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ANATOMICAL AND PHYSIOLOGICAL CHANGES IN CROP PLANTS EXPOSED TO HEAVY METAL CONTAMINATION

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ABSTRACT
Heavy metal contamination threatens crop productivity by altering plant structural development, physiological balance, and metal uptake behavior. This study evaluated anatomical and physiological changes in maize exposed to cadmium-contaminated soil using a secondary quantitative dataset from an amendment-based phytoremediation experiment. Maize was assessed across control and treatment groups using organ-level anatomical indicators, physiological stress markers, cadmium accumulation variables, and extraction efficiency. Anatomical responses were represented by shoot biomass, root biomass, total biomass, and root–shoot allocation, while physiological responses were evaluated through malondialdehyde, superoxide dismutase, catalase, and peroxidase activities. Results showed that amendment treatments substantially improved maize growth compared with the control. AG1 produced the highest total biomass, shoot cadmium concentration, extraction efficiency, and catalase activity, indicating the strongest combined anatomical and physiological response. G2 showed the lowest malondialdehyde level, suggesting reduced lipid peroxidation, while GG2 showed the highest peroxidase activity. Correlation analysis showed that extraction efficiency was strongly associated with catalase activity, cadmium translocation factor, shoot cadmium concentration, and shoot biomass. These findings indicated that successful cadmium extraction depended on coordinated biomass production, antioxidant defense, and metal movement into above-ground tissues. Maize exhibited clear organ-level anatomical and physiological adjustments under cadmium contamination, with AG1 identified as the most effective treatment for improving growth, stress tolerance, and phytoremediation performance.

KEYWORDS: Cadmium contamination, maize, anatomical changes, antioxidant enzyme activity, phytoremediation

1. INTRODUCTION
Soil pollution with heavy metals has become a major obstacle for agricultural production, soil properties, and food security. Cadmium is of special concern among toxic metals due to its mobility in soil, its suitability for uptake by plants' roots, and its possible transfer into the food chain. Cadmium does not have any known beneficial function in plants nor can it readily be incorporated into the metabolic processes of plants, and it can affect the uptake of other nutrients, photosynthesis, respiration, water relations, and cell redox balance. Cd pollution in soil can affect the germination rate of crop plants, their root growth, shoot growth, biomass, reproductive ability, and cause chlorosis. The impact of cadmium on the structure and function of plants under stress conditions constitutes a relevant model to explore the effect of heavy metals on plant structure and function under stress conditions (El Rasafi et al., 2022).
Anatomical and physiological adaptations occur in plants exposed to heavy metals. Anatomical changes can take place at various levels: root morphology, shoot development, tissue expansion, biomass partitioning, and root–shoot allocation. Heavy metals can inhibit the growth of the roots, cause injury to meristems, affect vascular transport, limit leaf expansion, and affect the development of functional plant organs. These changes have been linked with physiological changes such as oxidative stress, changes in the membranes, changes in water uptake, enzyme inhibition, and nutrient imbalance. Hence, the anatomical and physiological parameters have to be evaluated to assess the effect of heavy metal exposure on crop performance (Chukwu & Gulser, 2025).
The toxic effect of heavy metals on plants is closely associated with the disruption of cellular homeostasis. Cadmium and other toxic metals can chelate sulfhydryl groups, replace essential ions, interfere with enzymatic activity, and interfere with photosynthetic and respiratory pathways. These perturbations increase the formation of reactive oxygen species, such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals. Too much reactive oxygen species (ROS) can cause damage to lipids, proteins, nucleic acids, and membranes, which results in decreased cell viability and plant growth. Under

this stress, plants activate detoxification mechanisms, sequestration mechanisms, antioxidant enzymes, and stress-related metabolic changes (Ghuge et al., 2023).

