



## Hormetic Responses of Fodder Jowar (*Sorghum bicolor* L.) to Lead Contamination: Differential Effects on Germination, Root Growth, and Seedling Resilience

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### Abstract

Lead (Pb) contamination can impair early crop establishment, yet some cereals show partial tolerance at the seedling stage. This study evaluated the toxicological effects of increasing Pb concentrations (0–300 ppm) on the germination and seedling growth of Fodder Jowar (*Sorghum bicolor* L.). Results indicated a distinct tissue-specific response to metal stress. Root growth was the most sensitive parameter, declining drastically from 20.87 cm in controls to 3.40 cm at 300 ppm Pb(NO<sub>3</sub>)<sub>2</sub>, resulting in a sharp reduction of the root/shoot ratio (1.44 to 0.28). Conversely, shoot length displayed relative resilience. While seed germination followed a dose-dependent decline (100% to 78.5%) with a corresponding rise in phytotoxicity (up to 21.47%), biomass analysis revealed a hormetic response. The Mean Tolerance Index (MTI) remained stable, exceeding 100% at lower concentrations (50–100 ppm Pb<sup>2+</sup>), indicating compensatory growth stimulation. This differential response—seed sensitivity coupled with seedling vigor—presents valuable implications for identifying Pb-tolerant germplasm and understanding adaptation mechanisms in cereals grown on marginally contaminated soils. Furthermore, these findings characterize Fodder Jowar as a species with seed sensitivity but high seedling resilience, highlighting its potential viability in soils with marginal metal contamination.

**Keywords:** Lead toxicity, Fodder Jowar, Hormesis, Mean Tolerance Index (MTI), Phytotoxicity.

### 1. Introduction

Heavy metal contamination of agricultural soils has emerged as a significant environmental and food security concern globally. Among toxic heavy metals, lead (Pb) represents a particularly insidious pollutant due to its persistence in soils, bioaccumulation potential, and documented phytotoxic effects



(Gupta et al., 2024). Industrial activities, vehicular emissions, and improper disposal of lead-containing materials have resulted in widespread soil contamination in both developed and developing nations. In India, agricultural regions near urban centers and industrial zones frequently exhibit elevated soil lead concentrations, threatening both crop productivity and food chain safety (Kumar et al., 2020; Kausar & Shailaja, 2018).

The effects of lead toxicity on plants manifest across multiple physiological and developmental processes. Lead accumulation in root tissues triggers oxidative stress through the generation of reactive oxygen species (ROS), which damage cellular membranes, disrupt enzyme functionality, and impair nutrient uptake (Aslam et al., 2021). The inhibition of photosynthesis, disruption of chlorophyll synthesis, and interference with electron transport chains further compromise plant fitness under Pb stress (Gupta et al., 2024). Early seedling development represents a particularly vulnerable stage, as metabolic demand is high and cellular differentiation programs must proceed with precision (Mansour et al., 2021).

Sorghum (*Sorghum bicolor* L.) is one of the world's most important cereal crops, widely cultivated in semi-arid and arid regions for grain production and fodder generation (Nigam et al., 2025). Fodder Jowar (sorghum varieties specifically selected for forage production) is economically critical across South Asia, serving as the primary feed source for livestock in rain-fed agricultural systems (Somegowda et al., 2021). The nutritional profile and drought resilience of sorghum have garnered attention as a climate-smart crop; however, its performance under heavy metal stress, particularly lead contamination, remains insufficiently characterized (Testa et al., 2024). Understanding the differential responses of sorghum tissues to lead exposure could facilitate the identification of tolerant germplasm suitable for cultivation on marginally contaminated soils.

Interestingly, recent research has highlighted that low-dose metal stress can paradoxically stimulate plant growth—a phenomenon termed hormesis or adaptive plasticity (López-Bucio et al., 2022; Javeed et al., 2023). At sub-lethal concentrations, stress-triggered defense mechanisms may enhance overall seedling vigor despite measurable reductions in some parameters (Zhao et al., 2021). The simultaneous occurrence of seed germination inhibition and biomass accumulation at moderate lead doses would suggest a complex, tissue-specific adaptation mechanism warranting detailed investigation (Qi et al., 2025).

