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REVIEW ARTICLE

Plant toxicity of four HMs: Arsenate, cadmium, chromium and lead: A mini review

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Abstract

The presence of heavy metals (HMs) in agricultural soils plays a crucial role in plant life, as these elements are necessary for plant growth and development. However, they can also have detrimental effects on plants and the environment. In recent years, research on HMs has gained significant attention and is expected to become a dominant field due to their harmful impact on humans, animals and plants. The phytotoxicity of HMs is influenced by several factors, including the specific metal type, exposure route, dosage, plant age, nutritional status and environmental conditions. Among the most toxic metals to plants, arsenic, cadmium, chromium and lead are considered priority contaminants due to their severe impact on plant health. The current review discusses important HMs, their toxicity mechanisms to the plants and their interactions with special emphasis on the arsenate, cadmium, chromium and lead.

Keywords: analysis; growth; HMs; plants; toxicity

Introduction

The existence of HMs and their toxicity presents a considerable threat to natural ecosystems due to their high toxicity, persistence and tendency to accumulate in living organisms (1,2). HMs can be defined as metallic elements characterized by a density higher than that of water (3, 4). Due to the link between high density and toxicity of HMs, this category also includes metalloids such as arsenic, which can cause harm even at very low levels of exposure (5, 6). The accumulation of HMs in agricultural soils has emerged as a critical global challenge, driven by diverse sources like natural geological formations, landfills, synthetic fertilizers, pesticides, farming practices, industrial emissions and urban contaminants (7).

In biological systems, HMs are categorized as either essential or nonessential. Essential metals like iron, copper, manganese, chromium and cobalt play crucial roles in the physiological functions of living organisms and are required in trace amounts. On the other hand, nonessential metals such as lead, cadmium and mercury serve no known biological function, are highly toxic and are classified as biologically nonessential (8). Nonessential HMs can interfere with several biochemical processes in plants, including nutrient balance regulation, gas exchange, enzyme and antioxidant production, protein metabolism and photosynthesis (9-11).

The phytotoxicity effects of HMs typically has several mechanisms on plant health and life, mostly the generation of Reactive Oxygen Species (ROS), enzyme inactivation and the suppression of antioxidant defences (12, 13). However, certain HMs exhibit unique toxicity patterns by selectively binding to specific macromolecules. Understanding the various toxic mechanisms of HMs enhances the knowledge of their harmful impact on plant physiology, ultimately aiding in the effective management of reducing their impacts (3). This review aims to explore the existing literature on the toxicity of four HMs arsenate, cadmium, chromium and lead providing deeper insights into their detrimental effects plant life.

Arsenic (As)

As is one of the most important and toxic HMs in the world; and annually more than 70 million people are exposed to arsenic poisoning according to the WHO (14, 15). Different chemical forms of arsenic are existing and the species of arsenate (V) ($H_2AsO_4^-$: at pH 2-6); as well as arsenite (III) ($H_2AsO_3^-$: at pH 9-12), are the most dominant As species found in nature (16, 17). Several processes are responsible of arsenic distribution into the environment including weathering; mineral ores; fire; volcanic eruption and industrial activities such as energy production and fossil fuel burning; pesticides manufacturing and many other activities (18, 19, 10).

As is very toxic for human, animals and plants and could one of the causes of cardiovascular failure, neurological and gastrointestinal system abnormalities, liver and kidney dysfunctions (20-23).

As toxicity to the plants health and ecosystems poses significant risk due to its ability to disrupt cellular functions even at trace concentrations by interfering with critical metabolic processes, such as photosynthesis and respiration and by generating ROS that cause oxidative damage to lipids, proteins and DNA (24), as well as, disrupting nutrient homeostasis by competing with essential elements like phosphorus and sulfur, leading to deficiencies (25). Plants uptake As through phosphate transporters, as its chemical similarity to phosphate allows it to hijack these uptake mechanisms as known phosphate mimicry (26). Conversely, As is absorbed via aquaporins or silicon transporters, particularly in rice and other monocots (27).

Cadmium (Cd)

Cadmium is commonly found in natural and the major sources of cadmium emissions include industries such as nickel-cadmium battery production, electroplating, mining and metallurgy (28, 29). Additionally, nuclear power plants discharge waste containing high levels of Cd^{2+} ions. Other potential sources of Cd exposure include welding, the use of pesticides and fertilizers, cigarette smoking and smelter operations (30, 31).

