University Of Salahaddin - Erbil

Effect Of Lead On Plants

Research Project Submitted to the department of (Biology) in partial fulfillment of the requirements for the degree of B.A in Biology

By

Eman Azad Omer

Supervised By

Maqsuda Q. Muhammed

2023-2024

Superviser’s Certification

Research has been written under my supervision and has been submitted for the award of the degree of bachelors Of Science in Biology with my approval as supervisor.

Supervised

Lecturer: Maqsuda Q. Muhammed

Date: /4 /2024

Head of the Department of Biology

Dr. Sevan Omer Majeed

Date: /4 /2024

Table of Contents

Abstract

lead is nonessential element for plant although, it accumulates in different parts of plant and negatively affects various physiological processes. Such physiological processes include photosynthesis, respiration, mineral nutrition, membrane structure and properties and gene expression. Lead accumulation in the soil inhibits germination of seeds and retards growth of seedlings, decreases germination percent, germination index, root/shoot length, tolerance index and dry mass of roots and shoots. Therefore, this is the responsibility of Government and various environmental agencies to controlling heavy metals pollution especially lead.

Keywords: Lead; Plant; Growth; Toxicity.

1. Introduction

Environmental pollution is one of the most challenging sustainable development agendas today. Toxic metals, including Pb, are some pollutants that are most dangerous to human health. This is especially true in countries witnessing rapid industrialization (Usman, K., Al-Ghouti, M. A. & Abu-Dieyeh, 2018). Lead is a highly noxious and non-disintegrative heavy metal which comprises 0.002% of Earth's crust. Moreover Pb is the second most toxic metal after As because of its toxic effects on living organisms (ATSDR, 2015). Heavy metals, both essential and non-essential, have similar harmful effects on plants, such as low biomass accumulation, chlorosis, growth, and photosynthetic inhibition, altered water balance and nutrient assimilation, and senescence (Balkhair and Ashraf, 2016). The optimum pH of the soil should be 6.5–7.5. In recent years soil contamination with heavy metals like Cu, Ni, Cd, Zn, Cr, and On accumulation of heavy metals, the pH of the soil increases or decreases by 2–3 units, which makes it alkaline or acidic (Khan et al., 2015, Xiang et al., 2021). The accumulation of heavy metals contaminates food by interference between the soil and roots (Shahid et al., 2015). Adsorption of lead in the roots is observed in several species of plants. Absorbed lead is accumulated in the roots, and only a small fraction is transported to aerial plant parts (Kumar et al., 2017). As a result, root vegetables like carrots and sweet potatoes may contain the highest levels of lead (Kumar et al., 2017). Then come leafy greens like lettuce and Swiss chard. Tomatoes, for example, are the least likely to have Pb absorbed from the soil (Humberto et al., 2020). Lead can last up to 2000 years in the soil and is hazardous to plants in a variety of ways. Several hyperaccumulator plant species (e.g., Brassica pekinensis and Pelargonium) are capable of transporting higher concentrations of lead to aerial plant parts, without causing damage to their metabolic functions (Humberto et al., 2020).

Previously, we reviwed on the Bioaccumulation of lead (Pb) and its effects on human. This review addresses various morphological, physiological, and biochemical effects of lead toxicity in plants and also strategies adopted by plants for Pb detoxification and developing tolerance to Pb.

1.1. Lead

Lead (Pb) is one of the best-known heavy trace elements clas-sified as non-biodegradable, with a long history of toxicity to most living organisms through adverse effects on growth, mor-phology and photosynthetic processes of plants (Balakhnina et al. 2016). Lead is non-essential to plants and produces toxic effects such as metabolism disorders, which can inhibit plant growth and development and lead to death (Alongi 2017; Amari et al. 2017; Huang et al. 2020). When lead enters aquatic environ-ments, low concentrations may promote plant metabolic processes and enzyme activity, but high concentrations may cause inactivation, denaturation, and destruction of plant enzymes (Malar et al. 2016). Thus, it is important to study the influence of lead on plants.

1.2. Source of lead

Lead toxicity in soils and plants can have several sources. Some of the primary sources of lead toxicity are (Ankush et al. 2021):

1. Industrial activities: Lead is often used in the manufacturing of batteries, paint, and other industrial products. These activities can release lead into the air, soil, and water, leading to contamination of the surrounding environment.

2. Urbanization: Lead-based paint was commonly used in homes and buildings until the 1970s. As these buildings age and are renovated or demolished, lead-based paint can become a source of lead contamination in the soil.

3. Traffic emissions: Lead used to be added to gasoline to boost its octane rating. As a result, lead was a common component of vehicle emissions. Although leaded gasoline has been phased out in most countries, soils and plants near busy roads can still be contaminated with lead from historical emissions.

4. Mining and smelting: Mining and smelting of lead and other metals can release lead into the air, water, and soil. This can be a significant source of lead contamination in areas near mines and smelters.

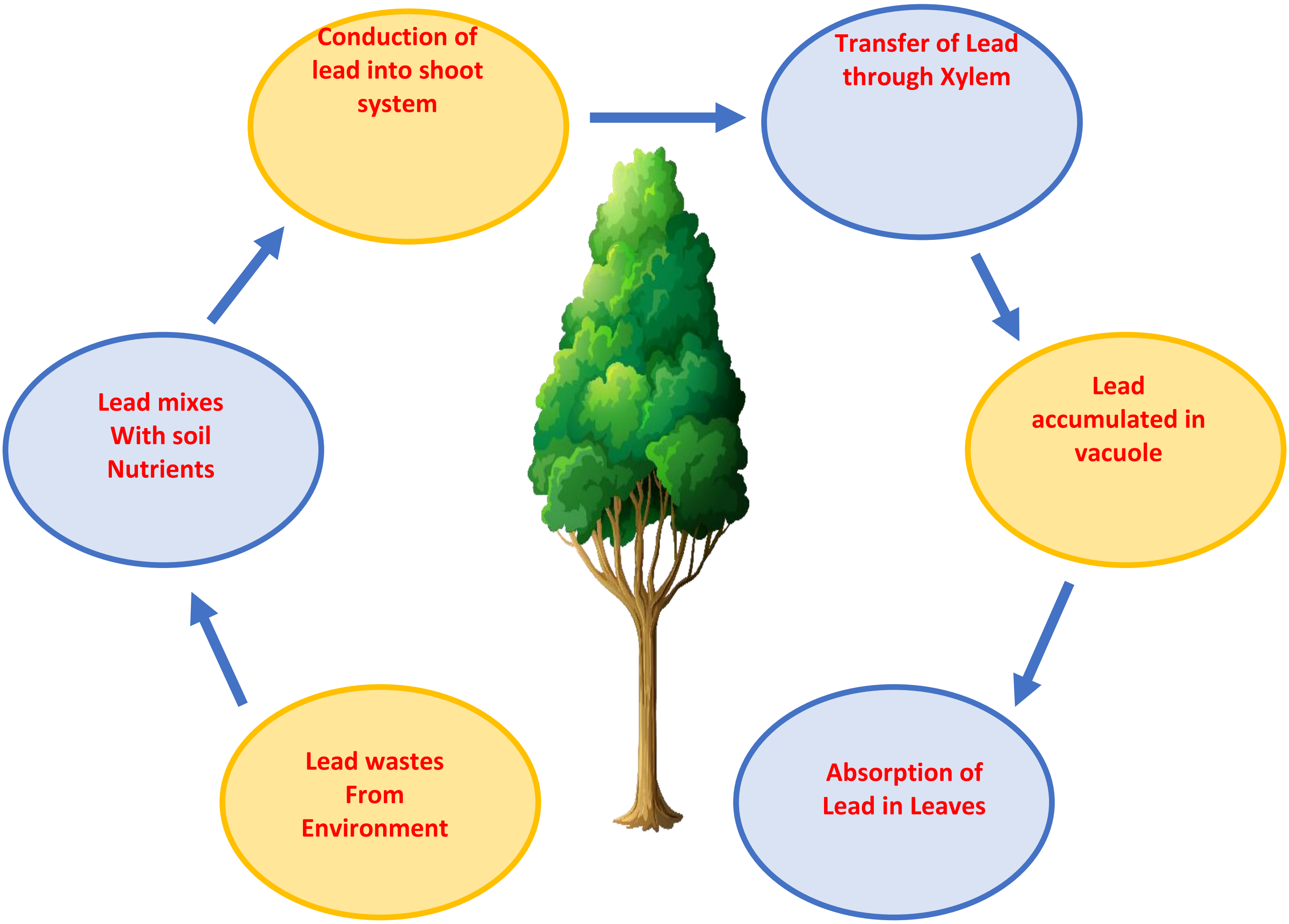
5. Natural sources: Some soils naturally contain high levels of lead due to their geology. These soils can lead to the accumulation of lead in plants grown on them.