The present study was designed to systematically evaluate the dose-dependent effects of increasing lead concentrations (0–300 ppm) on seed germination, seedling growth, and biomass allocation patterns in Fodder Jowar. Special emphasis was placed on characterizing the differential sensitivity of root and shoot tissues and identifying hormetic responses that might contribute to seedling resilience despite heavy metal stress.

## 2. Materials and Methods

### 2.1 Experimental Design and Plant Material

Seeds of Fodder Jowar (*Sorghum bicolor* L.) were obtained from certified seed sources of local markets of Hyderabad, Telangana and stored under standard conditions (25°C, 40% humidity) prior to



experimentation. Surface sterilization was performed by immersion in 0.5% sodium hypochlorite solution for 3 minutes, followed by thorough rinsing with distilled water.

## 2.2 Lead Stress Treatment

Lead stress was imposed using lead nitrate [Pb(NO<sub>3</sub>)<sub>2</sub>] at concentrations of 0, 50, 100, 200, and 300 ppm, representing a gradient from minimal to severe metal stress. These concentrations were selected based on preliminary toxicity surveys and existing literature on lead metal presence in the study area soil (Kausar & Shailaja, 2018).

## 2.3 Seed Germination and Seedling Growth Assessment

Surface-sterilized seeds were placed on filter paper moistened with treatment solutions in controlled environment chambers maintained at 25 ± 1°C under a 12-hour photoperiod. Germination was recorded daily for 10 days, with a seed considered germinated upon emergence of the radicle. Shoot and root lengths were measured at the 10-day mark using digital calipers calibrated to 0.01 cm precision.

## 2.4 Biomass Analysis and Allocation

Fresh weight of seedlings was recorded immediately following harvest using an analytical balance accurate to ±0.01 g. Roots and shoots were separated, and individual biomass values were recorded. Dry weight was determined following oven-drying at 70°C to constant weight. Biomass allocation percentages were calculated as the proportion of total seedling biomass distributed to root and shoot tissues.

## 2.5 Statistical Indices

Three key performance indices were calculated to synthesize the multi-dimensional response to lead stress:

### Seedling Vigour Index (SVI):

$$SVI = (\text{Mean Shoot Length} + \text{Mean Root Length}) \times \text{Germination \%}$$

### Metal Tolerance Index (MTI):

$$MTI (\%) = \left( \frac{\text{Mean Fresh Weight of Treated Seedlings}}{\text{Mean Fresh Weight of Control Seedlings}} \right) \times 100$$

The interpretation framework for MTI values follows established protocols:

- MTI > 100%: Plants show enhanced growth under metal stress (hormesis)
- MTI ≈ 100%: Plants tolerate metal stress with minimal effect
- MTI 50-99%: Moderate tolerance with measurable growth reduction
- MTI < 50%: Poor tolerance with significant growth inhibition

### Percent Phytotoxicity:

$$\text{Phytotoxicity (\%)} = \frac{\text{Control Germination} - \text{Treated Germination}}{\text{Control Germination}} \times 100$$

