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Impact of Cadmium and Lead Toxicity on the Growth and Metabolism of Pearl Millet (*Pennisetum typhoides* L.) Plants

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Abstract

Heavy metal contamination of agricultural soils has become one of the most persistent environmental challenges of our time, with cadmium (Cd) and lead (Pb) ranking among the most damaging metals for crop plants. Pearl millet (Pennisetum typhoides L.) is a staple cereal grown widely across semiarid regions of Africa and Asia, where soils are increasingly exposed to industrial effluents, mining runoff, and phosphate fertilizer residues carrying measurable metal loads. This article examines how cadmium and lead affect the growth, physiology, and metabolic functioning of pearl millet plants, drawing on experimental evidence accumulated over the past two decades. Both metals disrupt seed germination, suppress root and shoot elongation, impair chlorophyll synthesis, and interfere with enzyme activity at multiple metabolic checkpoints. Oxidative stress — driven by reactive oxygen species accumulation — emerges as a central mechanism through which these metals cause cellular damage. The plant's antioxidant defense systems respond, but often incompletely at higher metal concentrations. Understanding these effects in detail matters both for crop protection and for developing metal-tolerant varieties capable of sustaining yields in contaminated environments.

Keywords: *lead toxicity, heavy metal stress, plant metabolism, cadmium toxicity, pearl millet, oxidative stress*

I. Introduction

Pearl millet (Pennisetum typhoides L.) is widely recognized as a stress-tolerant cereal, capable of sustaining growth under conditions of heat, drought, and poor soil fertility. Under controlled laboratory conditions, however, its resilience shows clear limits when exposed to heavy metal contamination. Experimental studies have consistently demonstrated that even moderate concentrations of cadmium (Cd) and lead (Pb) in growth media are sufficient to impair normal physiological functioning in this crop.

Agricultural soils experience periodic contamination from cadmium and lead which happens at dangerous levels. Cd enters the environment through three main pathways which include phosphate fertilizers and sewage sludge applications and industrial atmospheric emissions. The Pb metal builds up in soil around roads and mining locations and smelting plants because emissions have contaminated these areas for many years. Plants do not need either metal for their biological processes. The two elements become poisonous because cadmium has a lower threshold than other metals while plants can take up cadmium through the same pathways which transport essential nutrients such as zinc and iron.

Pearl millet is a nutritionally significant cereal crop, valued for its content of calories, protein, and micronutrients. In the context of laboratory-based heavy metal research, it serves as a relevant model organism because of its agronomic importance and its capacity to reflect responses common to other cereal crops under abiotic stress conditions.

II. Cadmium and Lead in Agricultural Soils

2.1 Sources and Soil Accumulation

Cadmium reaches agricultural land through several well-documented pathways. Phosphate rock — the raw material for most phosphate fertilizers — naturally contains Cd at concentrations ranging from a few milligrams to over 100 mg per kilogram, depending on the geological source. Long-term fertilizer use therefore deposits a steady stream of Cd into cultivated soils. Industrial activities compound this: zinc smelting, battery manufacturing, and coal combustion all release Cd into the atmosphere, from where it settles onto soil surfaces over wide areas.

Lead contamination follows somewhat different pathways. Leaded petrol, before its phase-out across most countries, deposited enormous quantities of Pb along roadsides and in urban soils. Mining and ore processing operations create highly localized but intensely contaminated zones. Paint containing lead pigments, once common in older buildings, contributes to soil contamination in both urban and peri-urban areas. Lead remains in soil because it tightly binds to organic matter and clay particles but plant roots can still absorb it especially in acidic soils which increase its solubility.

Both metals persist in soil for decades after the original pollution source is removed. This is part of what makes them so problematic for agriculture. Under experimental conditions, plants grown in artificially contaminated nutrient solutions or spiked growth substrates consistently reflect this persistence — even after metal exposure is withdrawn, recovery of normal growth parameters takes multiple observation periods, underlining the lasting metabolic impact of Cd and Pb.