Various sources of lead enrichment in the environment

(Ankush et al. 2021)

1.3.Uptake of lead

The plants take up the absorbed free-Pb ions either by capillary action or from the atmospheric air through cellular respiration. After the absorption of lead into the soil directly from the external atmosphere, it enters the plant system. The well-developed root system of plants takes up nutrients from the soil and along with them the divalent free-Pb cations (Engwa, G. A. et al, 2019). Uptake of and tolerance to Pb depends on root system conditions. In sunflower, Pb accumulation and cell response was shown to differ between seedlings with a primary root system (PRS) and seedlings with adventitious root systems (ARS) only (in which the primary roots were cut off). The ARS was found to be more tolerant to Pb than the PRS in Helianthus annuus L. and Allium cepa (Michalak and Wierzbicka,1998; Strubińska, and Hanaka, 2011). This suggests that ARS have additional mechanisms that protect them against Pb penetration and Pb-induced oxidative stress. However, these mechanisms are still unknown. Rhizosphere organisms also affect the metals availability and speciation. In Lantana camara, Pb accumulation in roots increases in the presence of earthworms Pontoscolex corethrurus; (Jusselme et al., 2012). Lead uptake is greatly affected by rhizospheric processes. Lin et al. (2004) explained the ability of Oryza sativa L. to absorb high levels of Pb from soil by a decrease in soil pH due to root exudates, solubilization of Pb by rhizosphere microorganisms and complexation of Pb with organic matter at the soil–root interface. These authors also found larger amounts of NH4OAc extractable Pb in the rhizosphere than in bulk soil, pointing to the involvement of root activities in changes in Pb availability (Lin et al., 2004).



2. Results and Discussion:

2.1. Adverse effect of lead

The visual general symptoms of lead toxicity are fast inhibition of root growth, underdeveloped growth of the plant, blackening of root system and chlorosis. Lead inhibits photosynthesis, let downs mineral nutrition, water balance and enzyme activities (Sharma P.& Dubey RS. 2005) These disorders upset normal physiological activities of the plant. At high concentrations lead may finally result to cell death (Seregin IV,2001) Similarly, lead inhibits germination of seeds and retards growth of seedlings, decreases germination percent, germination index, root/shoot length, tolerance index and dry mass of roots and shoots (Mishra S.2006). The growth development, fresh biomass and growth tolerance index of root, shoot and leaves were negatively affected by increasing levels of lead concentrations in tomato seedlings. Similar results were obtained by some other studies at the calculated lead concentrations: root, shoot and leaf growth; fresh and dry biomass is greatly reduced in Pisum Sativum, in Zea mays. Extreme concentration of lead causes dangerous effects to plants; it also results in phytotoxicity of cell membrane. Possible unexpected mechanisms include changes in permeability of cell membrane, reaction of sulphydryl (-SH) groups with cations, possible attraction for reacting with phosphate groups and active groups of ADP and ATP. Effects of lead have been reported on flower production, plants produce less number of flowers in high concentration of lead (Opeolu BO. 2010). Study on soybean have indicated that the lead toxicity induced a histological change in leaves, and made a thin leaf blade, minified the xylem and phloem in the vascular bundles, and also reduced the diameter of the xylem vessels. Same pathological changes in ultra structure level were testified on other plant species by Patel et al. & Wozny et al. At the same time, all these damage could disrupt many plant activities including ant oxidative system, photosynthesis, respiration, mineral nutrition, membrane structure and properties and gene expression.

2.2 Effect of lead on biochemical properties of plants

The cytotoxic mechanisms of Pb in plants are not entirely understood. It has been reported that Pb leads to the overproduction of reactive oxygen species (ROS) such as superoxide radicals (radical O2-) and hydrogen peroxide (H2O2) in plant cells (Reddy et al., 2005; Liu et al., 2010). These can cause lipid peroxidation, membrane damages, and oxidative stress (Sharma and Dietz, 2009). When pea (Pisum sativum) roots were exposed to 0.1 and 0.5 mM of Pb(NO3)2, a rapid increase in superoxide anion (O−2) and H2O2 levels occurs after 2 and 8 h of Pb treatment, respectively (Malecka et al., 2009 Liu et al. 2012). reported that after Pb treatment, roots of Ficus microcarpa produced high concentrations of H2O2 along with an increase in O−2 accumulation. O−2 is produced by nicotinamide adenine dinucleotide phosphate (NADPH) oxidase in the plasma membrane, and is converted to H2O2 through non-enzymatic pathways or by superoxide dismutase SOD; (Passardi et al., 2004). Some ROS can alter gene expression and modulate the activity of specific proteins in the plant defense system (Sharma and Dubey, 2005). To protect cells and tissues from injury and dysfunction, plants have developed various strategies, such as over expression of SOD, catalase (CAT), peroxidase (POX), and ascorbate POX genes. In addition, non-enzymatic antioxidants with low molecular weights, such as proline, cysteine, non-protein thiol, ascorbic acid, and glutathione, which can reduce oxidative stress by scavenging ROS are synthesized (Choudhury and Panda, 2005; Singh et al., 2006; Malecka et al., 2009). Like different heavy metals, lead treatment also affects the activity of a wide range of enzymes of different metabolic pathways. Chloramphenicol acetyl tranferase (CAT) is oxidoreductase that decomposes H2O2 to water and molecular oxygen, and it is one of the important enzymes involved in the removal of toxic peroxides. CAT activities in cuttings and seedlings significantly increased at lower lead concentrations, while at higher lead concentrations, it decreased. Reduced CAT activity at higher concentration of lead might be attributed to inactivation of enzyme by ROS, decrease in synthesis of enzyme, or change in assembly of its subunits. In most the inhibition exerted by lead on enzyme activity results from the interaction of lead with enzyme –SH groups. The vital enzyme of chlorophyll biosynthesis, α-amino laevulinate dehydrogenase, is powerfully inhibited by lead ions. Lead also inhibits the activities of enzymes of the reductive pentose phosphate pathway. In leaf homogenates of spinach the activity of ribulose-bis-phosphate carboxylase/oxygenase was inhibited even at a lead nitrate concentration of 5µM. Lead was found to be highly definite in inhibiting ATP synthetase/ATPase. In vitro application of lead to mitochondrial preparations from plant cells exposed a decrease in respiration rate with increasing lead concentrations. Using isolated chloroplasts and mitochondria in different plant species it has been shown that lead affects the flow of electrons via the electron transport system. The inhibitory effect of lead at higher concentrations appears to be due to disconnection of oxidative phosphorylation. At lower concentrations, however, a stimulation of respiration is observed in whole plants, detached leaves, isolated protoplasts and mitochondria.39 At higher concentrations of lead, inhibition of respiration is observed. Respiration of corn root tips decreased by 10-17 % after 1 hour treatment with 20 mM Pb and by 28-40 % after 3 hours treatment. Lead is regarded as one of the most potent metal ions for the inhibition of chloroplastic ATP synthetase/ATPase activity and for the destruction of the membranes. Although the sensitivity of photophosphorylation to heavy metal ions is well documented, there is no general agreement regarding their site neither of action nor on the underlying mechanism.