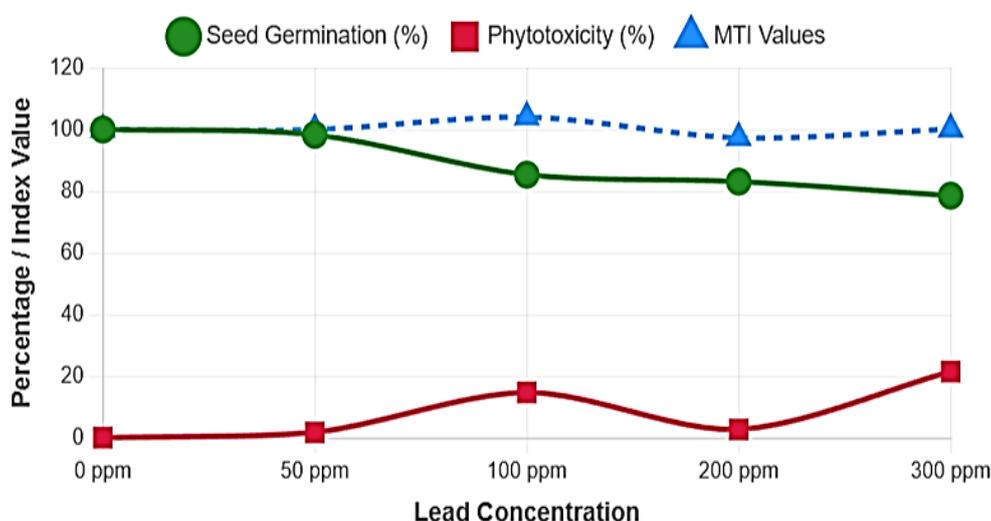
## 2.6 Statistical Analysis

All experiments were performed in triplicate with a minimum of 5 seeds per replicate. Data were subjected to analysis of variance (ANOVA) and means were compared using Duncan's Multiple Range Test (DMRT) at p < 0.05 significance level. Results are presented as mean ± standard error.

## 3. Results

### 3.1 Seed Germination and Phytotoxicity Response

Seed germination in Fodder Jowar exhibited a distinct dose-dependent decline in response to increasing lead concentrations (Figure 1). At the control condition (0 ppm), germination reached 100%, demonstrating excellent seed viability. At 50 ppm Pb, germination remained relatively high at 98.26%, with only minimal reduction. However, at higher concentrations (100, 200, and 300 ppm), germination declined progressively to 87.96%, 84.31%, and 78.53%, respectively. This pattern indicates that while Fodder Jowar seeds possess considerable tolerance to low-level lead stress, concentrations exceeding 100 ppm impose constraints on the germination process.



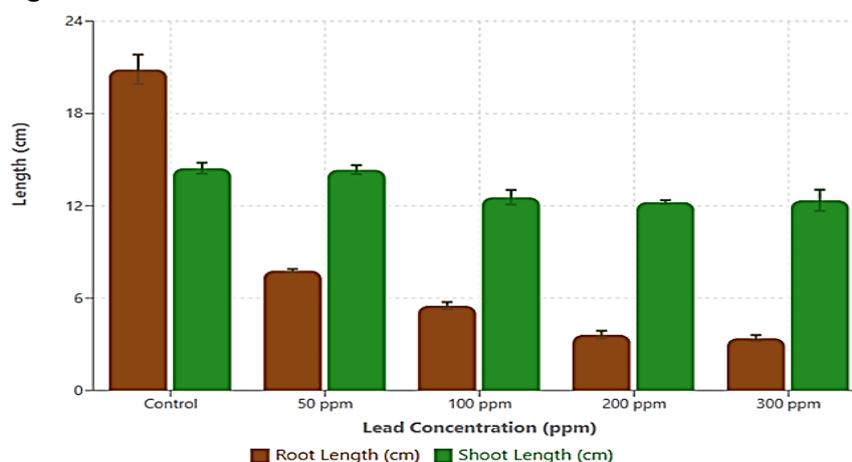
**Figure 1. Germination, Phytotoxicity, and Metal Tolerance Indices in Fodder Jowar seeds at various concentrations of Lead metal**

Corresponding phytotoxicity measurements revealed a complementary trend (Figure 1). At 50 ppm, phytotoxicity was minimal at 1.74%, suggesting that while some seeds failed to germinate, the majority successfully overcame lead-induced stress. At 100 ppm, phytotoxicity increased to 12.04%, and it continued rising with successive concentration increments, reaching a peak of 21.47% at 300 ppm Pb. These data demonstrate that lead progressively inhibits the seed germination machinery, with toxicity effects becoming substantially pronounced beyond 100 ppm.