The assessment of physiological stress due to heavy metal contamination is often carried out via oxidative damage and antioxidant defense markers. The malondialdehyde (MDA) is considered a marker of lipid peroxidation and injury to cell membranes, and three important enzymes engaged in antioxidant defenses are superoxide dismutase, catalase, and peroxidase. High antioxidant activity can be a sign of stress adaptation, and too much membrane damage can be a sign of failure of the physiological protection. These markers can be used for quantifying metal-induced oxidative stress (Mohamed et al., 2025) in crop plants under stress conditions.

Plant tolerance and ability for phytoremediation are also functions of metal uptake, transport, and sequestration. Heavy metal transporters control the uptake of heavy metals into the root membrane, xylem loading, vacuolar sequestration, and root-to-shoot transport. Certain plants will contain metals in the shoots and not in the roots to avoid toxicity to photosynthetic organs, and other plants will store metals in aboveground parts, which are suitable for the phytoextraction process. Therefore, the balance between metals' uptake, internal distribution, biomass production, and capacity for detoxification is crucial to understanding the responses of crops under contaminated environments (Panda et al., 2025).

The molecular regulation of plant responses to heavy metals includes antioxidant pathways, activation of transporters, hormone signaling, gene regulation, and stress-responsive proteins. They act through mechanisms that affect plant perception of metal toxicity and integration of defense responses between roots, shoots, and cellular compartments. In addition to the visible anatomical and physiological responses, such as biomass buildup, root development, enzyme activity, and stress tolerance, molecular regulation also plays a role in these responses (El-Sappah et al., 2024). Recent studies also highlight that the use of nano-remediation, plant defense signaling mechanisms, and integrated stress-management strategies are new emerging methods to help mitigate heavy metal toxicity in agriculture (Jarin et al., 2025).

Nutrient-mediated alleviation has been noticed due to the possibility of influence on nutrient balance on cadmium uptake, oxidative stress, and plant growth. Zinc, calcium, silicon, iron, and phosphorus can help minimize cadmium toxicity through the following means: Limiting uptake, increasing antioxidant activity, stabilizing membranes, and restoring metabolic function. These interventions are key for crop systems as they can increase productivity with lower metal content in edible tissues (Sun et al., 2025). In addition to the immediate physiological response to cadmium, plant adaptive response to heavy metal stress is also regulated by epigenetic changes, which are semi-permanent or heritable (Gao et al., 2025), demonstrating that epigenetic regulation also plays a part in cadmium stress memory and adaptation.

Maize is an appropriate crop model for studying heavy metal stress, as it is a widely cultivated crop with high biomass and exhibits measurable responses to contaminated soil conditions in terms of growth, metal uptake, and antioxidant activity. Chelation and plant growth regulators are among the amendment-based methods used to increase the bioavailability of Cd, plant uptake, and phytoremediation efficiency. This method enables the simultaneous assessment of anatomical growth performance, physiological defense, and cadmium extraction capacity (Yang et al., 2024). Crop responses can also be further affected by soil biological amendments, such as arbuscular mycorrhizal fungi, which have been shown to affect nutrient uptake, antioxidant defense, and cadmium stress mitigation in maize (Kuang et al., 2025). It is also observed that soil amendments like spent mushroom substrate biochar have a positive effect on maize growth and biochemical resilience under cadmium and chromium stress, highlighting the potential of soil amendments as a means of mitigating heavy metal stress (Dawar et al., 2025).

Objectives of the study:

To assess organ-level anatomical changes in maize using shoot biomass, root biomass, total biomass, and root–shoot allocation.

To evaluate physiological responses through lipid peroxidation and antioxidant enzyme activity under cadmium stress.

To determine cadmium uptake, translocation, and extraction efficiency across different amendment treatments.

2. METHODOLOGY

2.1 Study Design

This study was based on a secondary quantitative analysis of an open-access experimental dataset of maize in Cd-contaminated soil. The design was designed to assess the anatomical and physiological changes in a crop plant exposed to heavy metals. The crop model used was maize, and the stress condition was the heavy metal Cd. The differences in plant growth, cadmium uptake, oxidative stress response, and phytoremediation performance were compared between the control and amendment treatments.