2.3 Effect of lead photosynthesis

The process of photosynthesis is unfavorably affected by lead toxicity. Plants exposed to lead ions show a decline in photosynthetic rate which results from partial chloroplast ultra-structure, restrained synthesis of chlorophyll, plastoquinone and carotenoids, obstructed electron transport, inhibited activities of Calvin cycle enzymes, as well as deficiency of CO2 as a result of stomatal closure (Stefanov K, et al. 1995) Ceratophyllum demersumplants when grown in aquatic medium containing Pb(NO3)2 showed distinct changes in chloroplast fine structure. Leaf cells of such plants showed a reduction in grana stacks together with a reduction in the amount of stroma in relation to the lamellar system as well as absence of starch grains. Lead treatment also changes the lipid composition of thylakoid membranes. Lead inhibits chlorophyll synthesis by causing reduced uptake of essential elements such as Magnesium and Iron by plants. It harms the photosynthetic apparatus due to its affinity for protein N-and S-ligands (Ahmed A,& Tajmir–Riahi HA 1993). An enhancement of chlorophyll degradation occurs in lead-treated plants due to increased chlorophyllase activity. Chlorophyll b is reported to be more affected than chlorophyll a by lead treatment (Vodnik D, et al 1999).

2.4. Effects on Germination and Growth

When plants are exposed to lead, even at micromolar levels, adverse effects on germination occur. Germination is strongly inhibited by very low concentrations of Pb2+. Lead induced inhibition of seed germination has been reported in Hordeum vulgare, Elsholtzia argyi, Spartina alterniflora, Pinus halepensis, Oryza sativa, and Zea mays. At higher concentrations, lead may speed up germination and simultaneously induce adverse effects on the length of radical and hypocotyl in E. argyi. Inhibition of germination may result from the interference of lead with protease and amylase enzymes. Lead exposure in plants also strongly limits the development and sprouting of seedlings. (Nas FS & Ali M. 2018). At low concentrations, lead inhibits the growth of roots and aerial plant parts. This inhibition is stronger for the root, which may be correlated to its higher lead content. Lead toxicity may also cause swollen, bent, short and stubby roots that show an increased number of secondary roots per unit root length. (Nas FS & Ali M. 2018). Arias et al. (2010) reported significantly inhibited root elongation in Mesquite (Prosopis sp.). Plant biomass can also be restricted by high doses of lead exposure. Under severe lead toxicity stress, plants displayed obvious symptoms of growth inhibition, with fewer, smaller, and more brittle leaves having dark purplish abaxial surfaces. (Singh R, et al. 2010).

2.5. Effect of lead on root growth

Lead (Pb) is one of the most widespread heavy metal contaminants in soils. It is highly toxic to living organisms. Pb has no biological function but can cause morphological, physiological, and biochemical dysfunctions in plants. Plants have developed a wide range of tolerance mechanisms that are activated in response to Pb exposure. Pb affects plants primarily through their root systems. Plant roots rapidly respond either (i) by the synthesis and deposition of callose, creating a barrier that stops Pb entering (ii) through the uptake of large amounts of Pb and its sequestration in the vacuole accompanied by changes in root growth and branching pattern or (iii) by its translocation to the aboveground parts of plant in the case of hyperaccumulators plants. Here we review the interactions of roots with the presence of Pb in the rhizosphere and the effect of Pb on the physiological and biochemical mechanisms of root development. In addition, lead strongly inhibits seed germination, root elongation, seedling development, plant growth, transpiration, chlorophyll production, and

Fig. 1. Effect of Pb(NO3)2 on Leucaena leucocephala growth. (A–G) Shoot and root growth (from left to right; control (A), 25 (B), 50 (C), 100 (D), 300 (E), 500 (F) and 700 lM (G).

The plants treated with 25, 50 or 100 µM Pb did not show any visible reduction in their shoot heights and root lengths, and the overall physical appearance of the shoots and roots was very similar to the control plants. In contrast, the shoot heights and root lengths of Pb-treated plants with 300, 500 and 700 µM Pb were severely reduced as compared to control plants. In addition, Pb-treated plants with 300, 500 and 700 µM Pb showed growth retardation, which resulted in a severe reduction in leaf area. Also, severe chlorosis was noticed on leaves. On the other hand, roots showed changes in branching pattern and some discoloration (brownish) in response to Pb treatments (Fig. 1).(Alkhatib, R., et al., 2019).

2.6. Bioaccumulation of lead effects in plants:

Heavy metals (HM) toxicity is becoming a major threat to living organisms in recent years due to the increase in population and anthropogenic activities. Lead (Pb) shares about 10% of total pollution produced by heavy metals. The uptake of lead by the primary producers (plants) is found to affect their metabolic functions, growth, and photosynthetic activity. The accumulation of lead in excess can cause up to a 42% reduction in the growth of the roots. The current review addresses the global status of lead contamination in soil, potential lead sources, and the mechanism of lead uptake by the plants. This article also provides information about the lead concentration in plants in polluted and non-polluted areas. Humans are directly or indirectly dependent on plants to meet their daily requirements. So, it becomes necessary to review the problems associated with lead pollution in plants and its mode of action affecting the plant system. Factors like bioaccumulation, bioavailability, bioconcentration, transfer factor, and the role of Casparian strips as a natural physical barrier are discussed. Further, the updated literature survey about the various bioremediation strategies utilized for its elimination is also presented. The current study suggests that more attention needs to be focused on evaluating the effectiveness of bioremediation methods. (Samuel G. et al. 2022).

2.7. Root defense against lead stress

In response to Pb exposure, plants have developed a variety of tolerance mechanisms (Figure 2). Roots are the first organs, exposed to Pb ions (Piechalak et al., 2002). The first defense strategy is to stop the metal entering the root tissues by excluding it (Mishra et al., 2006). Roots rapidly respond to the presence of Pb by form- ing mechanical barrier. In some plants, there is synthesis and deposition of callose between the plasma membrane and the cell wall. This newly formed structure functions as a barrier against stress factors including metals (Bacic et al., 2009; Krzesłowska, 2011). Samardakiewicz etal. (2012) examined whether callose forms an efficient barrier against Pb penetration in the roots of Lemna minor L. exposed to 15 µM of Pb for 6 h. This treat- ment resulted in the synthesis and deposition of callose in the newly formed cell wall in the protoderm in the center of the root tip. After callose deposition the Pb concentration was restricted in these superficial cells. Similar observations have been made in other species exposed to Pb including Arabidopsis thaliana (Lum- merzheim et al.,1995) and Funaria hygrometrica (Krzeslowska et al., 2009). Pb-induced callose deposition has been detected in the rhizodermis and in the center of the stele of Pb-treated soy- bean Glycine max roots tips (Samardakiewicz et al.,1996). Under metal stress, the synthesized callose inhibits cell-to-cell transport.