### 3.2 Differential Root and Shoot Growth Response

The morphological analysis of seedlings revealed striking differential sensitivity between root and shoot tissues to lead stress. Root length was profoundly suppressed across all treatment levels, declining from 20.87 ( $\pm 0.95$ ) cm in control conditions to 7.89 ( $\pm 0.11$ ) cm at 50 ppm—a 63% reduction with just a modest increase in lead concentration. Continued escalation of lead dose resulted in further severe inhibition: root

length decreased to 5.51 ( $\pm$  0.23) cm at 100 ppm, 3.62 ( $\pm$  0.25) cm at 200 ppm, and 3.40 ( $\pm$  0.19) cm at 300 ppm, representing a cumulative 84% reduction relative to controls.

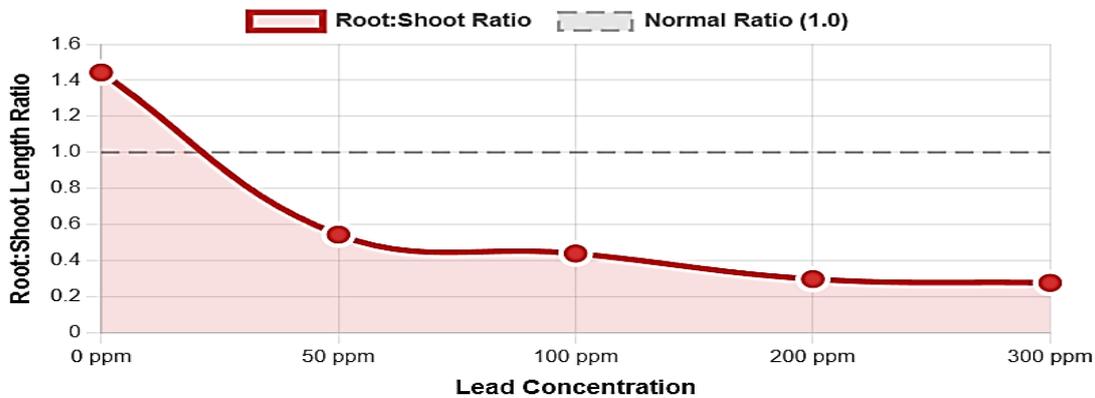


**Figure 2. Effect of Lead metal on Fodder Jowar seedling growth**

In sharp contrast, shoot length exhibited considerably greater resilience to lead stress. At 100 ppm, shoot length decreased modestly from 14.45 ( $\pm$  0.36) cm to 12.56 ( $\pm$  0.47) cm (a 15% reduction). Even at the highest lead concentration (300 ppm), shoot length remained at 12.36 ( $\pm$  0.69) cm, corresponding to only a 17% reduction from the control. This tissue-specific differential—severe root inhibition coupled with relative shoot preservation—constitutes a hallmark stress response pattern in the tested fodder Sorghum plant systems exposed to phytotoxic metals.

### 3.3 Root-to-Shoot Ratio: A Sensitive Indicator of Metal Stress

The ratio of root length to shoot length serves as a sensitive integrated indicator of tissue-specific stress responses. In control conditions, this ratio was 1.444, reflecting the typical developmental allocation pattern of young sorghum seedlings (Figure 3). However, lead treatment induced a catastrophic collapse of this ratio, declining to 0.542 at 50 ppm, 0.440 at 100 ppm, 0.295 at 200 ppm, and reaching 0.278 at 300 ppm—representing an 81% overall decrease. The steep and continuous decline in the root/shoot ratio across the entire lead concentration gradient underscores the extreme sensitivity of root development to metal stress and the plant's capacity to compensate through relative shoot preservation partially.