2.2 Uptake Mechanisms in Plants

Plants take up cadmium through root cell membrane transporters which usually move zinc and iron and manganese through their system. The transporters show high competition with Cd because its ionic radius matches the ionic radius of zinc. Cd enters root cells where it moves into the xylem and travels upward until it reaches shoots and leaves which it uses to disrupt many biochemical processes. The upward transport efficiency shows major differences between different plant species and different plant varieties within the same species.

Plants show greater restrictions on lead uptake which scientists observe as a general trend. Most Pb that reaches root surfaces gets immobilized in the cell wall or trapped in root vacuoles rather than moving further into the plant. The containment system fails at high external concentrations because Pb then moves to shoot tissues. Young seedlings show greater Pb movement to their aerial parts because their cell walls remain underdeveloped compared to mature plants.

III. Effects on Germination and Early Seedling Development

Germination represents the initial point where heavy metal stress begins to affect pear millet seeds because scientists can measure its impact at even low metal concentrations. The seeds which researchers soaked in cadmium solutions above 50 µM concentration showed both reduced germination rates and slower radicle development when compared to the control group which received no treatment. Lead requires higher amounts than 200 µM to achieve the same level of germination inhibition as other substances but its effects remain valid whenever they occur.

Metal ions disrupt the function of hydrolytic enzymes which need to break down seed storage compounds for the germination process to start. The growth of the seedling depends on alpha-amylase because it transforms starch into sugars which provide energy for development. Cd attaches to sulfhydryl groups on enzyme proteins which causes their three-dimensional structure to change and leads to a decline in their catalytic performance. The seedling cannot obtain sufficient energy to force its radicle through the seed coat and into the soil when amylase activity decreases.

The data from Figure 1 shows that pearl millet germination rate increases with higher metal concentrations until it reaches a maximum level which does not increase further. The data from Figure 1 shows that pearl millet germination rate increases with higher metal concentrations until it reaches a maximum level which does not increase further. The data from Figure 1 shows that pearl millet germination rate increases with higher metal concentrations until it reaches a maximum level which does not increase further. The data from Figure 1 shows that pearl millet germination rate increases with higher metal concentrations until it reaches a maximum level which does not increase further.

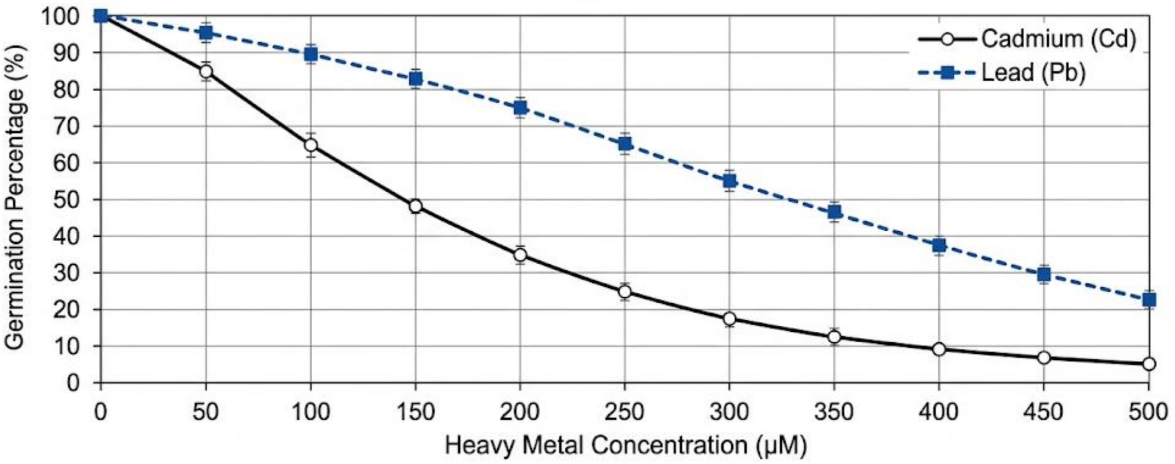

Figure 1: Dose-Response Relationship Between Cadmium and Lead Concentrations and Germination Percentage in Pearl Millet Seeds

Germination percentage decreases as heavy metal concentration increases from 0 to 500 µM through two curves which show germination results for cadmium and lead treatments applied to pearl millet seeds in controlled experiments. The cadmium curve declines more steeply, reaching below 50% germination at approximately 150 µM, while the lead curve shows a more gradual decline reaching equivalent inhibition near 350 µM. The main finding demonstrates that cadmium causes greater harm to plants than lead does because cadmium becomes more accessible to plants at the germination stage through its superior ability to cross biological membranes.

