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## Cadmium and Lead Toxicity in Maize (*Zea mays* L.): Effects on Growth and Root–Shoot Metal Accumulation

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### ABSTRACT

Cadmium (Cd) and lead (Pb) contamination can impair crop growth and promote metal accumulation in plant tissues. This pot experiment evaluated the effects of increasing Cd (150–900  $\mu$ M) and Pb (150–1500  $\mu$ M) concentrations on root length, shoot height, and root–shoot metal accumulation in maize (*Zea mays* L.). Plants were exposed to six concentrations of each metal plus an untreated control. Growth was assessed at 25, 40, and 60 days, and Cd and Pb concentrations in roots and shoots were quantified by atomic absorption spectrophotometry. At 60 days, Cd exposure reduced root length from 67.86 cm in the control to 11.87 cm at 900  $\mu$ M and shoot height from 57.89 to 28.32 cm. Under Pb exposure, root length decreased from 28.21 cm in the control to 13.97 cm at 1500  $\mu$ M, while shoot height decreased from 58.79 to 33.42 cm. Both metals accumulated predominantly in roots. The highest reported root Cd concentration was 116.32 mg/g dry weight at 750  $\mu$ M Cd, whereas the highest root Pb concentration was 85.97 mg/g dry weight at 1200  $\mu$ M Pb. At the highest treatment concentration, tissue metal concentrations declined relative to the preceding treatment, indicating that tissue accumulation was not strictly proportional to external concentration. Overall, the results demonstrate concentration-dependent phytotoxic responses and substantial root retention of Cd and Pb in maize.

### Introduction

Cadmium (Cd) and lead (Pb) are non-essential toxic elements that persist in agricultural environments and can enter crop production systems through industrial activities, mining and smelting, wastewater irrigation, sewage-derived amendments, and other anthropogenic inputs. Their effects on plants depend not only on total metal concentration but also on chemical form, soil properties, bioavailability, and duration of exposure. Because crops can transfer toxic elements from contaminated soils into edible tissues, understanding plant uptake and internal partitioning is important for both crop production and food safety [1–3].

Cadmium is relatively mobile in the soil–plant system and can enter roots through transport pathways associated with essential divalent cations. Once absorbed, Cd can disturb mineral nutrition, photosynthesis, membrane stability, and cellular redox homeostasis, resulting in impaired root and shoot development [1,4,10,11]. Root tissues are often the principal site of Cd retention because Cd can bind to cell-wall components and can be complexed and sequestered in intracellular compartments. These processes can restrict Cd movement to the shoot and contribute to differences in root and shoot metal concentrations [5,10,11]. Experimental studies in maize have likewise shown that Cd accumulation is commonly greater in roots than in shoots and that high Cd exposure can suppress growth [4,6].

Lead is generally less mobile than Cd in many soil systems, but bioavailable Pb can be absorbed by plant roots and is frequently retained in below-ground tissues. Root cell walls and other extracellular binding sites can contribute to Pb retention, while translocation to shoots is often comparatively limited [2,7,11]. Maize studies have demonstrated Pb accumulation in roots with relatively low root-to-shoot transfer, although the magnitude of the response

varies with exposure conditions and plant developmental stage [7,8].

Maize (*Zea mays* L.) is an agronomically important cereal cultivated across diverse environments and is therefore a useful model for evaluating crop responses to metal stress. Previous maize studies have documented distinct physiological responses to Cd and Pb, including stronger growth impairment under Cd at high exposure and substantial root-associated metal accumulation [8]. However, responses can vary with cultivar, exposure duration, growth medium, and metal concentration [3,4]. The present study therefore examined (i) the effects of increasing Cd and Pb concentrations on maize root length and shoot height, (ii) Cd and Pb accumulation in roots and shoots at different developmental stages, and (iii) the distribution of accumulated metals between below-ground and above-ground tissues.

### Materials and Methods

#### Plant material and experimental conditions

Seeds of maize (*Zea mays* L.) were sown in earthen pots containing homogeneously mixed soil and farmyard manure. Pots were maintained under natural photoperiodic conditions (approximately 12–13 h light) at  $28 \pm 4$  °C in the botanical garden/micro-model facility of Apex University, Jaipur. Plants were watered daily while avoiding drainage of the treatment solution. After germination, plants were exposed to CdSO<sub>4</sub>•8H<sub>2</sub>O or lead acetate [Pb(C<sub>2</sub>H<sub>3</sub>O<sub>2</sub>)<sub>2</sub>]. Cd treatments were 150, 300, 450, 600, 750, and 900  $\mu$ M; Pb treatments were 150, 300, 600, 900, 1200, and 1500  $\mu$ M. Untreated plants served as controls.

Growth observations and plant sampling were conducted at 25, 40, and 60 days after germination. Each treatment was reported to contain five replicate pots, with five plants per pot. The experimental unit and replication structure should correspond to the original experimental design and statistical analysis.