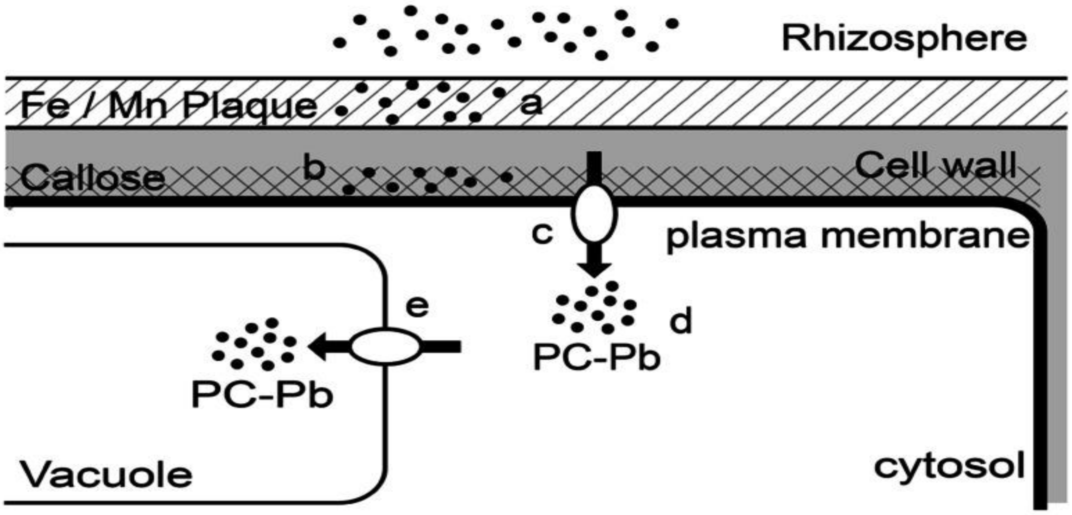


FIGURE 2| Schematic representation of the types of root responses to lead toxicity in higher plants. (a) Pb sequestration in the Fe/Mn plaques; (b) Pb binding in callose formed in the new cell wall; (c) Pb fluxes across the plasma membrane; (d) Chelation of Pb in the cytosol by phytochelatin; (e) Transport of PC–Pb complex and sequestration in the vacuole.

This may result in the prevention of a wide incursion of Pb ions, but it can simultaneously inhibit the transport of other molecules. However, the synthesis of callose is not a general pattern in plants in response to Pb, in Zea mays and G. max, low level Pb treatment did not result in any callose deposition in root tissue. Although, these species synthesized callose in response to cadmium or arsenic (Pirselova et al.,2012). It seems that the formation of callose was closely related to the amount of Pb entering the cell, and subsequently the level of stress.

In some plants, the formation of Fe and Mn plaques on roots surface may provide a means of attenuation and external exclu- sion of metals. These plaques increase the sequestration of Pb on the root surface and in the rhizosphere, providing a means of external exclusion of soil Pb (Hansel et al., 2002). In some rice cultivars, Fe plaques were shown to affect patterns of Pb uptake and accumulation. Lower concentrations of Pb were found in the root tissues of rice plants with plaque compared to concentra- tions found in the plants without plaque. But the functions of plaque are limited as they are only efficient in relatively low or moderately Pb-contaminated soil (Liu et al., 2011). Fe plaque and organic matrix with high Pb affinity were found in root epidermis of Typha latifolia, and were shown to prevent the accumulation and the translocation of Pb within the root (Qian et al., 2012; Feng et al., 2013).

In most plants, 90% of the total Pb is accumulated in roots (Kumar et al., 1995). Most Pb in roots is localized in the insoluble fraction of cell walls and nuclei, which is linked with the detoxifica- tion mechanism (Piechalak et al., 2002). After exposure to Pb, cell mechanisms that minimize the potential for toxicity are rapidly activated. In the roots of several species including Pisum sativum (Malecka et al., 2009); Allium sativum (Jiang and Liu, 2010), and Athyrium yokoscense (Nishizono et al., 1987), the cell walls, the first barrier against Pb stress, can immobilize and accumulate some or even most Pb ions. The important role of the cell wall in the defense response of plants to trace metals was recently reviewed by Krzeslowska (2011). The capacity of cell walls to bind divalent metal cations mainly depends on the amount of polysaccharides with many carboxyl groups (Inoue et al., 2013). In Arabidopsis thaliana, Pb-galacturonic acid fragments were detected in root treated with Pb (Polec-Pawlak et al., 2007). Brunet et al. (2008) showed that root of Lathyrus sativus L. exposed to Pb contained much less calcium than control plants, and explained the reduc- tion in Ca content by the replacement of Ca ions by Pb ions, which have a high affinity for pectin in cell walls. In Raphanus sativus, Pb2+ was also shown to bind to carboxyl groups of pectin in cell walls (Inoue et al., 2013). All the examples described above clearly show that the cell wall is one of the preferred and essential compartments for Pb accumulation, deposition, and sequestra- tion. Therefore, these results shed a new light on the functioning of the cell walls in plant cell defense strategy against Pb. Heavy metals including Pb are likely to enter plant cells via essentials cations transporters. AtCNGC, homologous to a non-selective cation channel, was suggested to enable Pb2+ entry since over- expression of the truncated gene resulted in tolerance to Pb2+ (Sunkar et al., 2000). Ca2+ was also reported to compete with Pb2+ for entry into rice root cells. When Ca2+ was supplied in the medium, it reduced Pb uptake and toxicity (Kim et al., 2002) .This suggests that Pb enters the root cells via Ca2+/Mg2+ gated channel (Kim et al., 2002).

In Allium sativum, as soon as excessive Pb ions enter the cytoplasm, a defense mechanism is activated, protecting the cells against Pb toxicity. Endocytotic and exocytotic processes are involved in these phenomena. The plasma membrane rep- resents a “living” barrier of the cell to free inward diffusion of Pb ions. Invaginations of plasmalemma and some vesicles from dic- tyosomes and endoplasmic reticulum (ER) could prevent the free circulation of Pb ions in the cytoplasm. The vacuole is ultimately one of the main storage sites for metal sequestration (Sharma and Dubey, 2005). In Allium sativum roots, cysteine-rich peptides commonly referred as phytochelatins (PCs) were detected only after 2 h of Pb exposure (Jiang and Liu, 2010). This indicates that Pb ions can induce synthesis of PCs. Piechalak et al. (2002) demonstrated that the synthesis of PCs takes place under the influence of Pb ions in root cells of three tested plant species of the Fabaceae family: Pisum sativum, V. faba, and Phaseolus vulgaris. The complex PC–Pb formed is then transported through the cytosol into the vacuoles (Piechalak et al.,2002). AtHMA3, encoding a P1B−2-ATPase, a heavy metal transporter, is localized in the vacuolar membrane of roots cells in Arabidopsis thaliana (Talke et al., 2006; Morel et al., 2009). This transporter is involved in the transfer of complexed heavy met- als, including Pb, from the cytoplasm to the vacuole (Morel et al., 2009). Root length was less affected by Pb in Arabidopsis thaliana plants overexpressing AtHMA3 than in wild-type plants (Morel et al., 2009). B. juncea appears to tolerate high concentrations of Pb thanks to its efficient cell roots vacuolar storage mechanisms. In this species, Pb sequestration was restricted to vacuoles (Meyers et al., 2008). In addition, it was suggested that exposure to Pb causes the production of additional vacuole specifically for Pb stor- age in the root tips of B. juncea (Meyers et al., 2008). The increase in the production of vacuoles could be regarded as a defense and adaptation strategy to elevated levels of Pb in the root cells. This roots potential storage can be used in phytoremediation processes. Table 1 shows a list of plant species effective in the accumulation of Pb in roots that could be used in rhizoremediation. In a metallicolous ecotype of Elsholtzia argyi, Pb is found in fine particles dispersed through root cell membranes and cell wall fractions whereas in non-metallicolous roots, most Pb was found as large aggregates deposited in the cell wall fractions. These differences in localization explained why non-metallicolous roots were not able to transfer Pb to above ground parts via the apoplast (Islam et al., 2007). In some plants, Pb can be transported via vascular tissues to aerial parts (Hanc et al., 2009). In Sesbania drummondii, Pb is transported to leaves after complexation with acetate, nitrate, and sulfide (Sharma et al., 2004). In tobacco, a cyclic nucleotide gated channel (NtCBP4) was suggested to be involved in Pb transport (Sunkar et al., 2000).

