synthesis of the enzyme in response to nitrate (Zielke and Filner, 1971; Somers *et al*., 1983). Nitrate reduction catalyzed by this enzyme is considered as the rate-limiting step in the overall process of nitrate assimilation pathway (Srivastava, 1980). Supply of inorganic mercury inhibited substantially in vivo as well as in vitro NR activity and endogenous nitrate pool in excised bean leaf segments. Though in vitro specific activity of the enzyme remains unchanged, it has been suggested that mercury has an inhibitory role on NR activity in bean leaf segments (Vyas and Puranik, 1993).

Application of mercury to excised bean leaf segments increased glutamate dehydrogenase (NADH-GDH, EC 1.4.1.3) activity substantially. However, specific activity of the enzyme decreased at lower concentration of mercury and increased to a lesser extent at higher concentration of mercury. Eventually, pronounced increase in mercury activity indicated the possible role of the enzyme under mercury stress (Gupta and Gadre, 2005). Mercury supply increased glutamate synthase [NAD (P) H-GOGAT, EC 1.4.1.14] (Basak *et al*., 2001) activity. It has been suggested that mercury activates the NADH-GDH enzyme by binding to thiol groups of protein.

In the presence of mercury ($HgCl_2$) demonstrates Increase in NR activity by glutathione (GSH) involves its thiol groups (Vyas and Puranik, 1993).

GDH is found in all higher plants examined and is often present at high levels in senescing and root tissues (Loyolevargas and Jiminez, 1984). One of these alternative pathways is the reaction catalyzed by the mitochondrial NAD(H)-dependent glutamic acid dehydrogenase (GDH; EC 1.4.1.2), which possesses the capacity to assimilate ammonium in vitro utilizing the organic molecule 2-oxoglutarate to synthesize glutamic acid.

This observation led a number of authors to propose that GDH could operate in the direction of ammonium assimilation (Yamaya and Oaks, 1987; Oaks, 1995; Melo-Oliveira *et al*., 1996), although all the ^{15}N labeling experiments performed in vivo on a variety of plants demonstrated that GDH operates in the direction of glutamic acid deamination (Robinson *et al*., 1992; Aubert *et al*., 2001). It was concluded that GDH is involved in the supply of 2-oxoglutarate rather than in the assimilation of ammonium when carbon becomes limiting (Robinson *et al*., 1992; Aubert *et al*., 2001; Miflin and Habash, 2002). The physiological role of GDH in the whole-plant context remains speculative given the recent finding that the majority of the GDH protein is located in the mitochondria of companion cells (Dubois *et al*., 2003). GDH was increased in the mitochondria and appeared in the cytosol of companion cells. Taken together, our results suggest that the enzyme plays a dual role in companion cells, either in the mitochondria when mineral nitrogen availability is low or in the cytosol when ammonium concentration increases above a certain

threshold (Tercé-Laforgue *et al*., 2004). Inhibition of NADH-GDH by arsenate in excised bean leaf segment (Jot and Gadre, 1995).

Ammonia in higher plants is believed to be assimilated primarily by the glutamine synthetase–glutamate pathway (Miflin and Lea, 1980). The GDH enzyme could operate primarily in the assimilation or reassimilation of ammonium and play a complementary role to the GOGAT cycle (Srivastava and Singh, 1987). Two isozymic forms of GOGAT (i.e., Fd-GOGAT and NAD(P)H-GOGAT) are of common occurrence in the tissues of higher plants and are involved in the assimilation of primary ammonia as well as of photo-respiratory ammonia (Miflin and Lea, 1980). The GS and GOGAT cyclic mechanism is largely active when exogenous nitrogen concentrations are limiting, due to the high affinity of GS for ammonium.

This pathway utilizes approximately 15% of the cells' adenosine triphosphate (ATP) requirement (Reitzer, 2003) for the production of glutamine and its activity is, therefore, strictly regulated at both transcriptional and post-translational levels in order to prevent energy wastage. Thus the enzyme seems to be playing a pivotal role in linking the enzyme activity in plants, but the effect seems to be dependent on the isoform and the plant species analyzed (Puranik and Srivastava, 1994).

5. DETOXIFICATION MECHANISMS

Plants have developed defense mechanisms that ensure tolerance characteristics to cope with the negative effect of toxic metals or metalloids. These mechanisms include chelation, compartmentalization, biotransformation, and cellular repair (Salt *et al*., 1998).

The toxicity of inorganic Hg forms (e.g., $HgCl_2$) is at least in part explained by the element's great affinity for biomolecules containing SH groups (Goyer, 2001). Phytochelatins (PCs) are cysteine-rich polypeptides of general structure [y(-Glu-Cys)$_{2\text{-}11}$-Gly], which play an essential role in the detoxification of some heavy metals (cadmium [Cd], copper [Cu], zinc [Zn], mercury [Hg], and lead [Pb]) and metalloids (arsenic) in fungi, plants, nematodes, and other organisms (Grill *et al*., 1987; Clemens *et al*., 1999; Cobbett and Goldsbrough, 2002; Vivares *et al*., 2005). The inhibitory effect of heavy metals may be due to the (a) blocking of the supply of reducing equivalents of nitrate reduction, (b) formation of mercurial derivatives of –SH of NR, and (c) synthesis of PCs (Subhadra and Sharma, 2007). The strength of mercury (II) binding to GSH and PC follows the given order: Y Glu-Cys-Gly(y Glu-Cys)2 Gly(y Glu-Cys)3 Gly(y Glu-Cys)4 Gly (Patra and Sharma, 2000).