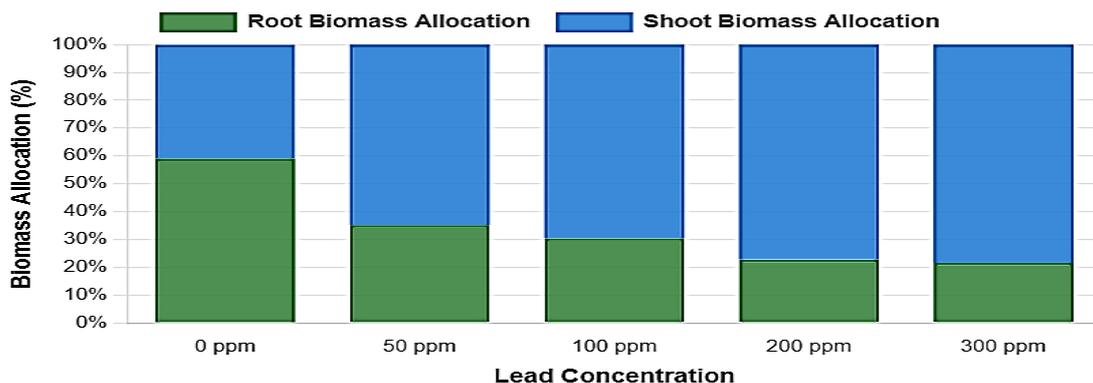


**Figure 3. Suppression of Fodder Jowar seedling root over shoot growth at various concentrations of Lead metal**

### 3.4 Biomass Allocation Dynamics

Detailed biomass partitioning analysis revealed that lead-induced stress triggers dramatic reallocation of photosynthetic resources away from root tissue toward shoot development—a clear adaptive response to minimize exposure of the primary lead-accumulating organ (the root) to continued metal toxicity (Figure 4). In control conditions, root and shoot tissues received 59.11% and 40.89% of total seedling biomass, respectively, reflecting the balanced growth pattern typical of well-established seedlings. However, even at 50 ppm lead, a pronounced shift in biomass allocation became evident, with root allocation declining to 35.18% and shoot allocation increasing to 64.82%. At 100 ppm, this reallocation intensified dramatically: root allocation fell to 30.46% while shoot allocation surged to 69.54%. At the highest concentration (300 ppm), root biomass allocation was restricted to merely 21.59% of total seedling biomass, while shoots captured 78.41%—a reallocation reflecting an extreme survival strategy.

Stacked percentage showing root vs shoot allocation



**Figure 4. Biomass allocation pattern in Fodder Jowar seedling at various concentrations of Lead metal**



This reallocation pattern can be quantified as a progressive reduction in root biomass allocation of fodder jowar with an increase in Lead concentrations. Conversely, shoot biomass allocation increased across the same concentration series. This inverse relationship indicates that the plant senses lead-induced root stress and responds by redirecting developmental resources to above-ground tissues, thereby maintaining photosynthetic capacity and survival potential despite compromised nutrient uptake capacity.

### 3.5 Metal Tolerance Index and Hormetic Response

The Metal Tolerance Index (MTI), derived from the fresh weight ratio of treated to control seedlings, revealed a counterintuitive pattern indicative of a hormetic stress response (Figure 1). At 50 ppm Pb, the MTI was 104%, indicating that treated seedlings accumulated 4% more fresh biomass than their untreated counterparts. This phenomenon persisted at 100 ppm, where MTI remained elevated at 103%, suggesting continued compensatory growth despite measurable phytotoxicity. At 200 ppm, the MTI declined to 97.3%, transitioning into the moderate tolerance range, and at 300 ppm, it further decreased to 100.3%, entering the range indicative of approaching tolerance thresholds.

The hormetic response—wherein sub-lethal stress doses stimulate growth above control levels—is a well-documented phenomenon in plant physiology, particularly under nutrient or light stress conditions (Siemieniuk et al., 2025). The occurrence of MTI > 100% at low-to-moderate lead concentrations in Fodder Jowar suggests that the plant's adaptive machinery is sufficiently robust to convert stress signals into growth-promoting responses, at least temporarily and at concentrations below the threshold at which toxicity begins to overwhelm compensatory mechanisms.