To sum up, Pb pathway may include the following stages in roots: Pb can bound with physical barrier (callose, Fe/Mn plaques, cell wall…). At high concentration, this barrier is broken and the flux of Pb enters the cell through the plasma membrane using the ions transporters. In cytoplasm, Pb is chelated with PCs. The complex formed is then sequestered in the vacuoles. In accumulator plants, Pb can be transported via phloem to aerial parts .

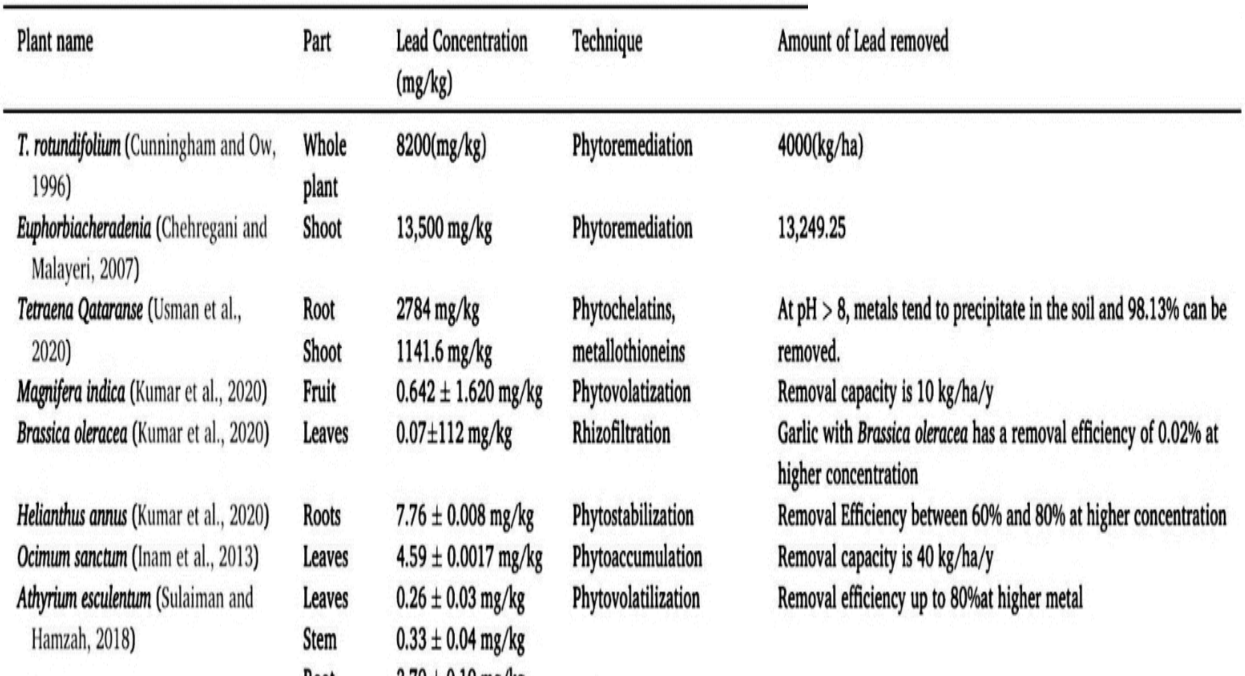
Compared to Zn and Cd, very little is known about the molecular mechanisms of acquisition, transport, and accumulation of Pb. This is due first to the characteristics of Pb which precipitates with some components of the culture media making difficult to study its bioavailability to the roots. On the other hand, the lack of model plant for studying the mechanisms of tolerance to this metal. Among the 450 species known as metal hyperaccumulator and tolerant plants, Pb accumulating species are rather exceptional. Recently, Auguy et al. (2013) identified *Hirschfeldia incana*, a member of the Brassicaceae family, as a Pb accumulator plant. They demonstrated that this species, owing to its close genetic proximity to Arabidopsis, is a good model to identify genes involved in Pb tolerance and accumulation. This can open up new possibilities for understanding the molecular mechanisms of Pb tolerance in plants.

2.8. Physiology And ultrastructural effects of lead:

The primary effect of Pb toxicity in plants is a rapid inhibition of root growth, probably due to the inhibition of cell division in the root tip (Eun et al., 2000). It was demonstrated that Pb caused inhibition of cell division in Lemna minor roots (Samar D. and Wozny, 2005). In several plant species, including Triticum aestivum (Dey et al., 2007; Kaur et al., 2013), Z. mays L. (Kozhevnikova etal., 2009), Pisum sativum (Malecka et al., 2009), and Sedum alfredii (Gupta et al., 2010), a decrease in the length and in root dry mass under Pb toxicity have been reported (Mun zuroglu and Geckil, 2002). Verma and Dubey (2003) showed that growthof rice roots wassignificantly inhibited at 0.5–1 mMPb^{2+}; up to 40% reduction in root length was observed in 20-day-old rice seedlings. In Pb-treated Elsholtzia argyi and

Table 1

Plants used for bioremediation, concentration of Lead (Pb) accumulated and their remediation techniques. (Ferrer M A& Cimini S, 2018)



Plant name	Part	Lead Concentration (mg/kg)	Technique	Amount of Lead removed
T. rotundifolium (Cunningham and Ow, 1996)	Whole plant	8200(mg/kg)	Phytoremediation	4000(kg/ha)
Euphorbiacheradenia (Chehregani and Malayeri, 2007)	Shoot	13,500 mg/kg	Phytoremediation	13,249.25
Tetraena Qataranse (Usman et al., 2020)	Root	2784 mg/kg	Phytochelatins, metallothioneins	At pH > 8, metals tend to precipitate in the soil and 98.13% can be removed.
	Shoot	1141.6 mg/kg		
Magnifera indica (Kumar et al., 2020)	Fruit	0.642 ± 1.620 mg/kg	Phytovolatization	Removal capacity is 10 kg/ha/y
Brassica oleracea (Kumar et al., 2020)	Leaves	0.07±112 mg/kg	Rhizofiltration	Garlic with *Brassica oleracea* has a removal efficiency of 0.02% at higher concentration
Helianthus annus (Kumar et al., 2020)	Roots	7.76 ± 0.008 mg/kg	Phytostabilization	Removal Efficiency between 60% and 80% at higher concentration
Ocimum sanctum (Inam et al., 2013)	Leaves	4.59 ± 0.0017 mg/kg	Phytoaccumulation	Removal capacity is 40 kg/ha/y
Athyrium esculentum (Sulaiman and Hamzah, 2018)	Leaves	0.26 ± 0.03 mg/kg	Phytovolatilization	Removal efficiency up to 80%at higher metal
	Stem	0.33 ± 0.04 mg/kg		

The evaluation of T. qataranse growth parameters suggests that Pb has no adverse effect on the plant at concentrations of less than 100 mg/L Pb. However, at 100 mg/L, the metal disturbed healthy growth and, in particular, interfered with root development. Consistent with our findings, a similar study using Z. fabago reported that Pb negatively affects root development (Ferrer M A,& Cimini S, 2018). The root plays a vital role in plant health and development, influencing other tissues response to stress conditions. Despite it being one of the most critical parameters in the assessment of plant health, a significant reduction in total chlorophyll content was observed. However, Pb toxicity symptoms (e.g., leaf chlorosis and root darkening) were not apparent across any of the treatments. Typically, Pb accumulation in plants raises the level of chlorophyllase, an enzyme that negatively affects chlorophyll. An increased level of chlorophyllase slows down photosynthesis and, therefore, affects overall growth and develop-ment. Consequently, due to slow metabolic activities, cell division is adversely affected and healthy growth is inhibited (Hu R et al, 2012).

