Heavy Metals and Aluminum Toxicity Effect and its Adaptation Mechanism of Plants: A Review

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Review Article

Received: 09-March-2022, Manuscript No. JBS- 56730; **Editor assigned:** 11- March -2022, PreQC No. JES- 56730 (PQ); **Reviewed:** 23-March -2022, QC No. JES-56730; **Revised:** 30- March -2022, Manuscript No. JES-56730 (R); **Published:** 06-April-2022, DOI:10.4172/2320-0189.11.3.002

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Keywords: Exclusion; Plant; Toxicity; Uptake; Plant symplasm

ABSTRACT

Heavy metals and Al toxicity issues in plants and soils are a significant problem throughout the world. The most common heavy metal contaminants are Cadmium, Chromium, lead; Arsenic and Mercury do not have any beneficial effect on organisms, plant and environment. Heavy metals affect the plant both directly and indirectly. Adaptation mechanism of heavy metals and Al toxicity to plants are exclusion from the root apex and mechanisms that confer the ability to tolerate Al in the plant symplasm. Apoplast mechanisms are release of phenol compounds, mucilage formation, and genetic mechanisms of tolerance. Heavy metals and Al^{3+} are extremely problem on crop production. Therefore, intensive research will conducted in order to ascertain the mechanisms inherent to the heavy metals and Al toxicity and tolerance through selection and breeding process strategies to develop heavy metal and Al tolerant plants.

INTRODUCTION

Heavy metals are conventionally defined as elements with metallic properties asnd an atomic number greater 20. The most common heavy metal contaminants are Cd, Cr, Hg, As and Pb do not have any beneficial effect on organisms, plant and pollute air and water [1,2]. It is an excess of required concentrated as a result of human caused activities, enter in plant, animal and human tissues *via* inhalation, diet and manual handling, and can bind to, and interfere with the functioning of vital cellular components [3].

Heavy metals do not undergo decomposition. It is cannot be destroyed biologically; they can only be transformed from one oxidation state to another. They are adversely affect the plant both directly and indirectly and some of the direct toxic effects caused by high metal concentration include inhibition of cytoplasm enzymes and damage to cell structures due to oxidative stress. Indirect toxic effect is the replacement of essential nutrients at cation exchange sites of plants [4]. Remediation of soil contaminated with heavy metals is more difficult than the remediation of other contaminations [2,5]. Aluminum toxicity is the most widespread form of metal toxicity to plants and the major stresses to plants in acid soils.

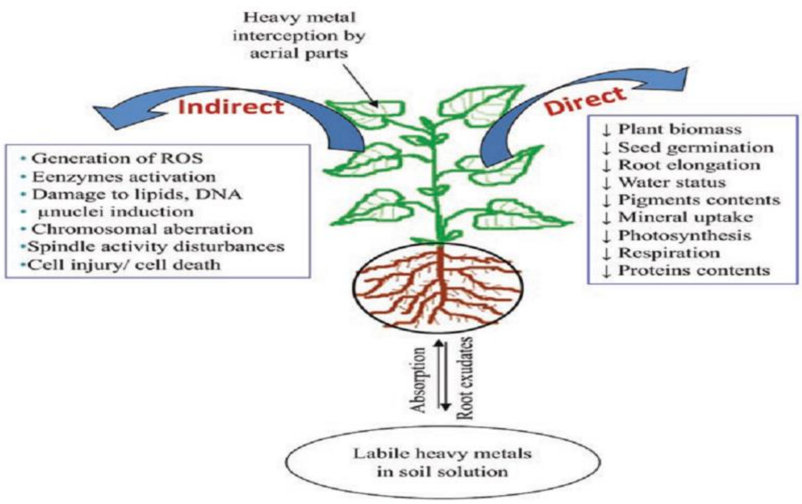
Most of the Al in soils is incorporated into alumino silicates and other precipitated forms, which are harmless to plants. Under acid soil conditions, these minerals solubilize to a limited extent, and the toxic ion Al^{3+} is released into the soil solution [6]. This form of Al is capable of inhibiting root growth and damaging cells at the root apex, which is the most sensitive part of the root to Al^{3+} [7]. Al toxicity occurs only at soil pH values below 5.5 and most severe in soils with low base saturation, poor in Ca and Mg. It is the most important factor, being a major constraint for crop production on 67% of the total acid soil area [8]. The objective of this paper is to review of heavy metals and aluminum toxicity effect, and its adaptation mechanism of plants.