The transport of both PCs and Cd as its peptide complex, from the cytoplasm into the vacuole (Saltz and Rauser, 1995). In a second detoxification step, the PC–heavy metal complex is transported to the vacuole.

An (ATP-binding cassette)- ABC transporter, Hmt1, accepting low-molecular-weight PC–heavy metal complexes as substrate, has been identified in *Schizosaccharomyces pombe* (Ortiz *et al*., 1995), and phytochelatins (PCn) an MgATP-dependent transport activity for PC3 and PC3 ± Cd complexes has also been demonstrated in plants (Salt and Rauser, 1995).

The high stability of the PC-Hg multicomplexes (mPC-nHg) seems to be the main reason for the lack of previous Hg-PC characterization studies. A modified method to detect and quantify unbound PC of Hg in plant extracts via high-performance liquid chromatography coupled to electrospray tandem mass spectrometry and inductively coupled plasma mass spectrometry in parallel. Iglesia-Turin (2006) separated PC from Hg by adding the chelating agent sodium 2, 3-dimercaptopropanesulfonate monohydrate. PC2 was observed in plant samples. The best activator tested was Cd followed by Ag, Bi, Pb, Zn, Cu, Hg, and Au cations; these metals also induce PC biosynthesis in vivo in plant cell cultures (Cobbett, 2000).

Mercury inactivates the GSH enzyme by binding to the thiol (–SH) groups of protein. In addition, it also provides evidence that GSH serve as a precursor for PC, and this was confirmed by using Buthionine sulphoximine (BSO), an inhibitor of γ-glutamyl- cystein synthethase and a key enzyme of synthesis pathway (Jot and Subhadra, 2010). Studies employing the GSH biosynthetic inhibitor, buthionine sulfoximine, suggested an increase in the level of PCs and maintenance of GSH homeostasis in transgenic plants during exposure to excess zinc as the possible mechanism behind this tolerance (Singla-Pareek *et al*., 2006). PC plays a key role in protecting macromolecules from damage by free radicals by trapping them in an aqueous phase (Freedman *et al*., 1989).

When the non-PC-based mechanism of detoxification gets exhausted and free metal ions become available to induce PC synthesis (Schat *et al*., 2002). Exposure to excess Cu is capable of stress induction, in which the role of oxidative stress and reactive oxygen species (ROS) production may be involved (Stadtman and Oliver, 1991, Waldermar *et al*., 1994). On the other hand, under Cu toxicity, excess copper is an efficient generator of ROS in Fenton-type reactions, leading to disturbances in metabolic pathways and macromolecule damages (Hegedus *et al*., 2001).

The oxidative stress is bound up with the increased metal accumulation in plants and decreased efficiency of the ascorbate–GSH cycle under the metal stress (Wang *et al*., 2009). Exposure to toxic metals also induces plants to accumulate high amounts of proline (Štefl and Vašáková, 1982). Increased accumulation of proline leads to the increase of glutamate kinase activity and creates a possibility for an increase in glutamic acid content due to the synthesis of GSH and PCs in plant cells (Pavlíková *et al*., 2007). An increase of free proline inhibits biosynthesis of its excessive amounts

in plants under heavy metal excess, and this results in the preferred utilization of glutamate for the metabolic route leading to PC synthesis (Pavlíková *et al*., 2008).

To control the level and effects of ROS, cells have developed various antioxidant defenses, including antioxidant enzymes and low-molecular-mass radical scavengers. They regenerate the active form of antioxidants and eliminate or reduce the damage caused by ROS (Alscher *et al*., 1997). An increase or decline in the activity of antioxidants is a direct indication of the adaptive response of plants to avoid metal toxicity (Srivastava *et al*., 2004).

Antioxidants are important substances that possess the ability of protecting organisms from damages caused by free radical-induced oxidative stress (Canadanovic-Brunet *et al*., 2005). The antioxidative system includes both enzymatic and nonenzymatic systems.

The nonenzymatic system includes ascorbic acid (vitamin C), ά-tocopherol, cartenes, and so forth, and the enzymatic system include superoxide dismutase (SOD), catalase (CAT), peroxidase (POX), ascorbate peroxidase (APX), glutathione reductase (GR), and polyphenol oxidase (PPO). SOD, the first major enzyme found in all aerobes, catalyzes dismutation of superoxide anion to H_2O_2 and molecular oxygen. Glutathione peroxidase (GSH-POX) protects membrane lipids from oxidative damage and detoxifies organic peroxides; it can also act on organic hydroperoxides (Kantol *et al*., 1998). The intracellular level of H_2O_2 is regulated by a wide range of enzymes, the most important being CAT and peroxidase. CAT inactivates H_2O_2 to oxygen and water (Rusina *et al*., 2004).