3. Conclusion:

Lead accumulation in the environment is constantly increasing due to increased anthropogenic activities. The metabolic functions of the plants have severely affected the presence of lead in the ecosystem. The absorbing tissues are responsible for the entry of lead from the external medium into the plant's system. Abnormal cell division of mitosis, lower growth of seedlings, germination percent, root/shoot length, and dry mass are some common problems observed in plants. Also, lead accumulation causes adverse effects on the photosynthetic rate by causing biochemical changes in fruits and flowers due to chlorosis. The hyperaccumulating plants have developed biochemical mechanisms that allow plants to be used for environmental bioremediation. Moreover, different bioremediation approaches have been reported for the elimination of toxic pollutants from the environment. Due to the increase in population and human activities, there is still a need for more focused research to evaluate the effectiveness of these bioremediation methods. Moreover, advancements are required for the development of new environmentally friendly remediation strategies which can help to mitigate lead toxicity. The governmental regulatory bodies need to enforce strict actions for the industrial sector which is responsible for the release of toxic chemicals into the ecosystem. These approaches will assist in lowering HM levels in the aquatic and terrestrial environment.

4. References:

Ahmed, A., and Tajmir-Riahi, H. A. (1993). Interaction of toxic metal ions Cd2+, Hg2+, and Pb2+ with light-harvesting proteins of chloroplast thylakoid membranes. An FTIR spectroscopic study. *Journal of inorganic biochemistry*, *50*(4), 235-243.

Alkhatib, R., Mheidat, M., Abdo, N., Tadros, M., Al-Eitan, L. and Al-Hadid, K., (2019). Effect of lead on the physiological, biochemical and ultrastructural properties of Leucaena leucocephala. Plant Biology, 21(6), pp.1132-1139.

Alongi, D. M. (2017). Micronutrients and mangroves: experimental evidence for copper limitation. Limnology and Oceanography 62 (6),2759–2772.

Amari, T., Ghnaya, T. & Abdelly, C. (2017). Nickel, cadmium and lead phytotoxicity and potential of halophytic plants in heavy metal extraction. South African Journal of Botany 111, 99–110.

Ankush, Prakash R, Singh V et al (2021) Sewage sludge impacts on yields, nutrients and heavy metals contents in pearl millet–wheat system grown under saline environment. Int J Plant Prod 15:93–105. https://doi.org/10.1007/s42106-020-00122-4

Arias JA, Peralta–Videa JR, Ellzey JT. (2010). Effects of Glomus deserticola inoculation on Prosopis: enhancing chromium and lead uptake and translocation as confirmed by X–ray mapping, ICP–OES and TEM techniques. Environ Exp Bot ;68(2):139–148.

ATSDR .(2015). CERCLA Priority list of hazardous substances. ATSDR Home. Retrieved March 22, 2011, from http://www.atsdr.cdc.gov/cercla/07list.html

Bacic, A., Fincher, G. B., and Stone, B. A. (2009). Chemistry, Biochemistry, and Biology of 1-3 Beta Glucans and Related Polysaccharides. San Diego, CA: Elsevier Science

Balakhnina I.T., Borkowska A., Nosalewicz M., Nosalewicz A., Włodarczyk M.T., Kosobryukhov A.A.,Fomina R.I. (2016) Effect of temperature on oxidative stress induced by lead in the leaves of Plantagomajor L. International Agrophysics, 30, 285–292

Balkhair, K.S., Ashraf, M.A., (2016). Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. Saudi J. Biol. Sci. 23 (1), S32–S44. https://doi.org/10.1016/j.sjbs.2015.09.023

Chehregani, A., Malayeri, B.E., (2007). Removal of heavy metals by native accumulator plants. Int. J. Agric. Biol.

Choudhury, S., and Panda, S. K. (2005). Toxic effects, oxidative stress and ultrastructural changes in moss Tax- ithelium nepalense (Schwaegr.) Broth. under chromium and lead phytotoxi- city. Water Air Soil Pollut. 167, 73–90. doi: 10.1007/s11270-005-8682-9

Clemens, S. (2006). Toxic metal accu- mulation, responses to exposure and mechanisms of tolerance in plants. Biochimie 88, 1707–1719. doi: 10.1016/j.biochi.2006.07.003

Cunningham, S.D., Ow, D.W., (1996). Promises and prospects of phytoremediation. Plant Physiol. 110 (3), 715. https://doi.org/10.1104/pp.110.3.715.

Dey, S. K., Dey, J., Patra, S., and Pothal, D. (2007). Changes in the antioxidative enzyme activities and lipid peroxidation in wheat seedlings exposed to cadmium and lead stress. Braz. J. Plant Physiol. 19, 53–60. doi: 10.1590/S1677-04202007000100 006

Engwa G A, Ferdinand P U, Nwalo F N, Unachukwu M N (2019): Mechanism and health effects of heavy metal toxicity in humans. Poisoning in the modern world-new tricks for an old dog 10. DOI: https://doi.org/10.5772/intechopen.82511

Eun, S. O., Youn, H. S., and Lee, Y. (2000). Lead disturbs micro- tubule organization in the root meris- tem of Zea mays. Physiol. Plant. 110, 357–365. doi: 10.1034/j.1399- 3054.2000.1100310.x

Fahr, M., Laplaze, L., Bendaou, N., Hocher, V., El Mzibri, M., Bogusz, D., & Smouni, A. (2013). Effect of lead on root growth. *Frontiers in plant science*, *4*, 47559.

Feng, H., Qian, Y., Gallagher, F., Wu, M., Zhang, W., Yu, L., et al. (2013). Lead accumulation and association with Fe on Typha latifolia root from an urban brownfield site. Environ. Sci. Pollut. Res. Int. 20, 3743– 3750. doi: 10.1007/s11356-012- 1298-x

Ferrer, M. A., Cimini, S., López-Orenes, A., Calderón, A. A. & De Gara, L. (2018). Differential Pb tolerance in metallicolous and non-metallicolous Zygophyllum fabago populations involves the strengthening of the antioxidative pathways. Environ. Exp. Bot. 150, 141-151.

Gupta, D. K., Huang, H. G., Yang, X. E., Razafindrabe, B. H. N., and Inouhe, M. (2010). The detoxification of lead in Sedum alfredii H. is not related to but the glutathione. J. Hazard. Mater. 177, 437–444. doi: 10.1016/j.jhazmat.2009.12.052

Hanc, A., Baralkiewicz, D., Piechalak, A., Tomaszewska, B., Wagner, B., and Bulska, E. (2009). An analysis of long-distance root to leaf transport of lead in Pisum sativum plants by laser ablation-ICP-MS. Int. J. Envi- ron. Anal. Chem. 89, 651–659. doi:10.1080/03067310802559366

Hansel, C. M., La Force, M. J., Fendorf, S., and Sutton, S. (2002). Spatial and temporal association of As and Fe species on aquatic plant roots. Environ. Sci. Technol. 36, 1988– 1994.

Hu, R., Sun, K., Su, X., Pan, Y. X., Zhang, Y. F., & Wang, X. P. (2012). Physiological responses and tolerance mechanisms to Pb in two xerophils: Salsola passerina Bunge and Chenopodium album L. *Journal of Hazardous Materials*, *205*, 131-138.

Huang, S. Z., Song, Q. X., Li, Q., Zhang, H., Luo, X. Z. & Zheng, Z. (2020). Damage of heavy metals to Vallisneria natans (V. natans) and characterization of microbial community in biofilm. Aquatic Toxicology 225, 105515.

Humberto, A., Paula, M., Butler, B., Jorge, P., Matus, F., Merino, C., Yakov, K. (2020). Meta-analysis of heavy metal effects on soil enzyme activities. Sci. Total Environ., 139744 https://doi.org/10.1016/j.scitotenv.2020.139744.