Root elongation in seedlings serves as the primary visible sign that indicates metal stress to researchers. Roots which experience Cd or Pb exposure develop a specific morphological pattern which produces short thick roots that exhibit brownish coloration, and this pattern becomes easily identifiable by experienced researchers. The growth inhibition occurs because toxins directly affect root meristem cells which need to divide for elongation, while toxins also produce indirect effects because they prevent the roots from absorbing water and nutrients. The apical meristem of Cd-stressed pearl millet roots shows a reduced mitotic index within 24 hours of exposure because cell division becomes restricted and cell expansion remains intact.

Shoot emergence and coleoptile elongation are also affected, though typically less dramatically than root growth at equivalent metal concentration. A plant will survive low metal concentrations if its leaves can grow above ground while its roots become damaged, but complete root failure will cause the plant to die quickly despite its healthy appearance above ground.

IV. Impacts on Vegetative Growth and Biomass Accumulation

The growth of pearl millet plants after their germination stage becomes inhibited when they face Cd and Pb stress which becomes more severe with higher stress levels and longer exposure times. Metal-stressed plants exhibit decreased plant height and tiller number and leaf area and total dry biomass when compared to clean-soil controls. The decline progresses through two stages which start with minimal growth effects at low concentrations and then lead to an abrupt decrease when concentrations reach higher levels. Cadmium-treated pearl millet plants typically show chlorosis — yellowing of leaves — as one of the early visible symptoms. The process occurs because cadmium disrupts the body functions that process iron which serves as a vital component for producing chlorophyll. The younger leaves present with yellowing symptoms because they need to take more iron from their surroundings, unlike older leaves which have already developed their chlorophyll content. Lead toxicity more often produces a different visual pattern: stunted, dark-green plants with brittle leaves and thickened stems, which show Pb's main disturbance of their cell wall and water balance functions instead of any direct impact on their chlorophyll production. Metal stress that continues for an extended period causes major changes to root structure. Plants develop root systems which have less branching and reduced root hair formation while their root-to-shoot ratio decreases and their root-to-shoot ratio decreases. The extreme stress condition causes plants to reduce their development of essential nutrient-absorbing roots. Heavy metal stress causes a real metabolic paradox because the plant's metal-induced nutrient deficiency response mechanism becomes blocked through the same metal elements that create nutrient shortages.

V. Photosynthesis and Chlorophyll Content

Heavy metal stress impacts plants through its most severe economic effects at the process of photosynthesis. A plant that cannot photosynthesize efficiently cannot fill its grains, regardless of how well other aspects of its metabolism are functioning. The photosynthetic system gets attacked by cadmium and lead through different methods of their multiple pathways.

Chlorophyll content in pearl millet leaves declines measurably at Cd concentrations above 25 µM and Pb concentrations above 100 µM in hydroponic studies. The process consists of multiple interconnected pathways. Cadmium blocks the function of delta-aminolevulinic acid dehydratase which represents an early chlorophyll biosynthesis enzyme that functions as a production control system for new chlorophyll creation. Lead displaces magnesium from the chlorophyll molecule itself — magnesium sits at the center of the chlorophyll ring structure, and Pb substitution produces a non-functional pigment that cannot capture light energy effectively.

The gas exchange measurements which researchers conducted on stressed plants reveal a single consistent pattern. Stomatal conductance decreases, limiting CO_2 entry into leaves. The plants experience reduced transpiration rates. The Calvin cycle receives less internal CO_2 which results in decreased carboxylation efficiency by Rubisco. Some of this stomatal response is actually a defense mechanism rather than direct damage: closing stomata limits further metal uptake through the transpiration stream. The reduced photosynthetic capacity creates a cost for plants which leads to lower crop yields in grain-producing crops.