2.2 Dataset Source and Description

The data were collected from an experimental study published by Yang et al. (2024) on optimizing phytoremediation of Cd-polluted soil using chelators and PCNs. It was supplied (in Excel format) with biomass, Cadmium concentration, Extraction efficiency, Antioxidant enzyme activity, Soil properties, Microbial composition, and Microbial diversity. The treatment groups included CK, AES, GLDA, G1, G2, G3, AG1, AG2, AG3, GG1, GG2, and GG3. The control treatment was identified as CK, whereas the other treatments were considered amendment-based. The main unit of comparison in these treatment groups was the individual treatments.

2.3 Variable Selection

The selection of variables was based on their relevance to the anatomical growth, physiological response, cadmium accumulation, and soil condition. Anatomical changes were indicated on an organ level (shoot biomass, root biomass, total biomass, root/shoot biomass ratio, and cadmium distribution in the root and shoot tissues). Malondialdehyde, superoxide dismutase, catalase, and peroxidase activities were measured for physiological responses. Cadmium-related variables were shoot cadmium concentration, root cadmium concentration, and the efficiency of extraction of cadmium. Under contaminated soil conditions, the plant response was supported by soil pH, available cadmium, total nitrogen, total phosphorus, total potassium, and microbial diversity indices.

2.4 Data Preparation

A review of the Excel workbook was conducted for the structure of the worksheet, treatment labels, variable names, missing or inconsistent entries, and units. The names of the treatments were standardized on each of the treatment sheets so that the data for biomass, cadmium concentrations, extraction efficiency, enzyme activity, and soil-related variables could be compared for each of the treatment types. The variables of relevance were kept and presented in analytical tables with respect to the treatments. Where necessary, derived indicators were calculated, such as the ratio of root to shoot biomass, the relative biomass change compared to the control, the relative enzyme activity change, the tendency of cadmium translocation, and the improvement of the relative extraction efficiency. These indicators bolstered the interpretation of the anatomical and physiological responses.

2.5 Statistical Analysis

The treatment-based variation in biomass, soil properties, concentration of cadmium, extraction efficiency, and activity of antioxidant enzymes was summarised by descriptive statistics computed using Python. In order to assess the effect of treatments on plant growth, metal uptake, oxidative stress response, and extraction efficiency, the percentage change from control was calculated in Python. Using Python, a correlation analysis was conducted to explore the relationships between the anatomical indicators, the physiological indicators, cadmium accumulation, and extraction efficiency. Where applicable, for each treatment group, a heatmap-based comparison and a principal component analysis were performed in Python to visualize treatment response patterns and major variables separating the treatment groups.

2.6 Analytical Interpretation

Anatomical changes were interpreted at the organ-growth level due to the lack of direct measurements at the microscopic anatomical level. Therefore, the biomass of shoots, roots, total biomass, and root–shoot allocation were considered structural measures of plant anatomical performance under Cd stress. Physiological changes were interpreted by using markers of oxidative stress and the defence mechanisms. The enzymatic antioxidant regulation is represented by SOD, CAT, and POD, while membrane lipid peroxidation is represented by MDA. The uptake and internal distribution of cadmium were determined by its concentration in roots and shoots, and the extraction efficiency was used to determine the phytoremediation capacity. The cooperation of the analysis enabled the study to evaluate the anatomical and physiological alterations of maize under heavy metal contamination.

3. RESULTS

3.1 Dataset Structure and Analytical Coverage

The observations were the number of observations collected in the soil contaminated with Cadmium per treatment for the maize crop. The data comprised biomass, cadmium concentration, extraction efficiency, antioxidant enzyme activity, soil properties, microbial composition, and microbial diversity included in the workbook. The main analysis was performed in 12 treatment groups (CK, AES, GLDA, G1, G2, G3, AG1, AG2, AG3, GG1, GG2, GG3). CK was treated as the control. Organ-level indicators were used to assess anatomical changes, such as shoot biomass, root biomass, total biomass, and root-to-shoot allocation. The physiological responses were determined by measuring the activities of MDA, SOD, CAT, and POD. Three different approaches were used to assess Cadmium response: shoot Cd concentration, root Cd concentration, the translocation factor, and the extraction efficiency. The data elements and their analytical significance can be seen in Table 1.