Hussain, J., Wei, X., Xue-Gang, L., Shah, S.R.U., Aslam, M., Ahmed, I., Azam, T. (2021). Garlic (Allium sativum) based interplanting alters the heavy metals absorption and bacterial diversity in neighboring plants. Sci. Rep. 11 (1), 1–13. https://doi.org/10.1038/s41598-021-85269-4.

Ihedioha, J.N., Ujam, O.T., Nwuche, C.O., Ekere, N.R., Chime, C.C. (2016). Assessment of heavy metal contamination of rice grains (Oryza sativa) and soil from Ada field, Enugu, Nigeria: estimating the human healtrisk. Hum. Ecol. Risk Assess. Int. J. 22 (8), 1665–1677. https://doi.org/10.1080/10807039.2016.1217390.

Inam, F., Deo, S., Narkhede, N. (2013). Analysis of minerals and heavy metals in some spices collected from local market. J. Pharm. Biol. Sci. 8 (2), 40–43. https://doi.org/10.9790/3008-0824043.

Inoue, H., Fukuoka, D., Tatai, Y., Kamachi, H., Hayatsu, M., Ono, M. (2013). Properties of lead deposits in cell walls of radish (Raphanus sativus) roots. J. Plant. Res. 126, 51–61. doi: 10.1007/s10265- 012-0494-6

Islam, E., Yang, X., Li, T., Liu, D., Jin, X., and Meng, F. (2007). Effect of Pb toxicity on root morphology, physiology and ultrastructure in the two ecotypes of Elsholtzia argyi. J. Hazard. Mater. 147, 806–816. doi: 10.1016/j.jhazmat.2007.01.117

Jiang W, Liu D. (2010). Pb–induced cellular defense system in the root meristematic cells of Allium sativum L. BMC Plant Biol. 10:40.

Jusselme, M. D., Poly, F., Miambi, E., Mora, P., Blouin, M., Pando, A. (2012). Effect of earthworms on plant Lantana camara Pb-uptake and on bacterial communities in root-adhering soil. Sci. Total Environ. 416, 200–207. doi:10.1016/j.scitotenv.2011.10.070

Kaur, G., Singh, H. P., Batish, D. R., and Kohli, R. K. (2013). Lead (Pb)-induced biochemical and ultra- structural changes in wheat (Triticum aestivum) roots. Protoplasma 1, 53–62. doi: 10.1007/s00709-011-0372-4

Khan, A., Khan, S., Khan, M.A., Qamar, Z., Waqas, M. (2015). The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. Environ. Sci. Pollut. Res. 22 (18), 13772–13799. https://doi.org/10.1007/s11356-015-4881-0.

Khan, A., Khan, S., Khan, M.A., Qamar, Z., Waqas, M. (2015). The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. Environ. Sci. Pollut. Res. 22 (18), 13772–13799. https://doi.org/10.1007/s11356-015-4881-0.

Kim, Y. Y., Yang, Y. Y., and Lee, Y. (2002). Pb and Cd uptake in rice roots. Physiol. Plant. 116, 368–372. doi:10.1034/j.1399-3054.2002.1160312.x

Krzesłowska, M. (2011). The cell wall in plant cell response to trace metals: polysaccharide remodeling and its role in defense strategy. Acta Physiol. Plant. 33, 35–51. doi: 10.1007/s11738-010-0581-zpp.35-51

Krzeslowska, M., Lenartowska, M., Mellerowicz, E., Samardakiewicz, S., and Wozny, A. (2009). Pectinous cell wall thickenings formation – a response of moss protonemata cells to lead. Environ. Exp. Bot. 65, 119–131. doi:10.1016/j.envexpbot.2008.05.006

Kumar B, Smita K, Flores L C (2017): Plant mediated detoxification of mercury and lead. Arabian Journal of Chemistry 10 S2335-S2342. DOI: https://doi.org/10.1016/j.arabjc.2013.08.010

Kumar, A., Mms, C.P., Chaturvedi, A.K., Shabnam, A.A., Subrahmanyam, G., Mondal, R., Yadav, K.K. (2020). Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. Int. J. Environ. Res. Public Health 17 (7), 2179. https://doi.org/10.3390/ijerph17072179.

Kumar, P., Dushenkov, V., Motto, H., and Raskin, I. (1995). Phytoextrac- tion: the use of plants to remove heavy metals from soils. Environ. Sci. Technol. 29, 1232–1238. doi: 10.1021/es00005a014

Liu, J., Leng, X., Wang, M., Zhu, Z., and Dai, Q. (2011). Iron plaque formation on roots of dif- ferent rice cultivars and the rela- tion with lead uptake. Ecotoxicol. Environ. Saf. 74, 1304–1309. doi: 10.1016/j.ecoenv.2011.01.017

Liu, N., Lin, Z. F., Lin, G. Z., Song, L. Y., Chen, S. W., Mo, H., et al. (2010). Lead and cad- mium induced alterations of cel- lular functions in leaves of Aloca- sia macrorrhiza L. Schott. Ecotoxicol. Environ. Saf. 73, 1238–1245. doi: 10.1016/j.ecoenv.2010.06.017

Liu, N., Lin, Z., and Mo, H. (2012). Metal (Pb, Cd, and Cu)-induced reactive oxygen species accumula- tions in aerial root cells of the Chinese banyan (Ficus microcarpa). Ecotoxicology 21, 2004–2011. doi: 10.1007/s10646-012-0935-y

Lummerzheim, M., Sandroni, M., Castresana, C., Deoliveira, D., Vanmontagu, M., Roby, D., et al. (1995). Comparative microscopic and enzymatic characterization of the leaf necrosis induced in Arabidopsis thaliana by lead nitrate and by Xanthomonas campestris pv campestris after foliar spray. Plant Cell Environ. 18, 499–509. doi: 10.1111/j.1365-3040.1995.tb00550.x

Malar, S., Vikram, S. S., Favas, P. J. & Perumal, V. (2016). Lead heavy metal toxicity induced changes on growth and antioxidative enzymes level in water hyacinths [Eichhornia crassipes (Mart.)]. Botanical Studies 55 (1), 1–11.

Malecka, A., Piechalak, A., and Tomaszewska, B. (2009). Reac- tive oxygen species production and antioxidative defense system in pea root tissues treated with lead ions: the whole roots level. Acta Physiol. Plant. 31, 1053–1063. doi: 10.1007/s11738- 009-0326-z

Meyers, D. E. R., Auchterlonie, G. J., Webb, R. I., and Wood, B. (2008). Uptake and localisation of lead in the root system of Brassica juncea. Environ. Pollut. 153, 323–332. doi: 10.1016/j.envpol.2007.08.029

Michalak, E., and Wierzbicka, M. (1998). Differences in lead tolerance between Allium cepa plants devel- oping from seeds and bulbs. Plant Soil 199, 251–260. doi: 10.1023/ A:1004321331708

Mishra S, Srivastava S, Tripathi R, et al. Lead detoxification by coontail (Ceratophyllum demersum L.) involves induction of phytochelatins and antioxidant system in response to its accumulation. Chemosphere. 2006;65(6):1027–1039.

Mishra, S., Srivastava, S., Tripathi, R. D., Kumar, R., Seth, C. S., and Gupta, D. K. (2006). Lead detoxification by coontail (Ceratophyllum demersum L.) involves induction of phytochelatins and antioxidant system in response to its accumulation. Chemosphere 65, 1027–1039. doi: 10.1016/j.chemosphere.2006. 03.033

Morel, M., Crouzet, J., Gravot, A., Auroy, P., Leonhardt, N., Vavasseur, A., et al. (2009). AtHMA3, a P1B-ATPase allowing Cd/Zn/Co/Pb vacuolar storage in Arabidopsis. Plant Physiol. 149, 894–904. doi: 10.1104/pp.108.130294

Munzuroglu, O., and Geckil, H. (2002). Effects of metals on seed germination, root elongation, and coleoptile and hypocotyl growth in Triticum aes- tivum and Cucumis sativus. Arch. Env- iron. Contam. Toxicol. 43, 203–213. doi: 10.1007/s00244-002-1116-4

Nas FS, Ali M. (2018).The effect of lead on plants in terms of growing and biochemical parameters: a review. MOJ Eco Environ Sci.;3(4):265–268.