Regulatory bodies have set limits on heavy metal exposure. Cd primarily affects the respiratory system, bones and kidneys, leading to serious health issues such as renal failure, osteoporosis, osteomalacia, lung diseases, bone lesions, gastrointestinal disorders, bronchitis and cancer (22). Acute Cd poisoning symptoms often include loss of smell, weight loss, high blood pressure, pulmonary edema, headaches, nausea, vomiting and diarrhea. Long-term exposure can result in severe kidney damage and bone-related conditions disease (32). In plants, Cd disrupts mineral absorption, affects physiological and biochemical processes and inhibits overall growth (33, 8, 3).

Emerging studies suggest that Cd may not directly trigger ROS generation and accumulation in affected plants but instead function as pro-oxidants, impairing antioxidant activity (34); in way disrupted the balance between ROS production and scavenging mechanisms leads to oxidative burst (35, 36). Several mechanisms had been proposed for Cd inhibition for plant growth and development, such as reduced water absorption, diminished photosynthetic efficiency and visible symptoms like chlorosis, stunted growth and root tip browning: leading to cellular death (31). Another toxicity mechanism showed that the high level of soil Cd restricts nutrient accessibility for roots, as examined in cereal crops, Cd competes with essential micronutrients like iron and zinc during root uptake, exacerbating nutrient deficiencies and imbalances (37). High Cd levels also reduce nitrogen availability in soil, adversely impacting agricultural productivity (38).

Chromium (Cr)

Chromium is considered as one of the most hazardous HMs frequently found in industrial wastewater. In water, it primarily exists in two oxidation states: trivalent Cr (III) and hexavalent Cr (VI) (39, 29). Among these, Cr (VI) is considered the most toxic, commonly occurring as chromate or dichromate ions in oxygen-rich environments. Due to its mutagenic and carcinogenic properties, Cr (VI) is classified as a Group "A" human carcinogen (40). Furthermore, Cr (III) is relatively stable, less mobile and tends to form complexes with organic matter or precipitates in soils, limiting its bioavailability to plants. In contrast, Cr (VI) is highly soluble, reactive and readily absorbed by plant roots due to its structural similarity to essential nutrients like sulfate, allowing it to hijack sulfate transporters (41).

The exposing to Cr in human is through direct skin contact, inhalation, ingestion, or consumption of contaminated water. The primary source of Cr absorption is Cr (III), which is naturally present in various food items such as fruits, vegetables, meats, cereals, yeasts and other plant-based foods (42). Several industries, including dye and pigment production, photography, wood preservation, steel fabrication, canning, textile dyeing, leather tanning, electroplating and metal finishing, release Cr (VI) into water bodies via wastewater (43).

Additional health effects include allergic dermatitis, nausea, vomiting, severe diarrhoea, respiratory problems, immune system suppression and kidney and liver damage, potentially altering their function. In plants the Cr is one of the dangerous HMs with significant consequences on several physiological activities in plants, such as photosynthesis and many other biological functions (44, 45).

Once inside plants, Cr (VI) acts as a potent oxidant, generating ROS that damage cellular membranes, proteins and DNA, leading to symptoms such as stunted root growth, leaf chlorosis and impaired photosynthesis. Cr (III), while less toxic under normal conditions, can still disrupt metabolic processes at high concentrations by binding to cell wall components or interfering with enzyme function (46). However, Cr (VI) is far more hazardous due to its ability to translocate to aerial plant parts, accumulating in edible tissues and entering the food chain (47).

Lead (Pb)

Pb naturally occurs in three oxidation states which are Pb (0), Pb (II) and Pb (IV), with Pb (II) being the most common and highly prone to bioaccumulation through the food chain. It is often associated with other HMs such as zinc, copper and mercury (14). Pb contamination originates from multiple sources, including vehicle emissions, mining activities, coal and plastic combustion, battery manufacturing, gasoline additives, fertilizers, pesticides, paints, pigments, alloys and metal sheets (14). Pb, as a toxic heavy metal, detrimentally affects soil health by reducing fertility, diminishing nutrient availability and inhibiting microbial diversity (48, 49). Pb accumulation in soil alters critical soil properties such as pH and cation exchange capacity (50).