LITERATURE REVIEW

Heavy metals and aluminium toxicity effect and its adaptation mechanism of plants

Effects of heavy metal on plants: Plant inside, heavy metals are capable of inducing a range of morphological, physiological, and biochemical disorders, which in turn cause a decrease in crop productivity. However, all these heavy metal-induced toxic effects are the function of exposure duration, stage of plant development in Figure 1 [9].

Figure 1. Heavy metals uptake by plant roots and possible direct and indirect toxic effects on crop production.



Cadmium (Cd): It is a highly toxic metal pollutant of soils, inhibits root and shoot growth and yield production, affects nutrient uptake and homeostasis, and is frequently accumulated by agriculturally important crops and then enters the food chain with a significant potential to impair animal and human health [10,11].

Plants grown in soil containing high levels of cadmium show visible symptoms of injury reflected in terms of chlorosis, growth inhibition, browning of root tips and finally death. The reduction of biomass by Cd toxicity could be the direct consequence of the inhibition of chlorophyll synthesis and photosynthesis [12]. Excessive amount of Cd may cause decreased uptake of nutrient elements, inhibition of various enzyme activities, and induction of oxidative stress including alterations in enzymes of the antioxidant defence system [13,14].

Chromium (Cr): It is found in all phases of the environment including air, water, and soil. It is also, highly toxic to plants and are injurious to their growth and development, animals [15]. Its' induced oxidative stress involves induction of lipid per oxidation in plants that causes severe damage to cell membranes, initiates the degradation of photosynthetic pigments causing decline in growth. High Cr concentration can disturb the chloroplast ultra-structure there by disturbing the photosynthetic process. Since seed germination is the first physiological process affected by Cr, the ability of a seed to germinate in a medium containing Cr would be indicative of its level of tolerance to this metal [16].

Mercury (Hg): Poisoning has become a problem of current interest because of environmental on a global scale. Natural emissions of mercury form two-thirds of the input; manmade releases form about one-third. Significant amounts of mercury may be added to agricultural land with sludge, fertilizers, lime, fungicides, and manures [17,18].

The dynamics between the amount of Hg that exist in the soil and its uptake by plants is not linear and depends on several variables. The large input of Hg into the arable lands has resulted in the widespread occurrence of Hg contamination in the entire food chain. It is a unique metal due to its existence in different forms: Hgs, Hg^{2+}, Hg^{o} and methyl-Hg. However, in agricultural soil, ionic form (Hg^{2+}) is predominant. Hg released to the soil mainly remains in solid phase through adsorption onto sulfides, clay particles and organic matters. High level of Hg^{2+} is strongly phytotoxic to plant cells [18].

Lead (Pb): It is a potentially toxic heavy metal with no known biological function, has attracted more and more considerable attention for its widespread distribution and potential risk to the environment. Pb contamination in soils not only aroused the changes of soil microorganism and its activities and resulted in soil fertility deterioration, but also directly affected the change of physiological indices and, furthermore, resulted in yield decline [19].

Plants on land tend to absorb lead from the soil and retain most of this in their roots. There is some evidence that plant foliage may also take up lead (and it is possible that this lead is moved to other parts of the plant). The uptake of lead by the roots of the plant may be reduced with the application of calcium and phosphorus to the soil [20].

Arsenic (As): It is an analog of phosphate (P) and competes forth-same uptake carriers in the root plasma lemma of plants [20]. In tomato arsenic reduces fruit yield, decreases the leaf fresh weight [21]. Whereas, in canola arsenic causes stunted growth, chlorosis and wilting. Further, arsenic in rice reduces seed germination, decrease in seedling height, and reduces leaf area and dry matter production [22].

Heavy metal adaptation mechanisms of plants

Exclusion from the plant: The mechanism of preventing or lessening the toxicity effects of metals is preventing excess metals from entering the plant. There are thought to be two main ways in which a plant could do this, either by precipitating or by complexing metals in the root environment. Plants could precipitate metals by increasing the pH of the rhizosphere or by excreting anions such as phosphate [23].