Ali *et al*. (2010) demonstrated that the enhanced production of SOD, POD, and CAT may serve as useful biomarkers for Cu tolerance in *Carthamus tinctorius*. Free radicals and intermediate products of peroxidation are capable of damaging the integrity and altering the function of biomembranes, which can lead to the development of many pathological processes (Gutteridge, 1993). Various specific enzymes that limit free-radical formation, such as SOD, CAT, and GSH-POX, play an important role in the protection of cell membranes against oxidative damage (Faix *et al*., 2003). Reactive oxygen intermediates (ROI: H_2O_2, $O_2^{\bullet-}$, $^{\bullet}OH$ and $^1O_2$), ROI damages a number of cellular targets, including DNA, resulting in genotoxic stress, leading to mutation, genomic instability, or apoptosis (Achary and Panda, 2010).

Mostly heavy metals at excess concentrations damage plant tissues by producing free-radical oxygen species or directly interacting with the DNA, and thus their accumulation within the cell causes deleterious effects (Al-Qurainy, 2009). The plant *Cleome gynandra* was exposed to the sublethal and half of sublethal concentration of cadmium and copper metal contaminated soils; it was clearly indicated that *C. gynandra* has the highest values of total phenolics, percent antioxidant activity, and enzymatic antioxidants, which help the plant to cope with oxidative stress (Haribabu and Sudha, 2011).

An enhancement of the amount of phenolic compounds can be observed under different environmental factors and stress conditions (Sakihama & Yamasaki, 2002). An increase of phenolics correlated to the increase in activity of enzymes involved in the metabolism of phenolic compounds was reported (Michalak, 2006), suggesting the synthesis of phenolics under heavy metal stress. Phenolics are generally thought to prevent oxidative damage by scavenging active oxygen species and by breaking the radical chain reactions during lipid peroxidation; these antioxidative effects require the reduced form of phenolics, in the oxidized form act as prooxidants (Sakihama and Yamasaki, 2002). The antioxidant activity of phenolics is mainly due to their redox properties, which allow them to act as reducing agents, hydrogen donors, singlet oxygen quenchers, and metal chelators (Sakihama *et al*., 2002). Studies indicate that increasing levels of lead treatment markedly increased the phenolic content of *Phaseolus vulgaris* (Hamid *et al*., 2010).

Phytoremediation defines the use of plants to extract, sequester, and/or detoxify various kinds of environmental pollutants (Salt *et al*., 1998). The physicochemical techniques for soil remediation render the land useless for plant growth as they remove all biological activities, including useful microbes, such as nitrogen-fixing bacteria, mycorrhiza, and fungi, as well as fauna in the process of decontamination (Burns *et al*., 1996). The most commonly used methods for dealing with heavy metal pollution are still extremely costly.

Phytoremediation is the use of plants to extract, sequester, and/or detoxify pollutants and is a new and powerful technique for environmental clean-up. The mechanism(s) of heavy metal effect on nitrate assimilation has not been worked out so far.

5.1. *Selenium*

Selenium (Se) is an essential micronutrient and trace metal. Plants require little amount, and when it exceeds the limit, it causes toxicity in humans and plants (Ellis and Salt, 2003; Sager, 2006).

Pyrzynska (2009) provides data on selenium speciation in enriched vegetables. Metabolic importance of selenium for plants and in higher plants described by Germ *et al*. (2007) and Terry *et al*. (2000).

5.1.1. Selenium Toxicity

The toxicity of selenium in wheat and buckwheat plants was proportional to the concentration added as sodium selenite to soil cultures and solution cultures studied by Martin (1936).

The toxicity of selenate (SeO_4^-) and selenite (SeO_3^-) to most plants can be attributed to a combination of three factors. First, selenate and selenite are readily absorbed from the soil by roots and translocated to other parts of the plant. Second, metabolic reactions convert these anions into organic forms of selenium. Third, organic selenium

metabolites, which act as analogues of essential sulfur compounds, interfere with cellular biochemical reactions Brown and Shrift (1982).

5.1.2. Selenium Antagonistic Effect

Dietary selenium (Se) status is inversely related to vulnerability to methylmercury (MeHg) toxicity (Ralston and Raymond, 2010).

According to the authors, Se has been shown to counteract the toxicity of heavy metals, such as cadmium, inorganic mercury, methylmercury, thallium, and, to a limited extent, silver. Vitamin E is very effective against lead toxicity but Se has little effect. The presumed protective effect of Se against cadmium and mercury toxicity is through the diversion in its binding from low-molecular-weight proteins to higher-molecular-weight ones (Whanger, 1992).

Exploring the structural basis for selenium/mercury antagonism in *Allium fistulosum* studied by McNear *et al*. (2012). The type of interaction of selenium and mercury and selenium and copper on the cell growth of the planktonic alga *Dunaliella minuta* Lerche had been studied by Gotsis (1982). An antagonism study in *Glycine max* (soybean) roots by size exclusion and reversed phase HPLC-ICPMS. The result shows that the Se distribution pattern was found to be unaffected by the presence of Hg, but the amount of Se assimilated was found to be higher in plants co-exposed to Hg (Yathavakilla and Caruso, 2007).