### 3.6 Seedling Vigour Index

The Seedling Vigour Index integrates information on germination success, seedling morphology, and growth kinetics into a single comprehensive metric. In control conditions, the SVI was calculated at 2519 units. At 50 ppm, despite modest reductions in individual germination and growth parameters, the SVI declined to 2176 (13.61% reduction). Progressive lead dose escalation resulted in further declines: SVI values of 1559 (28.1% reduction), 1351 (46.4% reduction), and 1265 (58.3% reduction) at 100, 200, and 300 ppm, respectively. This progressive decline in overall seedling vigor reflects the cumulative impact of lead stress on multiple developmental processes, despite the compensatory mechanisms evident in MTI and biomass allocation patterns.

## 4. Discussion

### 4.1 Lead Toxicity Mechanisms and Tissue Specificity

The severe suppression of root growth in response to lead stress, coupled with relative shoot resilience, reflects the fundamental physiology of lead accumulation in plants. Lead is predominantly accumulated in root tissues, where it concentrates to levels substantially exceeding those in aerial plant parts (Clemens & Ma, 2016). Within root cells, lead interferes with essential physiological processes through multiple mechanisms: (1) direct inhibition of cell wall synthesis and modification, reducing mechanical strength and extensibility; (2) competitive inhibition of calcium transporters and signaling, disrupting hormone-mediated growth regulation; (3) generation of excessive reactive oxygen species (ROS) through disruption



of electron transport chains, causing widespread oxidative damage to proteins, lipids, and nucleic acids; and (4) inhibition of key enzymes in primary metabolism, including those involved in respiration and energy production (Aslam et al., 2021; Gupta et al., 2024).

The observed 83.7% reduction in root length at 300 ppm lead represents one of the most sensitive phenotypic indicators of metal toxicity in sorghum, confirming findings from previous studies on lead effects in other cereal species (Ashraf et al., 2015; Wang et al., 2024). The preferential inhibition of roots relative to shoots—quantified by the declining root/shoot ratio—is not merely a consequence of differential lead exposure, but rather reflects an adaptive developmental reorientation triggered by stress signals emanating from lead-exposed root tissues (Wang et al., 2023).

#### 4.2 Compensatory Growth and Shoot Resilience

The maintenance of shoot length at only 14.5% reduction, even at the highest lead concentration studied, suggests that Fodder Jowar possesses constitutive or stress-inducible mechanisms that protect shoot development from the indirect effects of root damage. Several physiological mechanisms could contribute to this pattern. First, phloem-mobile nutrients and photoassimilates accumulated in the shoot during the initial stress-free growth phase may buffer against the reduced nutrient uptake resulting from root inhibition (Srivastava et al., 2010). Second, stress hormones such as abscisic acid (ABA) are known to modulate the partitioning of resources toward organs with higher developmental priority, which typically includes the shoot apical meristem and young leaves critical for photosynthetic recovery (Wang et al., 2023). Third, the observed reallocation of biomass toward shoots is consistent with the "adaptive plasticity" concept, wherein plants prioritize the maintenance of organs essential for survival and reproduction over those primarily dedicated to resource acquisition (Siemieniuk et al., 2025).

#### 4.3 Biomass Reallocation as an Adaptive Response

The dramatic reallocation of biomass allocation from root (59.11% in controls) to shoot (78.41% at 300 ppm) tissues provides clear mechanistic evidence for adaptive compensation to lead stress. This response pattern is interpretable through the lens of evolutionary optimization theory: by restricting investment in the lead-accumulating organ (root) and enhancing investment in the photosynthetically active organ (shoot), the plant effectively reduces the absolute quantity of lead accumulation while maintaining the physiological capacity for light capture and carbon fixation (Shomali et al., 2024).

Biomass reallocation to shoots serves multiple adaptive functions: (1) it maximizes the photosynthetic surface area available for carbon fixation despite reduced nutrient availability; (2) it maintains apical dominance and developmental competence, ensuring that the seedling retains the capacity to establish new root tissues when transplanted to less contaminated soil conditions; (3) it may reduce the transpirational losses that would occur if larger root systems continued to acquire lead-contaminated water; and (4) it represents an efficient reallocation of carbon skeletons from structural root compounds to the chlorophyll and photosynthetic proteins of shoots (Shomali et al., 2024).