Exposure to Pb has numerous adverse health effects, including reduced fertility, cardiovascular diseases, impaired kidney function and neurodevelopmental disorders. Pb poisoning primarily affects the kidneys, nervous system and circulatory system, leading to conditions such as anemia, brain damage, anorexia, fatigue, appetite loss, delirium, insomnia, seizures, gastrointestinal distress and cognitive impairment in children (51). While Pb can be absorbed through the skin, the digestive and respiratory systems are the primary routes of absorption. Pb exposure is also linked to oxidative stress, inflammation, immune dysfunction and disorders affecting the respiratory, urinary and cardiovascular systems (52). Additionally, several studies revealed the toxic effect of Pb on plant health leading to serious consequences and could be translocated from different parts of the plants to the fruits (1).

In cereal crops, research demonstrates that Pb exposure impairs seed germination, weakens seedling vigor and restricts root and shoot growth. Additionally, it was examined that Pb disrupts photosynthetic efficiency and enzymatic functions in cereal plants (8). While in wheat plants, lead toxicity interferes with spindle formation and cell wall development, hindering cell expansion and division, ultimately reducing root volume at the cellular level (53). International guidelines stipulate that Pb concentrations in cereal grains must not exceed 0.20 mg kg^{-1} (54).

Daily consumption limits of selected HMs

Several standards had been proposed to determine the maximum daily consumption limits (µg/day) for As, Cd, Cr and Pb. Table 1. Illustrated each of the maximum limits for daily consumption and the accredited institutes. Regarding drinking water, the Environmental Protection Agency (EPA) set criteria for the above- mentioned HMs; the Arsenate should not exceed the level of 0.01 ppm (part per million); the Cd level 5 ppb (part per billion), while the Cr level should be less than 0.1 ppm and 15 ppb for Pb.

The plant toxicity of selected HMs

HMs such as As, Pb, Cd and Cr are among the most hazardous contaminants in the environment, exerting profound toxic effects on plant growth and development. These metals disrupt various physiological, biochemical and molecular processes, leading to reduced productivity and, in severe cases, plant mortality (50).

As toxicity in plants occurs primarily because of interference with phosphate metabolism, due to chemical similarity arsenate (As^{5+}) competes most effectively with phosphate, leading to disruptions in ATP synthesis and energy metabolism (55). Furthermore, As induces oxidative stress by generating ROS, which damage cellular components, including proteins, lipids and nucleic acids. This results in chlorosis, necrosis and a decline in photosynthetic efficiency. Moreover, As affects water balance, causing reductions in transpiration and stomatal conductance, further limiting plant growth (56).

Pb is harmful to plants in many ways. It disrupts the absorption of water and nutrients, reduces photosynthesis rates and interfere with the required enzyme functions (57). Pb accumulates in roots, where it changes the wall structure of the cell, prevents root growth and prevents the formation of lateral roots. In the shoot, Pb affects chlorophyll production, causing chlorosis and photosynthetic efficiency. Additionally, Pb affects the hormonal balance of the plant, negatively affects seed germination, cell division and overall growth and development (58).

Cd is amongst the most phytotoxic of the HMs, showing adverse effects on plant physiology in trace amounts. The element is shown to have strong inhibition on absorptive assimilation of crucial macro and microelements, including calcium (Ca), magnesium (Mg) and zinc (Zn) and Pb to nutrient imbalance and metabolic disorders (59). Moreover, Cd forms adverse effects on integrity of plant architecture, in the context of breaking up of cell walls and plasma membranes and on water uptake and root formation (60). At the molecular level, Cd induced excessive ROS production, consequently initiating lipid peroxidation cascades and genomic deterioration. Additionally, Cd interferes with the enzymatic processes related to nitrogen and carbon metabolism, ultimately causing reduced biomass production and compromised plant defence mechanisms (61).

The phytotoxicity of Cr exhibits significant variation contingent upon oxidation state, with hexavalent Cr^{6+} being more toxic than trivalent Cr^{3+}. The translocation of Cr^{6+} into plant cellular structures occurs predominantly via sulfate transporters, which triggers oxidative stress and hampers photosynthesis. It disrupts electron transport in chloroplasts and mitochondria, thereby disrupting ATP production and energy metabolism (62). Additionally, Cr negatively influences seed germination, root growth and enzymatic activities associated with nutrient intake. Additionally, chromium influences seed germination, root growth and enzyme activity in nutrient intake. The Cr-induced stress is normally manifested in stunted plant growth, leaf chlorosis and disruption of cellular organelles (47).