6. CONCLUSION

Mercury pollution is all over the world. Despite above all known facts, there are many unknown facts. It is important to know the uptake mechanism, target and the extent to which it affects flora and fauna. In this review, findings support that mercury causes inhibition of enzyme activity namely nitrate, GDH and GOGAT *etc*. as previous results show that mercury causes toxicity in plants. Natural heavy metal accumulation could be a potential source for genetic manipulation of important agricultural crop plants.

Author Contributions

The tasks and responsibilities of this work were equally shared by all the authors.

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References

Achary VM, Panda BB (2010). Aluminium-induced DNA damage and adaptive response to genotoxic stress in plant cells are mediated through reactive oxygen intermediates. Mutagenesis, 25(2): 201-209, doi:10.1093/mutage/gep063.

Ali A, Ammarah H, Saeed A, *et al*. (2010). Antioxidant enzymes as bio-markers for copper tolerance in safflower (*Carthamus tinctorius* L.). African Journal of Biotechnology, 9(33): 5441-5444, ISSN 1684-5315.

Al-Qurainy F (2009). Toxicity of heavy metals and their molecular detection on *Phaseolus vulgaris* (L.). Australian Journal of Bas ic and Applied Sciences, 3(3): 3025-3035. ISSN 1991-8178.

Alscher RG, Donahue JL, Cramer CL (1997). Reactive oxygen species and antioxidants: relationships in green cells. Physiologia Plantarum, 100: 224-233.

Al-Attar AF, Martin MH, Nickless G (1988). Uptake and toxicity of cadmium, mercury *and thalium.* Chemosphere, 17: 1219-1225.

Al-Yemeni MN (2001). Effects of cadmium, mercury and lead on seed germination and early seedling growth of *Vigna ambacensis* L. Indian Journal of Plant Physiology, 6: 147-151.

Aubert S, Bligny R, Douce R, *et al*. (2001). Contribution of glutamate dehydrogenase to mitochondrial metabolism studied by 13C and 31P nuclear magnetic resonance. Journal of Experimental Botany, 52: 37-45.

Awasthi M, Rai LC (2005). Toxicity of Nickel, Zinc and Cadmium to nitrate uptake in free and immobilized cells of Scenedesmus quadricauda. Ecotoxicology and Environmental Safety, 61: 268-272.

Basak M, Sharma M, Chakraborty U (2001). Biochemical responses of Camellia sinensis (L.) O Kutenze to metal stress. Journal of Environmental Biology, 22(1): 29-36.

Battarbee R, Anderson N, Appleby P, *et al*. (1988). Lake Acidification in the United Kingdom. London: ENSIS.

Beauford W, Barber J, Barringer AR (1977). Uptake and distribution of Hg within higher plants. Physiologia Plantarum, 39: 261-265.

Beers R, Sizer I (1951). A spectrophotometric method for measuring the breakdown of hydrogen peroxide by catalase. Journal of Biological Chemistry, 195: 133.

Bonifacio RS, Montano MNE (1998). Inhibitory effects of mercury and cadmium on seed germination of *Enhalus acoroides* (L.f.) Royle. Bulletin of Environmental Contamination and Toxicology, 60: 45-51.

Brown TA, Shrift A (2008). Selenium: toxicity and tolerance in higher plants. Biological Reviews, 57(1): 59-84. February 1982 Article first published online: Jan 21, 2008. doi:10.1111/j.1469-185X.1982.tb00364.x

Burns RG, Rogers S, McGhee I (1996). Contaminants and the Soil Environment in the Australia Pacific Region. London: Kluwer Academic Publishers, pp: 361-410.

Canadanovic-Brunet JM, Djilas SM, Cetkovic GS, *et al*. (2005). Free-radical scavenging activity of wormwood (*Artemisia absinthium* L.) extracts. Journal of the Science of Food and Agriculture, 85: 265-272.

Cho U, Park J (2000). Mercury induced oxidative stress in tomato seedlings. Plant Science, 156: 1-9.

Chunilall V, Kindness A, Jonnalagadda SB (2004). Heavy metal uptake by spinach leaves grown on contaminated soils with lead, mercury, cadmium and nickel. Journal of Environmental Science and Health, Part B, 39: 473-481.

Clarkson TW (1987). Mercury. In "Trace Elements in Human and Animal Nutrition." Editor Mertz W.; San Diego, CA: Academic Press, pp: 417-428.

Clemens S, Kim EJ, Neumann D, *et al*. (1999). Tolerance to toxic metals by a gene family of phytochelatin synthases from plants and yeast. EMBO Journal, 18: 3325-3333.

Cobbett C, Goldsbrough P (2002). Phytochelatins and metallothioneins: roles in heavy metal detoxification and homeostasis. Annual Review of Plant Physiology, 53: 159-182.

Cobbett CS (July 2000). Phytochelatins and Their Roles in Heavy Metal Detoxification. Plant Physiology, 123: 825-832.