Plant roots secrete exudates into the soil matrix. The major roles of root exudates are to chelate metals and to prevent their uptake inside the cells [24]. For example, Ni-chelating histidine and citrate are present in root exudates and these reduce the uptake of Ni from soil. The binding of metal ions such as Cu and Zn in the apoplast also helps to control the metal content of root cells. Cation binding sites are also present on the root cell wall, and this allows metal exchange thus influencing the availability of ions for uptake and diffusion into the apoplast [25].

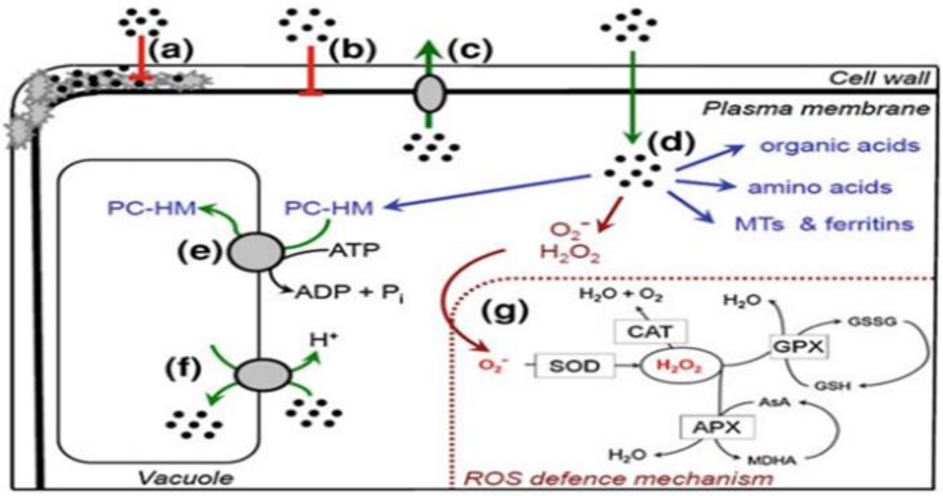
Active efflux pumping at the plasma membrane: It is an important role in plant response to heavy metals by preventing or reducing the uptake of metals into the cell or by active efflux pumping outside the cell. Active efflux systems are more common and used to control heavy metals accumulation inside the cell [20].

Heavy metal chelation in the cytosol: Inside the cell, heavy metal ions that are not immediately required metabolically may reach toxic concentrations, and plant cells have evolved various mechanisms to store excess metals to prevent their participation in unwanted toxic reactions. If the toxic metal concentration exceeds a certain threshold inside the cells, an active metabolic process contributes to the production of chelating compounds. Specific peptides such as PCs and MTs are used to chelate metals in the cytosol and to sequester them in specific sub-cellular compartments. A large number of small molecules are also involved in metal chelation inside the cells, including organic acids, amino acids, and phosphate derivatives [26].

Genetic mechanisms of tolerance: In contrast to a metal-sensitive plant species or non-metallophytes, a metal-tolerant plant species (metallophytes) maintains good performance, because it can cope with higher plant-internal metal levels due to genetic changes or adaptation [27]. Plants have genetically controlled mechanisms and adaptive mechanisms of overcoming high concentrations of various elements in their nutrient medium. The environment with all of its factors influence plant organisms, causing high variability in plants of the same inherited background. Knowing the genetic background of tolerance is greatly important for creating genotypes tolerant to acid medium, and to the presence of high concentrations of Al [28].

Complexing by organic acids: Act as metabolic intermediates in the formation of ATP from carbohydrates in N metabolism and in ionic balance. Hence, metabolic abnormalities in any of these processes would be reflected by changes in the concentrations of the intermediate organic acids. An increase in organic acids with increasing supply of metals could imply a detoxification mechanism (Figure 2) [29].

Figure 2. The response plants adaptation mechanisms to heavy metals. ***Note: a**- Metal ion binding to the cell wall and root exudates; **b**-reduction of metal influx across the plasma membrane; **c**- membrane efflux pumping into the apoplast; **d**- metal chelation in the cytosol by ligands such as phyto chelating, metallothioneins, organic acids, and amino acids; **e**- transport of metal–ligands complexes through the tonoplast and accumulation in the vacuole; **f**- sequestration in the vacuole by tonoplast transporters; **g**- induction of ROS and oxidative stress defense mechanisms.