The research measured chlorophyll fluorescence to assess photosynthetic light reaction efficiency which revealed that cadmium stress affects photosystem II which operates as the initial component of light-dependent reactions. The Fv/Fm ratio which serves as a common measurement of PSII efficiency shows a major decline in Cd-stressed pearl millet because the photochemical system instead of stomatal closure functions was harmed.

VI. Enzyme Activity and Metabolic Disruption

Heavy metals cause widespread cellular toxicity because of their ability to function as powerful enzyme inhibitors. Enzymes are proteins but metabolic enzymes need specific metal cofactors or sulfhydryl groups which are vulnerable to metal binding from outside sources. Nitrate reductase activity which converts soil nitrate into amino acids and proteins experiences a significant decline when Cd-stressed pearl millet. The grain protein content is directly affected by the need of protein synthesis for ongoing reduced nitrogen supply. Lead causes nitrate reductase suppression which occurs at higher amounts of lead than other substances. The plants that experience this suppression process usually develop higher ammonium levels which result in toxicity when present in excessive amounts thus creating additional stress on top of the direct metal impacts. Peroxidase and catalase are two enzymes that decompose hydrogen peroxide which acts as a reactive oxygen species produced during normal metabolic functions. The plant defense system against oxidative harm starts with an initial increase in enzyme activity but metal exposure leads to enzyme degradation which causes their operational capacity to decrease. Pearl millet research has repeatedly shown this rise and fall pattern which shows how plants protect themselves from stress while dealing with intense stress conditions. The plant cell process that controls phosphate supply through acid and alkaline phosphatase activities gets interrupted by both Cd and Pb. The inhibition of phosphate which functions as an ATP component results in decreased energy production for all cellular processes that need energy.

VII. Oxidative Stress and Antioxidant Defense

Scientists have studied heavy metal toxicity in plants because reactive oxygen species create damage to plant cells through their ability to create superoxide and hydrogen peroxide and hydroxyl radicals which harm membranes and proteins and DNA. Both Cd and Pb trigger ROS accumulation in pearl millet tissues, though through somewhat different mechanisms.

Cadmium generates ROS when it disrupts the normal binding of redox-active metals such as iron and copper which then enter the cell to start free radical reactions. Lead generates ROS through two different pathways which include its ability to stop antioxidant enzymes from working, which leads to a loss of cell power to eliminate oxygen radicals during their production. The net result in both cases is oxidative stress which occurs when harmful oxygen species production exceeds the plant's capacity to eliminate those dangerous substances.

As shown in Figure 2, pearl millet plants exhibit a coordinated but concentration-dependent antioxidant response to increasing Cd and Pb levels, with enzyme activities peaking at moderate stress levels before declining under severe exposure.

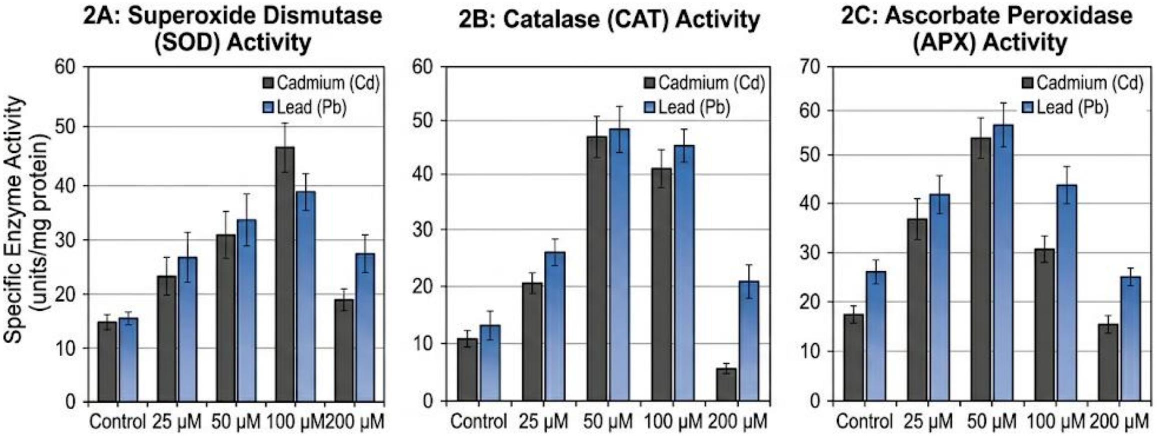

Figure 2: Antioxidant Enzyme Activity Profiles in Pearl Millet Leaves Under Increasing Cadmium and Lead Stress