Du X, Zhu YG, Liu WJ, *et al*. (2005). Uptake of mercury (Hg) by seedlings of rice (Oryza sativa L.) grown in solution culture and interactions with arsenate uptake. Environmental and Experimental Botany, 54: 1-7.

Dubois F, Tercé-Laforgue T, Gonzalez-Moro MB, *et al*. (2003). Glutamate dehydrogenase in plants; is there a new story for an old enzyme? Plant Physiology and Biochemistry, 41: 565-576.

Ellis RD, Salt ED (2003). Plants, selenium and human health. Current Opinion in Plant Biology, 6: 273-279.

Freedman JH, Ciriolo MR, Peisach J (1989). The role of glutathione in copper metabolism and toxicity. Journal of Biological Chemistry 264, 5598-5605.

Faix S, Faixova Z, Michnova E, *et al*. (2003). Effect of per os administration of mercuric chloride on peroxidation processes in Japanese Quail. Acta Veterinaria Brunensis, 72: 23-26.

Fridovich I (1986). Biological effects of the superoxide radical. Archives of Biochemistry and Biophysics, 24: 1-11.

Garcia EM, Reyes RE (2001). Synthesis pattern of an Hg-binding protein in Acetabularia calyculus during short-term exposure to mercury. Bulletin of Environmental Contamination and Toxicology, 66: 357-364.

Germ M, Stibilj V, Kreft I (2007). Metabolic importance of selenium for plants. The European Journal of Plant Science and Biotechnology, 1(1): 91-97.

Ghaedi M (2006). Pyrimidine-2-thiol as selective and sensitive ligand for preconcentration and determination of Pb2+. Chemia Analityczna, 51: 593-602.

Giannopolitis CN, Ries SK (1977). Superoxide dismutases: I. Occurrence in higher plants. Plant Physiology, 59: 309-314.

Godbold DL, Huettermann A (1988). Effect of zinc, cadmium and Hg on root elongation Picea (Karst) seedlings and the significance of these metals to forest die-back. Environmental Pollution, 53: 75-381.

Gotsis O (1982). Combined effects of selenium/mercury and selenium/copper on the cell population of the alga *Dunaliella minuta*. Marine Biology, 71(3): 217-222.

Goyer RA (2001). Toxic effects of metals. In "Casarett and Doull's Toxicology: The Basic Science of Poisons." Editors CD Klaassen, MO Amdur, J Doull; New York: McGraw-Hill, p: 1111.

Grill E, Winnacker E-L, Zenk MH (1987). Phytochelatins, a class of heavymetal-binding peptides from plants, are functionally analogous to metallothioneins. Proceedings of the National Academy of Sciences of the United States of America, 84: 439-443.

Gupta P, Gadre R (2005). Increase in NADH- glutamate dehydrogenase activity by mercury in excised bean leaf segments. Indian Journal of Experimental Biology, 43: 824-828.

Gutteridge JM (1993). Free radicals in disease processes: a compilation of cause and consequence. Free Radical Research Communications, 19: 141-158.

Hamid N, Bukhari N, Jawaid F (2010). Physiological responses of Phaseolus Vulgaris to different lead concentration. Pakistan Journal of Botany, 42(1): 239-246.

Haribabu TE, Sudha PN (2011). Effect of heavy metals copper and cadmium exposure on the antioxidant properties of the plant Cleome gynandra. International Journal of Plant, Animal and Environmental Sciences, 1(2). ISSN 2231-4490.

Hegedus A, Erdei S, Horvath G (2001). Comparative studies of H_2O_2 detoxifying enzymes in green and greening barley seedlings under cadmium stress. Plant Science, 160: 1085-1093.

Hewitt EJ, Nottan BA (1979). Nitrate reductases: properties and possible mechanisms. Biochemical Society Transactions, 7: 629-633.

Hutton M, Symon C (1986). The quantities of cadmium, lead, mercury and arsenic entering the U.K. environment from human activities. Science of the Total Environment, 57: 129-150.

Iglesia-Turin S (2006). Detection and quantification of unbound phytochelatin in plant extracts of brassica napus grown with different levels of mercury. Plant Physiology, 142: 742-774.

Jot S, Subhadra AV (2010). The effect of mercury on nitrate reductase activity. In "Bean Leaf Segments (*Phaseolus vulgaris*) And Its Chelation by Phytochelatin Synthesis. Life Sciences and Medicine Research, Volume 2010: LSMR-13.

Jot V, Gadre M (1995). Inhibition of NADH glutamate dehydrogenase by arsenate in excised bean leaf segments. Proceedings of the National Academy of Sciences, 65: 177-181.

Kantol M, Sarranen M, Vanha PT (1998). Selenium and glutathione peroxidase in serum, plasma of men and bulls. Journal of Reproduction Fertility, 83: 785-794.

Krupa Z, Baszynski T (1995). Some aspects of heavy metal toxicity towards photosynthetic apparatus: direct and indirect effects on light and dark reaction. Acta Physiologiae Plantarum, 17: 177-190.