Table 1. Dataset components and analytical relevance

Component	Main variables	Analytical relevance
Biomass	Shoot, root, total biomass	Organ-level anatomical response
Cd concentration	Shoot Cd, root Cd	Metal uptake and distribution
Extraction efficiency	Cd extraction efficiency	Phytoremediation performance
Enzyme activity	MDA, SOD, CAT, POD	Physiological stress response
Soil properties	pH, available Cd, nutrients	Soil-mediated support
Microbial data	Abundance, diversity indices	Biological support context

3.2 Anatomical Growth Response

The biomass data revealed distinct treatment differences in the growth of organs. The weakest growth was found in cadmium-contaminated water (CK), which resulted in the lowest total biomass. The total biomass in AG1 was the highest (2.91g/pot), which is 259.26% higher than what was obtained in CK. The other cultivars, G2, G1, G3, AG3, and AG2, also recorded totals of over 200% increase in total biomass.

Also, root biomass showed significant differences between the treatments. The root biomass of GG3 was the highest, followed by G2, AG1, G1, and G3. The results suggested that the above-ground and below-ground anatomical growth responses were improved by the amendment treatments. The growth response of maize is presented in Table 2 by treatment. Figure 1 shows the overall biomass response of the maize in the cadmium-contaminated soil when treated with different methods.

Table 2. Treatment-wise anatomical growth response

Treatment	Total biomass g/pot	Change vs CK (%)	Root biomass g/pot	Change vs CK (%)
CK	0.81	0.00	0.20	0.00
AG1	2.91	259.26	0.90	350.00
G2	2.57	217.28	0.91	355.00
G1	2.53	212.35	0.88	340.00
G3	2.45	202.47	0.85	325.00
AG3	2.44	201.23	—	—
AG2	2.43	200.00	—	—
GG3	—	—	0.93	365.00