#### Metal analysis

Cd and Pb concentrations in roots and shoots were determined using a PerkinElmer Analyst 300 atomic absorption spectrophotometer equipped with an air-acetylene burner. Metal concentrations were expressed on a dry-weight basis as mg/g. Tissue washing, drying, digestion, calibration, blanks, detection limits, and analytical recovery should be reported according to the original laboratory protocol.

Statistical analysis

Analysis of variance (ANOVA) was performed using SPSS (version 10), and treatment means were separated using Duncan’s multiple range test (DMRT) at P < 0.05. Values are presented as mean ± standard error (SE; n = 5), consistent with the supplied dataset.

Results and Discussion

Effects on root and shoot growth

Cd exposure was associated with a pronounced reduction in maize root length and shoot height at the higher treatment concentrations. At 60 days, root length declined from 67.86 cm in the control to 11.87 cm at 900 µM Cd, while shoot height declined from 57.89 to 28.32 cm. The response was not strictly monotonic across all Cd treatments because the reported values at 300 and 450 µM were higher for root length than the control-associated trend would suggest. Pb exposure produced a comparatively gradual reduction in growth, with the largest changes occurring at the upper treatment concentrations. At 60 days, root length decreased from 28.21 cm in the control to 13.97 cm at 1500 µM Pb, while shoot height decreased from 58.79 to 33.42 cm.

Table 1. Root length and shoot height of maize at 60 days under Cd and Pb exposure.

| Treatment (µM) | Cd root (cm) | Cd shoot (cm) | Pb root (cm) | Pb shoot (cm) |
|----------------|--------------|---------------|--------------|---------------|
| 0              | 67.86 ± 1.8  | 57.89 ± 4.4   | 28.21 ± 1.7  | 58.79 ± 3.8   |
| 150            | 27.21 ± 1.4  | 58.12 ± 4.3   | 27.98 ± 2.8  | 57.32 ± 4.1   |
| 300            | 55.33 ± 3.8  | 25.65 ± 1.3   | 27.31 ± 3.1  | 56.83 ± 4.2   |
| 450            | 49.18 ± 4.2  | 23.86 ± 2.1   | —            | —             |
| 600            | 21.75 ± 2.3  | 40.60 ± 2.8   | 26.23 ± 3.2  | 53.75 ± 3.9   |
| 750            | 15.12 ± 1.5  | 33.32 ± 3.3   | —            | —             |
| 900            | 11.87 ± 1.2  | 28.32 ± 2.2   | 21.86 ± 2.9  | 45.31 ± 4.2   |
| 1200           | —            | —             | 19.52 ± 1.2  | 35.42 ± 2.2   |
| 1500           | —            | —             | 13.97 ± 2.2  | 33.42 ± 2.3   |

Values are mean ± SE (n = 5). Dashes indicate that the corresponding treatment was not applied.

Figure 1. Root length and shoot height of maize at 60 days under increasing Cd concentrations. Points represent means and error bars represent SE.

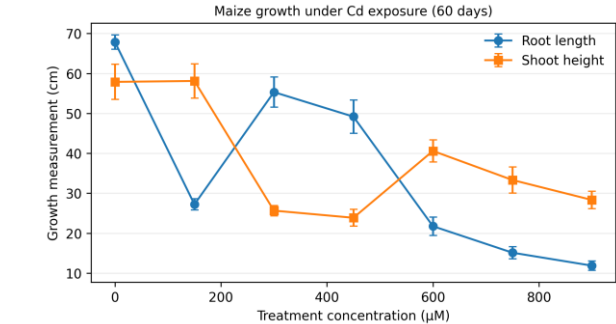
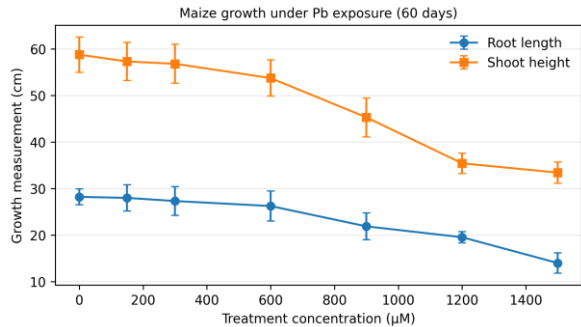


Figure 2. Root length and shoot height of maize at 60 days under increasing Pb concentrations. Points represent means and error bars represent SE.