Lam H-M (1996). The molecular-genetics of nitrogen assimilation into amino acids in higher plants. Annual Review of Plant Physiology and Plant Molecular Biology, 47: 569-593. doi:10.1146/annurev.arplant.47.1.569

Lenntech Water Treatment and Air Purification (2004). Water Treatment. Rotterdamseweg, Netherlands: Lenntech. www.excelwater.com/thp/filters/Water-Purification.htm

Lenti K, Fodor F, Boddi B (2002). Mercury inhibits the activity of NADPH: protochlorophyllide oxidoreductase (POR). Photosynthetica, 40(1): 145-151.

Lowry OH, Rosbrough NJ, Farr AL *et al.* (1951). Protein measurement with the folin phenol reagent. Journal of Biological Chemistry, 193: 265.

Loyolevargas VM, de Jimenez S (1984). Differential role of glutamate dehydrogenase in nitrogen metabolism of Maize tissue. Plant Physiology, 76: 536-540.

Ma C (1998). Mercury harm on cell membrane of rape leaf and cell endogenous protection effect. Ying Yong Shengtai Xuebao, 9: 23-26.

Maehly AC, Chance B (1954). The assay of catalases and peroxidase. In: Methods of Biochemical Analysis, 1: 357-324.

Martin AL (1936). Toxicity of Selenium to Plants and Animals. American Journal of Botany, 23(7): 471-483.

McNear DH Jr, Afton SE, Caruso JA (2012). Exploring the structural basis for selenium/mercury antagonism in Allium fistulosum. Metallomics, 4(3): 267-276. doi:10.1039/c2mt00158f. Epub 2012 Jan 26.

Melo-Oliveira R, Oliveira IC, Coruzzi GM (1996). Arabidopsis mutant analysis and gene regulation define a non-redundant role for glutamate dehydrogenase in nitrogen assimilationProceedings of the National Academy of Sciences of the United States of America, 96: 4718-4723.

Meucci V, Laschi S, Minunni M, *et al.* (2009). An optimized digestion method coupled to electrochemical sensor for the determination of Cd, Cu, Pb and Hg in fish by square wave anodic stripping voltammetry. Talanta, 77(3): 1143-1148.

Michalak, A. (2006). Phenolic compounds and their antioxidant activity in plants growing under heavy metal stress. Polish Journal of Environmental Studies, 15(4): 523-530.

Miflin BJ, Habash DZ (2002). The role of glutamine synthetase and glutamate dehydrogenase in nitrogen assimilation and possibilities for improvement in the nitrogen utilization of crops. Journal of Experimental Botany, 53: 979-987.

Miflin N, Lea PJ (1980). Ammonia assimilation. In "The Biochemistry of Plants." Editors, Stumrf PK, Conn EE; London: Academic Press; pp: 169-202.

Morch VM, Schetinges MRC, Martins AF, *et al.* (2002). Effects of cadmium, lead, mercury and zinc on delta amino levulinic acid dehydratase activity from radish leaves. Biologia Plantarum, 45(1): 85-89.

Niazi A, Momeni-Isfahani T, Ahmari Z (2009). Spectrophotometric determination of mercury in water samples after cloud point extraction using nonionic surfactant Triton X-114. Journal of Hazardous Materials, 165: 1200-1203.

Nriagu JO (1989). A global assessment of natural sources of atmospheric trace metals. Nature, 338: 47-49.

Nriagu JO (1990). Global metal pollution poisoning the biosphere. Environment, 32: 7-32.

Oaks A (1995). Evidence for deamination by glutamate dehydrogenase in higher plants: reply. Canadian Journal of Botany, 73: 1116-1117.

Ortiz DF, Kreppel L, Speiser DM, *et al.* (1992). Heavy metal tolerance in the fission yeast requires an ATP-binding cassette-type vacuolar membrane transporter. EMBO Journal, 11: 3491-3499.

Ortiz DF, Ruscitti T, MacCue KF, *et al.* (1995). Transport of metal-binding peptides by HMT1, a fission yeast ABC-type vacuolar membrane protein. Journal of Biological Chemistry, 270: 4721-4728.

Panda, BB, Panda KK (2002). Genotoxicity and mutagenicity of heavy metals in plants. In "Physiology and Biochemistry of Metal Tolerance in Plants." Prasad MNV, Strzalka K; Amsterdam, The Netherlands: Kluwer Academic Publishers; pp: 395-414.

Patra M, Bhowmik N, Bandopadhyay B, *et al.* (2004). Comparison of mercury, lead and arsenic with respect to genotoxic effects on plant systems and the development of genetic tolerance. Environmental and Experimental Botany, 52: 199-223.

Patra M, Sharma A (2000). Mercury toxicity in plants. The Botanical Review, 66(3): 379-422.

Pavlíková D, Pavlík M, Staszková L, *et al.* (2007). The effect of potentially toxic elements and sewage sludge on the activity of regulatory enzyme glutamate kinase. Plant, Soil and Environment, 53: 201-206.

Pavlíková D, Pavlík M, Staszková L, *et al.* (2008). Glutamate kinase as a potential biomarker of heavy metal stress in plants. Ecotoxicology and Environmental Safety, 70: 223-230.