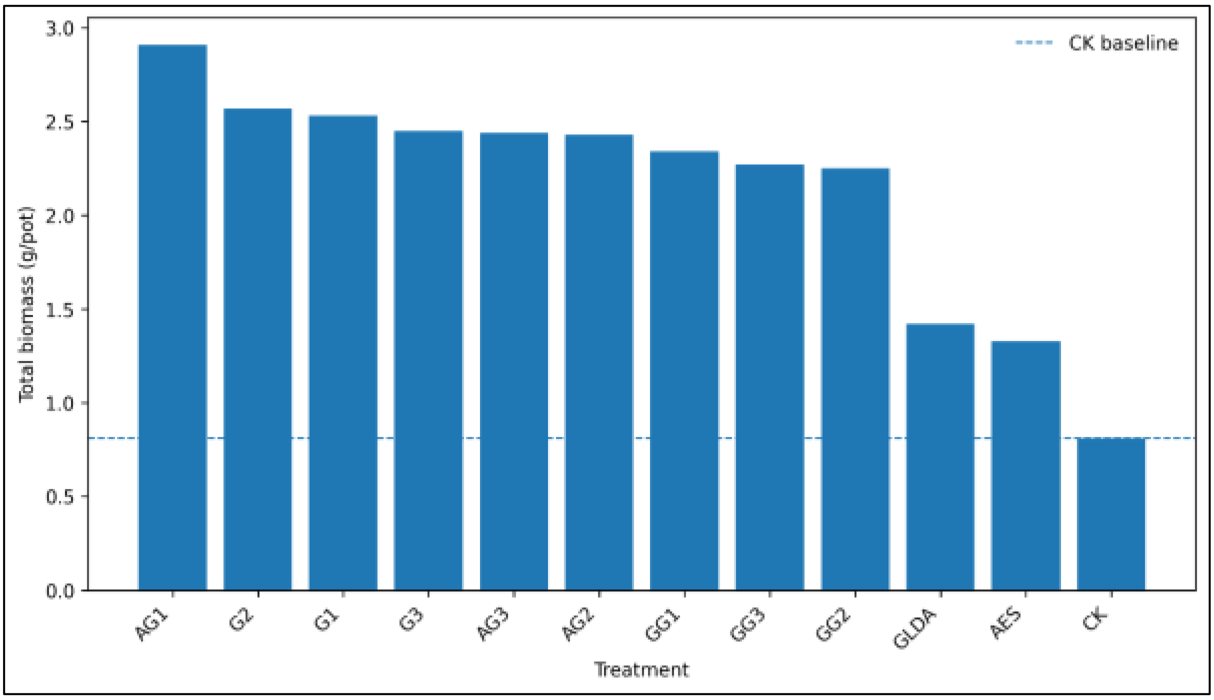

Figure 1. Treatment-wise Total Biomass Response of Maize under Cadmium Contamination

3.3 Cadmium Uptake and Extraction Efficiency

There was a significant rise in the concentration of shoot Cd under amendment treatments. The highest shoot Cd concentration was observed in AG1 (8.51 mg/kg), followed by AG2, AES, AG3, and GLDA. This suggests improved Cd uptake to above-ground tissues.

The extraction efficiency was the lowest for CK, and the highest for AG1. AG1 finally settled at 0.524%, which is 8.89 times the settlement price of CK. The extraction efficiency was also high for AG2 and AG3, and moderate to strong for GG1, GG2, and GG3. The highest Cd translocation factor was observed in AG1, which shows efficient translocation of Cd from the root to the shoot tissue. Cadmium uptake and efficiency in the extraction of cadmium under various treatments are shown in Table 3. The results of the cadmium extraction efficiency test are shown in Figure 2.

Table 3. Cadmium uptake and extraction response

Treatment	Shoot Cd mg/kg	Change vs CK (%)	Extraction efficiency (%)	Fold change vs CK
CK	3.15	0.00	0.059	1.00
AG1	8.51	170.16	0.524	8.89
AG2	8.20	160.32	0.409	6.95
AES	7.95	152.38	—	—
AG3	7.72	145.08	0.400	6.79
GLDA	7.51	138.41	—	—
GG1	—	—	0.386	6.56
GG2	—	—	0.329	5.58
GG3	—	—	0.302	5.14