3.2 Root–shoot metal accumulation

Both Cd and Pb accumulated to substantially higher concentrations

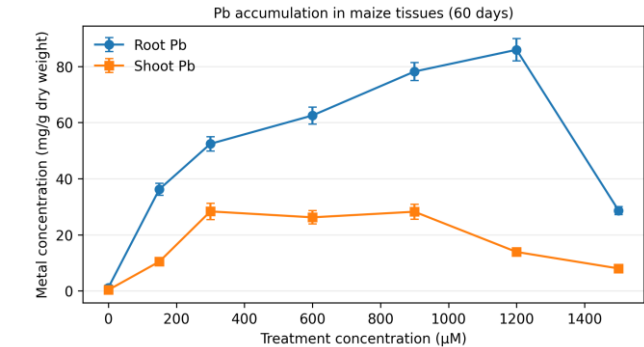
in roots than in shoots across the reported 60-day treatments. For Cd, root concentration increased from 0.51 mg/g in the control to 116.32 mg/g at 750 µM, followed by a decrease to 55.21 mg/g at 900 µM. Shoot Cd reached 16.43 mg/g at 600 µM and decreased to 11.64 mg/g at 900 µM. For Pb, root concentration increased from 1.12 mg/g in the control to 85.97 mg/g at 1200 µM and then decreased to 28.64 mg/g at 1500 µM. Shoot Pb was lower than root Pb and decreased from 13.87 mg/g at 1200 µM to 7.97 mg/g at 1500 µM. Thus, the highest external concentration did not correspond to the highest tissue concentration for either metal.

Table 2. Cd and Pb accumulation in maize roots and shoots at 60 days.

| Treatment (µM) | Cd shoot (mg/g) | Cd root (mg/g) | Pb shoot (mg/g) | Pb root (mg/g) |
|----------------|-----------------|----------------|-----------------|----------------|
| 0              | 0.28 ± 0.05     | 0.51 ± 0.02    | 0.31 ± 0.02     | 1.12 ± 0.91    |
| 150            | 7.85 ± 0.08     | 51.11 ± 2.50   | 10.42 ± 1.03    | 36.22 ± 2.12   |
| 300            | 12.74 ± 0.15    | 60.23 ± 3.70   | 28.32 ± 2.91    | 52.43 ± 2.54   |
| 450            | 13.86 ± 0.10    | 85.91 ± 4.45   | —               | —              |
| 600            | 16.43 ± 1.03    | 95.21 ± 7.31   | 26.21 ± 2.40    | 62.54 ± 3.03   |
| 750            | 13.21 ± 1.21    | 116.32 ± 8.32  | —               | —              |
| 900            | 11.64 ± 0.95    | 55.21 ± 3.76   | 28.21 ± 2.65    | 78.21 ± 3.21   |
| 1200           | —               | —              | 13.87 ± 1.43    | 85.97 ± 4.01   |
| 1500           | —               | —              | 7.97 ± 1.01     | 28.64 ± 1.43   |

Values are mean ± SE (n = 5), expressed on a dry-weight basis. Figure 3. Cd concentrations in maize roots and shoots at 60 days across Cd treatments. Points represent means and error bars represent SE.

Figure 4. Pb concentrations in maize roots and shoots at 60 days across Pb treatments. Points represent means and error bars represent SE.



The growth reductions observed under Cd exposure are consistent with the established phytotoxic effects of Cd on plant development. Cd can interfere with mineral nutrition, photosynthesis, membrane function, and cellular redox balance, and these effects can become more pronounced as exposure increases [3,4,10,11]. Studies in maize have similarly reported reduced growth under relatively high Cd exposure and increased Cd accumulation, particularly in roots [4,6]. The root-dominant Cd accumulation observed in the present experiment is also consistent with established models of Cd partitioning in plants. Cd can be retained in root apoplastic and simplistic compartments through cell-wall binding, complexation, and vacuolar sequestration, while endodermal and other barriers can restrict movement toward the xylem [5]. Consequently, root Cd concentrations can greatly exceed shoot concentrations under elevated exposure. Pb showed a similar root-retention pattern. Previous work in maize has demonstrated substantial Pb accumulation in roots and relatively limited translocation to shoots [7,8,11]. Root cell walls can provide important binding sites for Pb, thereby reducing its movement into aerial tissues [2,11]. The present data therefore support a predominantly below-ground distribution of Pb under the tested conditions. The decline in tissue concentration at the highest Cd and Pb treatments should be interpreted cautiously. Possible explanations include reduced root activity and biomass, altered metal availability,

or limitation of uptake and sequestration processes under severe stress. However, the present experiment did not directly measure soil metal availability, root physiological activity, transpiration, or metal flux; therefore, a specific mechanism cannot be established from the current dataset. An important feature of the present dataset is the non-monotonic response at some intermediate Cd concentrations. Such responses are not necessarily biologically impossible because hermetic or concentration-dependent responses have been reported in plant metal-stress experiments, but the magnitude of the present deviations warrants careful interpretation [4,6]. Accordingly, the reported values are presented as measured rather than being mathematically smoothed or adjusted.

### Conclusions

Under the conditions of this pot experiment, Cd and Pb exposure was associated with reduced maize root and shoot growth and preferential accumulation of both metals in roots. Cd produced pronounced growth inhibition at the upper treatment concentrations, whereas Pb showed its clearest growth effects at the higher exposure levels. For both metals, maximum reported tissue accumulation occurred below the highest applied concentration, indicating that tissue concentration was not linearly proportional to external treatment concentration. These findings demonstrate the importance of root retention in the response of maize to Cd and Pb exposure. Further work incorporating soil metal availability, biomass production, translocation factors, and field-scale validation would strengthen interpretation of the Phyto management potential of maize.

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