Aluminum toxicity

Al toxicity is interferes with in cell division in root tips and lateral increases cell wall rigidity by cross linking pectin; reduces DNA replication. It fixes phosphorous in less available forms in soils and on root surfaces; decreases root respiration; and deposition of cell wall polysaccharides and the uptake; transport and use of several essential nutrients are Ca, Mg, K, P and Fe [30].

Effects on leaves: The symptoms of Al toxicity are not easily identifiable. In plants, the foliar symptoms resemble those of phosphorous deficiency (overall stunting, small, dark green leaves and late maturity, purpling of stems, leaves, and leaf veins, yellowing and death of leaf tips). In some cases, Al toxicity appears as an induced calcium deficiency (curling or rolling of young leaves and collapse of growing points or petioles). Excess Al even induces iron (Fe) deficiency symptoms in rice, sorghum and wheat [30,31].

Effects on root: It does not affect the seed germination, but helps in new root development and seedling establishment. Root growth inhibition detected 2–4 days after the initiation of seed germination [30]. It could be observed in the root system particularly in root-tips and in lateral roots; lateral roots become thickened and turn brown [32]. The root system as a whole is coralloid in appearance with many stubby lateral roots, but lacks fine branching. The toxicity appears to be determined by the availability of certain monomeric species of Al to the plant roots. Losses of phytoactive, monomeric Al can occur by polymerization of Al as the pH and the Al concentrations rise to make complex formation or chelating with phosphate and organic acids [33].

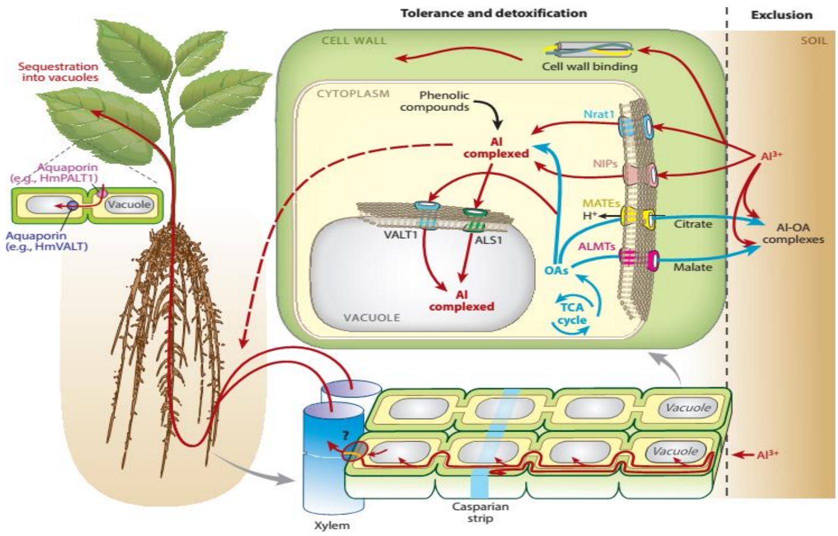
Effects on plant physiology and morphology: Al interfere with cell division in plant roots, decrease root respiration; interfere with certain enzymes governing the deposition of polysaccharides in cell walls; increase cell wall rigidity and interfere with the uptake, transport and with some essential nutrients (Ca, Mg, K, P) and water supply to plants [34]. Al becomes soluble or exchangeable and toxic depending on the soil pH and many other factors including the predominant clay minerals, organic matter levels, concentrations of other cations, anions and total salts, and the plant species [35].

Aluminum toxicity adaptation mechanisms of plants

Exclusion mechanisms: Aluminum tolerance divided into mechanisms that facilitate Al exclusion from the root apex (external tolerance mechanisms) and mechanisms that confer the ability to tolerate Al in the plant symplasm (internal tolerance mechanisms). The most important internal tolerance mechanisms are Al-binding proteins; chelation in the cytosol; compartmentation in the vacuole; evolution of Al tolerant enzymes, and elevated enzyme activity [36]. In symplastic mechanisms, Al enters the cytoplasm and detoxified once inside the cell by compilation with organic compounds. Several compounds can form stable complexes with Al inside the cell, including organic acids such as citrate, oxalate, and malate. Free Al^{3+} or Al complexes with chelating agents are transported to cell vacuoles, where they are stored without causing toxicity in Figure 3 [37].