Pilon-Smits E, Pilon M (2000). Breeding mercury-breathing plants for environmental cleanup. Trends in Plant Sciences, 5: 235-236.

Puranik RM, Shrivastava HS (1990). Increase in glutamate synthase activity in bean leaf segments by light. Current Science, 59: 1001-1003.

Puranik RM, Shrivastava HS (1994). Glutamate synthasa. In "Nutration of Higher Plants." Editors Shrivastava HS, Singh RP; New Delhi: Associated Publishing Co.; pp: 229-243.

Pyrzynska K (2009). Selenium speciation in enriched vegetables Food Chemistry, 114: 1183-1191.

Ralston NV, Raymond LJ (2010). Dietary selenium's protective effects against methylmercury toxicity. Toxicology, 278(1): 112-23. doi:1016/j.tox.2010.06.004. Epub 2010 Jun 16.

Reitzer L (2003). Nitrogen assimilation and global regulation in *Escherichia coli*. Annual Review of Microbiology, 57: 155-176.

Ribeiro CAO, Guimarães JRD, Pfeiffer WC (1996). Accumulation and distribution of inorganic mercury in a tropical fish (*Trichomycterus zonatus*). Ecotoxicology and Environmental Safety, 34:190-195.

Robinson SA, Stewart GR, Phillips R (1992). Regulation of glutamate dehydrogenase activity in relation to carbon limitation and protein catabolism in carrot cell suspension cultures. Plant Physiology, 98: 1190-1195.

Robyt JF, White BJ (1987). Qualitative and quantitative methods for determining biological molecules. In "Biochemical Techniques, Theory and Practice." California: Cele Publishing Company, CH 7; pp: 213- 252.

Rusina Y, Kaloyan N, Christov L, *et al*. (2004). Antioxidative enzymes in barley plants subjected to soil flooding. Environment and Experimental Botany, 51: 93-101.

Sager M. (2006). Selenium in agriculture, food, nutrition. Pure and Applied Chemistry, 78: 111-133.

Sakihama Y, Cohen MF, Grace S, *et al*. (2002). Plant phenolic antioxidant and prooxidant activities: phenolics-induced oxidative damage mediated by metals in plants. Toxicology, 17: 67-80.

Sakihama Y, Yamasaki H (2002). Lipid peroxidation induces by phenolics in cinjunction with aluminium ions. Biologia Plantarum, 45: 249-254.

Salt DE, Rauser WE (1995). MgATP-dependent transport of phytochelatins across the tonoplast of oat roots. Plant Physiology, 107: 1293-1301.

Salt DE, Smith RD, Raskin I (1998). Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology, 49: 643-668.

Saltz DE, Rauser WE (1995). MgATP-dependent transport of phytochelatins across the tonoplast of oat roots. Plant Physiology, 107: 1293-1301.

Schat H, Liugany M, Vooijis R, *et al*. (2002). The role of phytochelatins in constitutive and adaptive heavy metal tolerances in hyperaccumulator and non-hyperaccumulator metallophytes. Journal of Experimental Botany, 53: 2381-2392.

Schmidt G, Thannhauser SJ (1945). A method for the determination of DNA, RNA and the phosphoproteins in animal tissues. Journal of Biological Chemistry, 161: 83-89.

Seaward MRD, Richardson DHS (1990). Atmospheric sources of metal pollution and effects on vegetation. In "Heavy Metal Tolerance in Plants: Evohaionary Aspects." Editor Shaw AJ; Boca Raton, FL: CRC Press; pp: 75-92.

Sharma SS (1985). Effect of mercury on germination and seedling growth, mobilization of food reserves and activity of hydrolytic enzymes in *Pisum sativum*. Environmental and Experimental Botany, 25: 189-193.

Shaw BP, Rout NP (2002). Hg and Cd induced changes in proline content and activities of proline biosynthesizing enzymes in Phaseolus aureus and Triticum aestivum. Biologia Plantarum, 45(2): 267-271.

Sigh RP, Shrivastava HS (1983). Regulation of glutamate dehydrogenase activity by amino acids in Maize seedling. Physiologia Plantarum, 57: 549-554.

Singla-Pareek SL, Yadav SK, Pareek A, *et al*. (2006). Transgenic tobacco overexpressing glyoxalase pathway enzymes grow and set viable seeds in zinc-spiked soils. Plant Physiology, 140: 613-623.

Somers DA, Kuo T, Kleinhofs A, *et al*. (1983). Synthesis and degradation of barley nitrate reductase. Plant Physiology, 72: 949-952.

Srivastava HS (1974). In vivo activity of nitrate reductase in maize seedlings. Indian Journal of Biochemistry and Biophysics, 11: 230-232.

Srivastava HS (1980). Regulation of nitrate reductase activity in higher plants. Phytochemistry, 19: 725-733.

Srivastava HS, Singh Rana P (1987). Role and regulation of glutamate dehydrogenase activity in higher plants. Phytochemistry, 26: 597-610.

Srivastava S, Tripathi RD, Dwivedi UN (2004). Synthesis of phytochelatins and modulation of antioxidants in response to cadmium stress in Cuscuta reflexa—an angiospermic parasite. Journal of Plant Physiology, 161: 665-674.