In general, the harmful effects of these HMs result in marked declines in plant growth, productivity and overall viability, particularly in polluted environments. When subjected to HMs stress, plants frequently activate a variety of defensive mechanisms, including antioxidant enzyme systems, metal-binding proteins (such as phytochelatins and metallothioneins) and compartmentalization strategies to mitigate toxicity. Nevertheless, prolonged exposure to high levels of these metals can overcome these defence mechanisms, leading to significant physiological and metabolic distortions, as illustrated in Table 2, the detailed toxic effect of selected HMs in plant physiology (63, 64).

Conclusion

There are several routes for HMs to enter the plant, most important is the soil route and the airborne way. As a consequent for the absorption, the HMs tend to accumulate at high levels in different parts of plant. The Bioaccumulation of these toxic HMs in plants tissues leads to multiple damages on cellular levels, either as acute or chronic impact. HMs are well- known for their physiological, biochemical and

Table 1. Maximum daily consumption limits of selected HMs (µg/day)*

Institute	Daily consumption limits (µg/day)			
	Arsenate	Cadmium	Chromium	Lead
American National Standards Institute	10	6	-	20
The Food and Agricultural Organization	150	55	120	250
Europe/WHO	150	70	150	250
American Herbal Products Association	10	4.1	10	10

***** Balali-Mood et al. (2021)

Table 2. The toxic effect of selected HMs (As; Ad; Cr and Pb) in plant physiology

Toxic Effect	Arsenic (As)	Cadmium (Cd)	Chromium (Cr)	Lead (Pb)
Photosynthesis	Reduces photosynthetic efficiency due to oxidative stress and membrane damage.	Reduces photosynthetic efficiency by disrupting enzymes and cellular structures.	Decreases photosynthesis by disrupting electron transport in chloroplasts.	Decreases photosynthetic efficiency by affecting chlorophyll synthesis.
Root growth	Inhibits root growth by affecting water and nutrient uptake.	Inhibits root elongation significantly and affects secondary root development.	Decreases root length due to direct toxicity to root cells.	Reduces root growth by affecting cell division and lateral root formation.
Nutrient uptake	Interferes with phosphate uptake and other essential nutrients.	Competes with essential nutrients such as calcium, magnesium and zinc.	Interferes with nutrient uptake by affecting root membranes.	Reduces the ability of roots to absorb essential nutrients like nitrogen and potassium.
Oxidative stress	Causes an increase in ROS production, leading to oxidative damage to lipids, proteins and DNA.	Accelerates ROS production, leading to lipid peroxidation and protein damage.	Causes ROS accumulation, leading to cellular damage and disruption.	Increases ROS production and oxidative stress.
Chlorosis (leaf yellowing)	Causes chlorosis due to chlorophyll degradation.	Causes leaf chlorosis through inhibition of chlorophyll biosynthesis.	Leads to chlorosis due to cellular damage in leaf tissues.	Causes chlorosis due to disruption of chlorophyll structures.
Effects on enzymes	Inhibits several enzymes involved in metabolic pathways.	Inhibits essential enzymes such as oxidases and enzymes involved in carbohydrate metabolism.	Inhibits various enzymes involved in plant metabolic processes.	Affects key enzymes such as catalase and peroxidase.
Overall growth effects	Reduces overall plant growth, including stem and leaf elongation.	Leads to a significant decrease in plant growth and dry weight.	Results in reduced overall plant growth, particularly during germination.	Causes stunted overall growth and reduces biomass accumulation.
Germination effects	Inhibits germination due to oxidative stress.	Reduces germination rates due to oxidative damage.	Inhibits germination due to toxicity to seed tissues.	Inhibits germination by affecting embryo tissues.

molecular impact, leading to reduced productivity and, in severe cases, plant mortality. Several studies revealed the HMs toxicity affecting seed germination, seedling growth and development, differentiation, DNA damage and protein degradation. Toxic metals lead to high ROS concentrations which in turn lead to oxidative damage.

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Authors' contributions

All authors contributed equally to the literature review, writing and editing of this manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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