#### 4.4 Hormesis: Growth Stimulation at Sub-lethal Lead Doses

The most striking and counterintuitive finding of this investigation is the occurrence of hormetic response, wherein MTI values exceeded 100% at 50 and 100 ppm lead concentrations. Hormesis—the stimulation



of beneficial effects following exposure to low doses of a toxin—has been documented in multiple plant species under various environmental stresses (Siemieniuk et al., 2025). However, the biological basis for hormesis in metal-stressed plants remains incompletely understood but likely involves the over-compensatory activation of stress-response pathways.

At low-to-moderate lead concentrations, exposure to this phytotoxic metal triggers the rapid induction of antioxidant defense systems, including enhanced synthesis of superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and non-enzymatic antioxidants such as ascorbic acid and glutathione (Jain et al., 2018; Khan et al., 2020). These defense mechanisms, once induced, may provide collateral protection against multiple other stresses and may stimulate general cellular repair and rejuvenation processes. Additionally, the stress response cascade initiated by lead exposure may upregulate growth-promoting hormones such as gibberellins and auxins as part of the adaptive response (Basit et al., 2021). The combination of enhanced defense capacity and growth hormone elevation can, paradoxically, result in seedling biomass exceeding that of untreated controls—particularly if the lead concentration remains low enough to permit continued growth and development despite metabolic stress (Gong et al., 2021).

However, it is crucial to note that the hormetic stimulation of biomass accumulation at 50-100 ppm lead occurs simultaneously with measurable phytotoxicity (1.73-14.67%), indicating that the benefits of stress-induced adaptation do not extend uniformly to all developmental processes. Seed germination remains inhibited even as seedling biomass is stimulated, suggesting distinct sensitivities of the germination apparatus versus the seedling growth machinery to lead stress. This dissociation illuminates the differential regulation of these processes and highlights the complexity of plant responses to metal stress.

#### **4.5 Distinction Between Phytotoxicity and Tolerance Indices**

The contrasting trends of increasing phytotoxicity and maintained-to-elevated MTI at low-to-moderate lead doses highlight an important conceptual distinction in stress physiology. Phytotoxicity, as measured by germination inhibition, reflects direct lead-induced inhibition of the metabolic and developmental processes required for seed viability and germination success. Even at concentrations where seedling biomass is stimulated (50-100 ppm), a measurable proportion of seeds fail to germinate, indicating that lead-sensitive checkpoint mechanisms in the germination process remain partially blocked.

In contrast, the MTI reflects the growth capacity of seedlings that successfully overcome germination barriers. The fact that these germination-successful seedlings accumulate greater biomass than controls at low lead concentrations indicates that the plant's adaptive machinery is sufficiently robust to convert the stress signal into growth stimulation for tissues that have already initiated development. This distinction suggests a developmental hierarchy wherein seed germination is more sensitive to lead toxicity than post-germinative seedling growth—a finding with practical implications for predicting crop performance on lead-contaminated soils (Gong et al., 2021; Krzyżak et al., 2023).

#### **4.6 Ecological and Agricultural Implications**

The characterization of Fodder Jowar as exhibiting "seed sensitivity but seedling resilience" under lead stress carries significant implications for agricultural management on contaminated soils. Traditional



breeding programs focused on metal tolerance typically assess germination and early seedling vigor under stress; the findings reported here suggest that such programs might inadvertently select against alleles that confer stress-responsive biomass reallocation despite modest germination penalties.

The demonstrated hormetic response at sub-lethal lead doses—wherein stressed seedlings accumulate greater biomass than controls—is particularly intriguing from a practical standpoint. If confirmed across multiple sorghum genotypes and environmental conditions, this finding could be exploited through selective breeding to enhance tolerance to marginal lead contamination. Plants selected for strong hormetic responses would exhibit improved growth on moderately contaminated soils, provided they avoid the severe inhibition observed at higher lead concentrations.