The figure shows bar graphs which display the specific activities of three antioxidant enzymes. The three antioxidant enzymes tested in the study include superoxide dismutase (SOD) and catalase (CAT) and ascorbate peroxidase (APX). The study tested five treatment levels which included control and 25 µM and 50 µM and 100 µM and 200 µM treatments for both cadmium and lead. The y-axis shows enzyme activity which is measured as units per milligram of protein. The three enzymes reach their highest activity between 50 to 100 micromolar metal concentration. At 200 micromolar concentration all three enzymes showed peak activity. At equal concentrations cadmium treatments produced more intense suppression than lead. Your body detects moderate stress which triggers your antioxidant system to begin working. Your body reaches the high metal concentration point which disables your antioxidant system. Your body will experience severe oxidative damage because you reached this point. The researchers conducted a study to test how malondialdehyde content levels increased when metal concentration in pearl millet rose. The study measured electrolyte leakage from leaf cells to show how membrane integrity was lost. The two measurements display how membranes suffer from an attack because metal-induced ROS are damaging the lipid components of cell membranes. This damage causes cell membranes to become porous and lose their normal functions.

The plant establishes its antioxidant defense system through two types of components which the system uses to combat oxidative damage. The plant uses specific enzymes which include SOD, CAT, APX and glutathione reductase together with non-enzymatic elements which contain ascorbate, glutathione, tocopherols and proline. Proline accumulation in particular is a well-documented response to multiple abiotic stresses in pearl millet. The compound functions as two separate roles because it works as an osmotic adjustment molecule while it also serves as a direct ROS scavenger. The plant shows its active use of flexible stress response mechanisms through its buildup of stress response system.

VIII. Nutrient Uptake Interference

The presence of heavy metal stress creates two harmful effects for plant life because its toxins directly damage plants while it prevents plants from obtaining essential nutrients from soil. The indirect effects of metal toxicity lead to plant growth inhibition which matches the detrimental impact of direct metal damage especially when plants face nutrient deficits in field settings.

At root uptake sites cadmium establishes direct competition with zinc iron and calcium which are essential minerals. Plants growing in Cd-contaminated soils display symptoms of zinc or iron deficiency which include chlorosis and poor growth even though these nutrients exist in sufficient amounts within the soil. The deficiency exists as a functional condition because the nutrients are present in the plant but cadmium prevents their absorption. Lead creates problems for calcium uptake because calcium functions as a critical component for maintaining plant cell wall strength and membrane security and plant signaling activities.

Plants face magnesium uptake problems when exposed to heavy metal stress because magnesium serves as the main element in chlorophyll molecules which creates a direct connection between metal-related nutrient disruption and the already established photosynthesis problems. The metabolic disruptions caused by Cd and Pb create a total impact which exceeds the combined effects of each individual disruption.

IX. Conclusion

Cadmium and lead impose a genuine and multi-layered burden on pearl millet plants, from the very first hours of seed germination through every stage of vegetative and reproductive development. The evidence accumulated over two decades of research is clear on the fundamentals: both metals reduce growth, impair photosynthesis, disrupt enzyme function, and trigger oxidative stress that damages cellular structures when the plant's defenses are overwhelmed.

Cadmium is consistently more phytotoxic than lead at equivalent concentrations, primarily because it enters plant cells more readily. But lead should not be dismissed — at the high concentrations found near industrial sites and mining areas, Pb causes serious damage that rivals cadmium in practical agricultural impact.

The laboratory findings presented here establish clear dose-response relationships and physiological benchmarks for Cd and Pb toxicity in pearl millet. Future experimental work should focus on identifying biochemical markers that can be used as early indicators of metal stress under controlled conditions, evaluating antioxidant supplementation or chelator treatments in hydroponic systems, and screening germplasm collections under standardized laboratory protocols to identify metal-tolerant lines for further study.

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