Stadtman ER, Oliver CN (1991). Metal-catalyzed oxidation of proteins. The Journal of Biological Chemistry, 266: 2005-2008.

Štefl M, Vašáková L (1982). Allosteric regulation of proline-inhibitable glutamate kinase from winterwheat leaves by l-proline, adenosine diphosphate and low temperatures. Collection of Czechoslovak Chemical Communications, 47: 360-369.

Stevens OL, Oaks A (1973). The influence of nitrate in the induction of nitrate reductase in Maize roots. Canadian Journal of Botany, 51: 1225-1258.

Storelli MM, Giacominelli-Stuffler R, Marcotrigiano GO (2000). Total and methyl mercury residues in cartilaginous fish from Mediterranean Sea. Marine Pollution Bulletin, 44: 1354-1358.

Subhadra AV, Sharma J (2007). Phytoremediation technology – a nature's bliss. Research Journal of Biotechnology, 2(3): 52-57.

Suszeynsky EM, Shann JR (1995). Phytotoxicity and accumulation of mercury in tobacco subjected to different exposure routes. Environmental Toxicology and Chemistry, 14: 61-67.

Swain T, Hillis WE (1959). The phenolic constituents of *Prunus domestica*. I. The quantitative analysis of phenolic constituents. Journal of the Science of Food and Agriculture, 10: 63-68.

Tercé-Laforgue T, Dubois F, Ferrario-Méry S, *et al*. (December 2004). Glutamate dehydrogenase of tobacco is mainly induced in the cytosol of phloem companion cells when ammonia is provided either externally or released during photorespiration. Plant Physiology, 136: 4308-4317.

Terry N, Zayed AM, de Souza MP, *et al*. (2000). Selenium in higher plants. Annual Review of Plant Physiology and Plant Molecular Biology, 51: 401-432.

Tukendroff A, Rauser WE (1990). Changes in glutathione and Phytochelatins in roots of Maize seedlings exposed to Cadmium. Plant Science, 70: 155-166.

Tuzen M, Soylak M (2005). Mercury contamination in mushroom samples from Tokat, Turkey. Bulletin of Environmental Contamination and Toxicology, 74: 968-972.

United Nations Environmental Protection/Global Program of Action (2004). Why The Marine Environment Needs Protection From Heavy Metals, Heavy Metals 2004, UNEP/GPA Coordination Office (http://www.oceansatlas.org/unatlas/uses/uneptextsph/wastesph/2602gpa.)

Umadevi P, Kannikaparameswari N, Selvi S, *et al*. (2009). Effect of mercury exposure on *Vigna unguiculata* (cowpea) seeds. Nature Environment and Pollution Technology, 8: 53-58.

Vivares D, Arnoux P, Pignol D (2005). A papain-like enzyme at work: native and acyl-enzyme intermediate structures in phytochelatin synthesis. Proceedings of the National Academy of Sciences of the United States of America, 102: 18848-18853.

Vyas J, Puranik RM (1993). Inhibition of nitrate reductase activity by mercury in bean leaf segments. Indian Journal of Plant Physiology, 36: 57-60.

Waldermar M, Ryszard R, Teresa U (1994). Effect of excess Cu on the photosynthetic apparatus of runner bean leaves treated at two different growth stages. Physiology Plantarium, 91: 715-721.

Wang Y, Greger M (2004). Clonal differences in mercury tolerance, accumulation and distribution in willow. Journal of Environmental Quality, 33: 1779-1785.

Wang C, Zhang SH, Wang PF, *et al*. (2009). Excess Zn alters the nutrient uptake and induces the antioxidative responses in submerged plant *Hydrilla verticillata* (L.f.) Royle. Chemosphere, 76: 938-945.

Whanger PD (1992). Selenium in the treatment of heavy metal poisoning and chemical carcinogenesis. Journal of Trace Elements and Electrolytes in Health and Disease, 6(4): 209-221.

Yamaya T, Oaks A (1987). Synthesis of glutamate by mitochondria: an anaplerotic function for glutamate dehydrogenase. Physiologia Plantarum, 70: 749-756.

Yathavakilla SK, Caruso JA (2007). A study of Se-Hg antagonism in Glycine max (soybean) roots by size exclusion and reversed phase HPLC-ICPMS. Analytical and Bioanalytical Chemistry, 389(3): 715-23. Epub 2007 Jul 26.

Yemm EW, Willis AJ (1954). The estimation of carbohydrate in the plant extract by anthrone reagent. Journal of Biochemistry, 57: 508-514.

Zhang W, Tyerman SD (1999). Inhibition of water channels by $HgCl_2$ in intact wheat root cells. Plant Physiology, 120: 849-857.

Zhou ZS, Huang SQ, Guo K, *et al*. (2007). Metabolic adaptations to mercury- induced oxidative stress in roots of Medicago sativa L. Journal of Inorganic Biochemistry, 101: 1-9.

Zielke HR, Filner P (1971). Synthesis and turnover of nitrate reductase induced by nitrate in cultured tobacco cells. Journal of Biochemistry, 246: 1772-1780.

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