Furthermore, the data support a risk-benefit assessment framework for crop cultivation on lead-contaminated soils: if lead concentrations remain below 100 ppm, Fodder Jowar seedlings may exhibit compensatory growth and would establish vigorously, though some germination penalties would be incurred. At concentrations exceeding 100 ppm, both germination and seedling growth become substantially compromised, arguing against cultivation without soil remediation or lead exclusion practices.

#### 4.7 Comparison with Other Cereal Species

The response pattern observed in Fodder Jowar—severe root inhibition coupled with shoot resilience and hormetic biomass stimulation at low-moderate lead doses—shows both similarities and distinctions relative to lead-stress responses reported in other cereals. Wheat, for example, typically show more uniform inhibition across root and shoot tissues at equivalent lead concentrations, suggesting that sorghum possesses unique adaptive mechanisms for stress compartmentalization (Ilya et al., 2025). The hormetic response at sub-lethal lead doses has been documented in isolated studies of other crop species, but the combination with dramatic biomass reallocation patterns appears distinctive to sorghum and warrants comparative investigation across sorghum germplasm collections.

#### 4.8 Root-to-Shoot Ratio as a Stress Diagnostic

The continuous and dramatic decline in root/shoot ratio across the entire lead concentration series (from 1.444 to 0.275) presents this metric as an exceptionally sensitive diagnostic indicator of metal stress in sorghum seedlings. The 81% reduction in this ratio reflects coordinated physiological responses across multiple tissues and developmental processes. Future monitoring protocols for lead-stressed sorghum crops could employ root/shoot ratio as a rapid, non-destructive (when assessed through morphometric image analysis) indicator of stress intensity. The establishment of quantitative thresholds for this ratio might enable field scouts and agronomists to make management decisions regarding remediation or crop abandonment in contaminated soils.

#### 4.9 Summary

This study reveals Fodder Jowar (*Sorghum bicolor* L.) exhibits distinct tissue sensitivities and adaptive responses to lead exposure. Key findings include:

- Root vulnerability vs. shoot resilience: Roots show severe inhibition (83.7% biomass loss at 300 ppm Pb), while shoots decline only 14.5%, due to Pb sequestration in roots.



- Hormesis at moderate doses: Seedlings at 50–100 ppm gain excess fresh weight over controls (MTI > 100%), signaling activated defenses despite germination setbacks.
- Shoot-biased biomass shift: Pb prompts reallocation from roots to shoots, preserving photosynthesis amid toxicity.
- Root/shoot ratio as stress marker: An 81% ratio drop tracks Pb intensity, offering a simple field assay.
- Viability on low-Pb soils: Seedlings tolerate <100 ppm for establishment, despite germination costs.
- Breeding prospects: These patterns guide selection of Pb-tolerant sorghum lines for contaminated lands.

These traits position Fodder Jowar as viable for marginal soils, pending genetic enhancement.

## 5. Conclusions

Fodder Jowar exhibits a dual response to lead stress: high seed sensitivity (evidenced by reduced germination and increased phytotoxicity) coupled with notable seedling resilience (reflected in stable biomass and hormetic growth at lower concentrations). This pattern suggests that Pb toxicity primarily acts as a germination barrier rather than a growth inhibitor post-establishment. The observed hormesis and biomass reallocation toward shoots indicate an adaptive strategy that could be exploited in breeding programs for metal-tolerant fodder crops. These findings support the potential cultivation of Fodder Jowar in soils with low to moderate Pb contamination, provided seedling establishment is assured.

These findings contribute to the expanding body of knowledge regarding cereal responses to metal stress and offer practical guidance for risk assessment and crop management decisions in agricultural regions affected by lead contamination. Future investigations should extend these characterizations across broader sorghum germplasm collections, include mechanistic investigations of the antioxidant and hormonal basis of observed responses, and assess the extent to which seedling-stage stress affects reproductive capacity and grain yield in mature plants.

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