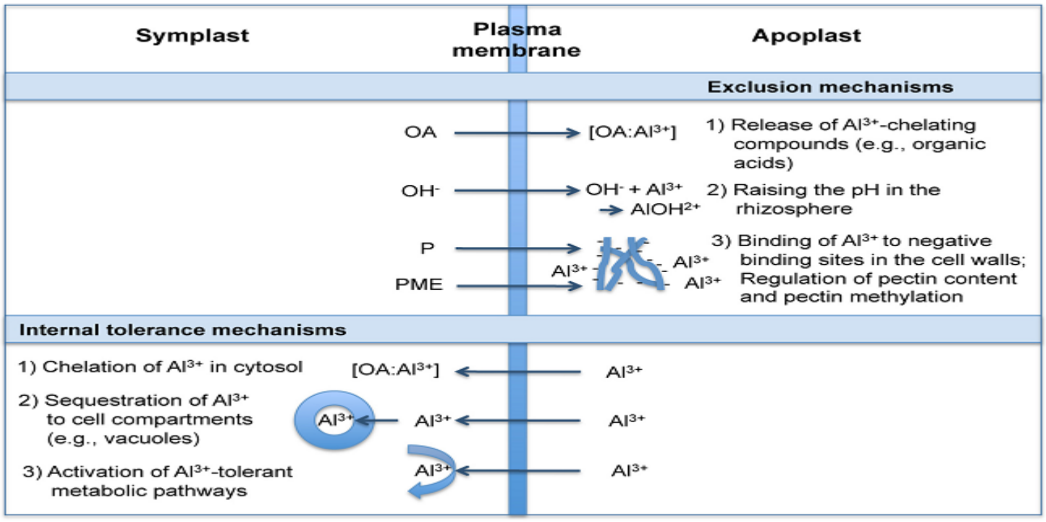
An Apoplastic mechanism is release of phenolic compounds, mucilage formation [38], "pH barrier" resulting from increased pH in the rhizosphere and organic acid exudation. Roots of several plant species secrete organic acids in response to Al, which are mediated by membrane transporters, resulting in the formation of non-toxic complexes with the metal. Thus, this mechanism prevents Al from crossing the plasma membrane into the symplast [39,40].

Figure 3. Summarizes Al exclusion and Al tolerance mechanisms in plants.



Internal detoxification mechanism: In some plants has the opposite response to Al, and will take Al up in large quantities. Since an effective exclusionary resistance mechanism would prevent Al accumulation by a plant, accumulator resistance must be conferred by an internal resistance mechanism [41]. The main mechanism of Al resistance in Al accumulators is compartmentalization, transport of Al toxicity in plants detoxification of Al after its entry the plant [38]. The other detoxification mechanism involves sequestration of Al in vacuole or other organelles, so as to prevent its toxic effect in the cytoplasm (Figure 4) [39].

Figure 4. Mechanism of plant roots to deal with Al^{3+}.



DISCUSSION AND CONCLUSION

Heavy metals and Al toxicity issues in plants and soils are a significant problem throughout the world. The most common heavy metal contaminants are Cd, Cr, Pb, As and Hg do not have any beneficial effect on organisms, plant and environment. Heavy metals cannot be broken down, when concentrations within the plant exceed optimal levels; they adversely affect the plant both directly and indirectly.

Adaptation mechanism of heavy metals and Al toxicity to plants are exclusion from the root apex and mechanisms that confer the ability to tolerate Al in the plant symplasm. Apoplast mechanisms are release of phenol compounds, mucilage formation, and genetic mechanisms of tolerance. In addition, complexing of organic acids act as metabolic intermediates in the formation of ATP from carbohydrates in nitrogen metabolism and in ionic balance.

Heavy metals and Al^{3+} are extremely problem on crop production. Therefore, intensive research will be conducted in order to ascertain the mechanisms inherent to the heavy metals and Al toxicity and tolerance through selection and breeding process strategies to develop heavy metal and Al tolerant plants.

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