Nishizono, H., Suzuki, S., and Ishii, F. (1987). Accumulation of heavy- metals in the metal tolerant fern, Athyrium yokoscense, growing on var- ious environments. Plant Soil 102, 65–70. doi: 10.1007/BF02370902

Opeolu BO, Adenuga PA, Ndakidemi Olujimi OO. (2010). Assessment of phyto–toxicity potential of lead on tomato (Lycopersicon esculentum L) planted on contaminated soils. International Journal of Physical Sciences. 5(2):68–73.

Passardi, F., Penel, C., and Dunand, C. (2004). Performing the paradox- ical: how plant peroxidases modify the cell wall. Trends Plant Sci. 9, 534–540. doi: 10.1016/j.tplants.2004. 09.002

Peng, H. Y., Tian, S. K., and Yang, X. E. (2005). Changes of root morphol- ogy and Pb uptake by two species of Elsholtzia under Pb toxicity. J. Zhejiang Univ. Sci. B 6, 546–552.

Piechalak, A., Tomaszewska, B., Baralkiewicz, D., and Malecka, A. (2002). Accumulation and detoxification of lead ions in legumes. Phytochemistry 60, 153–162. doi: 10.1016/S0031-9422(02)00067-5.

Pirselova, B., Mistrikova, V., Libantova, J., Moravcikova, J., and Matusikova, I. (2012). Study on metal-triggered callose deposition in roots of maize and soybean. Biologia 67, 698–705. doi: 10.2478/s11756-012-0051-8

Polec-Pawlak, K., Ruzik, R., Lipiec, E., Ciurzynska, M., and Gawronska, H. (2007).InvestigationofPb(II)bind- ing to pectin in Arabidopsis thaliana. J. Anal. At. Spectrom. 22, 968–972. doi: 10.1039/b704157h

Qian, Y., Gallagher, F. J., Feng, H., and Wu, M. (2012). A geochemi- cal study of toxic metal transloca- tion in an urban brownfield wetland. Environ. Pollut. 166, 23–30. doi: 10.1016/j.envpol.2012.02.027

Reddy, A. M., Kumar, S. G., Jyoth- snakumari, G., Thimmanaik, S., and Sudhakar, C. (2005). Lead induced changes in antioxidant metabolism of horsegram (Macroty- loma uniflorum (Lam.) Verdc.) and bengalgram (Cicer arietinum L.). Chemosphere 60, 97–104. doi: 10.1016/j.chemosphere.2004.11.092

Samardakiewicz, S., and Wozny, A. (2005). Cell division in Lemna minor roots treated with lead. Aquat. Bot. 83, 289–295. doi: 10.1016/j.aquabot.2005.06.007

Samardakiewicz, S., Krzesłowska, M.,Bilski, H., Bartosiewicz, R., and Wo´zny, A. (2012). Is callose a barrier for lead ions entering Lemna minor L. root cells? Protoplasma 249, 347–351. doi: 10.1007/s00709-011-0285-2

Samardakiewicz, S., Strawinski, P., and Wozny, A. (1996). The influence of lead on callose formation in roots of Lemna minor L. Biol. Plant. 38, 463–467. doi: 10.1007/BF02896682

Samuel Collin , Amritha Baskar , Deepthi Mariam Geevarghese , Mohamed Niyaz Vellala Syed Ali , Praveena Bahubali , Rajan Choudhary, Vladislav Lvov ,Gabriel Ibrahin Tovar , Fedor Senatov , Sivasankar Koppala , Sasikumar Swamiappana (2022). Bioaccumulation of lead (Pb) and its effects in plants: A review

Seregin IV, Ivanov VB. (2001). Physiological aspects of cadmium and lead toxic effects on higher plants. Russ J Plant Physiol. 48(4):523–544

Shahid, M., Khalid, S., Abbas, G., Shahid, N., Nadeem, M., Sabir, M., Dumat, C. (2015). Heavy metal stress and crop productivity. Crop Production and Global Environmental Issues. Springer, Cham, pp. 543–552. https://doi.org/10.1007/978-3-319-23162-4.

Sharma P, Dubey RS. (2005). Lead toxicity in plants. Braz J Plant Physiol. 17(1):35–52.

Sharma, N. C., Gardea-Torresdey, J. L., Parsons, J., and Sahi, S. V. (2004). Chemical speciation and cel- lular deposition of lead in Sesbania drummondii. Environ. Toxicol. Chem. 23, 2068–2073. doi: 10.1897/03-540

Sharma, S. S., and Dietz, K. J. (2009). The relationship between metal tox- icity and cellular redox imbalance. Trends Plant Sci. 14, 43–50. doi: 10.1016/j.tplants.2008.10.007

Singh R, Tripathi RD, Dwivedi S. (2010). Lead bioaccumulation potential of an aquatic macrophyte Najas indica are related to antioxidant system. Bioresour Technol.101(9):3025–3032.

Singh, S., Eapen, S., and D’souza, S. F. (2006). Cadmium accumulation and its influence on lipid peroxi- dation and antioxidative system in an aquatic plant, Bacopa monnieri L. Chemosphere 62, 233–246. doi: 10.1016/j.chemosphere.2005.05.017

Stefanov K, Seizova K, Popova I. (1995) Effects of lead ions on the phospholipid composition in leaves of Zea mays and Phaseolus vulgaris. Journal of Plant Physiology. 147(2):243–246

Strubin ́ska,J.,andHanaka,A.(2011). Adventitious root system reduces lead uptake and oxidative stress in sun- flower seedlings. Biol. Plant. 55, 771–774.

Sulaiman, F.R., Hamzah, H.A. (2018). Heavy metals accumulation in suburban roadside plants of a tropical area (Jengka, Malaysia). Ecol. Process. 7 (1), 1–11. https://doi.org/10.1186/s13717-018-0139-3.

Sunkar, R., Kaplan, B., Bouche, N., Arazi,T.,Dolev,D.,Talke,I.N. (2000). Expression of a trun- cated tobacco NtCBP4 channel in transgenic plants and disruption of the homologous Arabidopsis CNGC1 gene confer Pb2+ tolerance. Plant J. 24, 533–542. doi: 10.1046/j.1365- 313x.2000.00901.x

Talke, I. N., Hanikenne, M., and Kramer, U. (2006). Zinc-dependent global transcriptional control, tran- scriptional deregulation, and higher gene copy number for genes in metal homeostasis of the hyper- accumulator Arabidopsis halleri. Plant Physiol. 142, 148–167. doi: 10.1104/pp.105.076232

Usman, K., Abu-Dieyeh, M.H., Zouari, N., Al-Ghouti, M.A. (2018). Lead (Pb) bioaccumulation and antioxidative responses in Tetraena qataranse. Sci. Rep. 10 (1), 1–10. https://doi.org/10.1038/s41598-020-73621-z.

Vodnik D, Jentschke G, Fritz E. (1999). Root–applied cytokinin reduces lead uptake and affects its distribution in Norway spruce seedlings. Physiology of Plant. 106:75.

Xiang, M. (2021). Heavy metal contamination risk assessment and correlation analysis of heavy metal contents in soil and crops. Environ. Pollut. 278 (11), 6911. https://doi.org/10.1016/j.envpol.2021.116911.