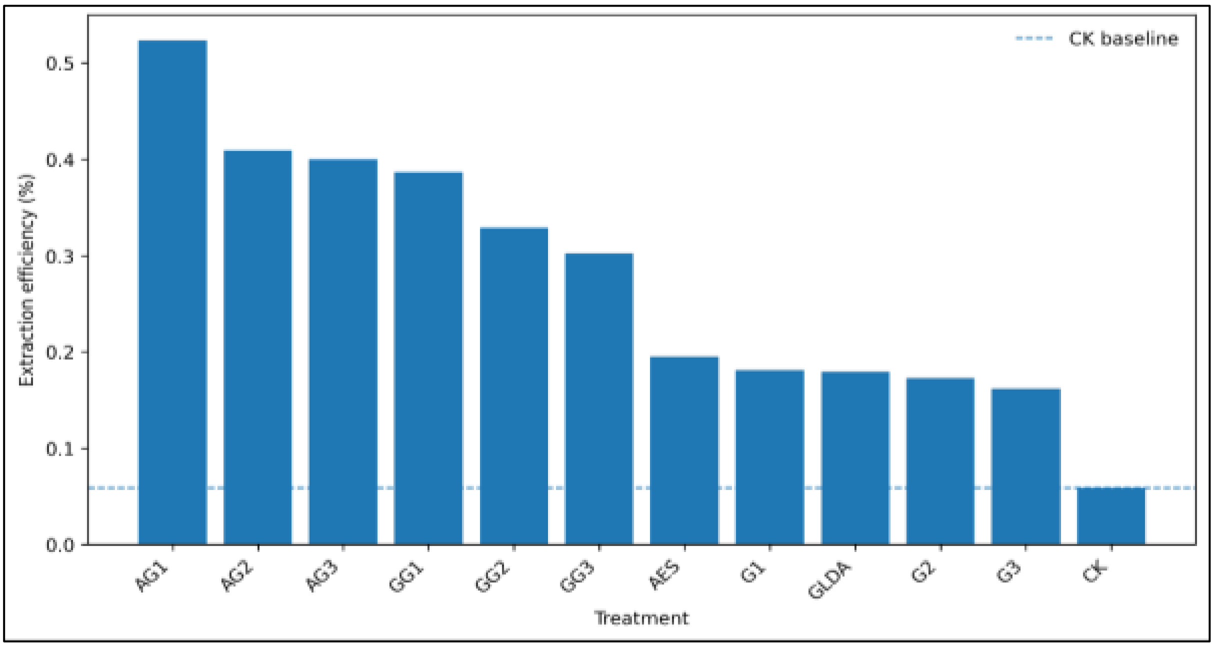

Figure 2. Treatment-wise Cadmium Extraction Efficiency of Maize under Cadmium Contamination

3.4 Physiological Stress and Antioxidant Response

Physiological variation among the treatments was evident in the activities of MDA, SOD, CAT, and POD. Lipid peroxidation was determined by the use of MDA. G2 had the lowest MDA value, reducing by 24.65% from the value of CK, whereas AG1 reduced the MDA by 17.26%.

The antioxidant activity was enhanced in a few treatments. The activity of SOD recorded in GG1 was the highest, the activity recorded in AG1 was the highest, and the POD activity recorded in GG2 was the highest. CAT exhibited the highest treatment response, with AG1 exhibiting 79.16% increase in CAT activity when compared with CK. These results indicated that amendment treatments decreased oxidative injury and enhanced the antioxidant defense under the cadmium stress. The responses to stress and antioxidant enzymes are shown in Table 4.

Table 4. Physiological stress and antioxidant response

Indicator	Best treatment	Value	Change vs CK (%)	Interpretation
MDA	G2	12.10 nmol/g	−24.65	Lowest lipid peroxidation
MDA	AG1	13.29 nmol/g	−17.26	Reduced membrane damage
SOD	GG1	588.20 U/g	+14.01	Strong superoxide detoxification
CAT	AG1	74.33 U/g	+79.16	Strong peroxide detoxification
POD	GG2	732.00 U/g	+23.65	Strong peroxidase response

3.5 Relationship Among Growth, Physiology, and Cadmium Extraction

The results of correlation analysis revealed that the Cd extraction efficiency is significantly correlated with the physiological defense and accumulation of Cd in the above-ground parts. The positive correlation with extraction efficiency was the greatest for CAT, followed by the translocation factor for Cd, shoot Cd, SOD, shoot biomass, POD, root Cd, and total biomass. There was a negative correlation with MDA, indicating that the less the lipid peroxidation, the better the extraction performance. The pattern of correlations between anatomical, physiological, and cadmium-response variables is shown in Figure 3. Table 5 gives the correlation coefficients for the extraction efficiency and selected variables of plant response.

Table 5. Correlation of selected variables with Cd extraction efficiency

Variable	Correlation with extraction efficiency	Interpretation
CAT	0.960	Strongest physiological association
Cd translocation factor	0.779	Strong shootward Cd movement
Shoot Cd	0.763	Higher shoot Cd supported extraction
SOD	0.705	Positive antioxidant association
Shoot biomass	0.694	Above-ground growth supported extraction
POD	0.687	Positive antioxidant association
Root Cd	0.663	Root uptake contributed to the extraction
Total biomass	0.650	Larger plants supported Cd removal
MDA	−0.372	Lower oxidative damage favored extraction

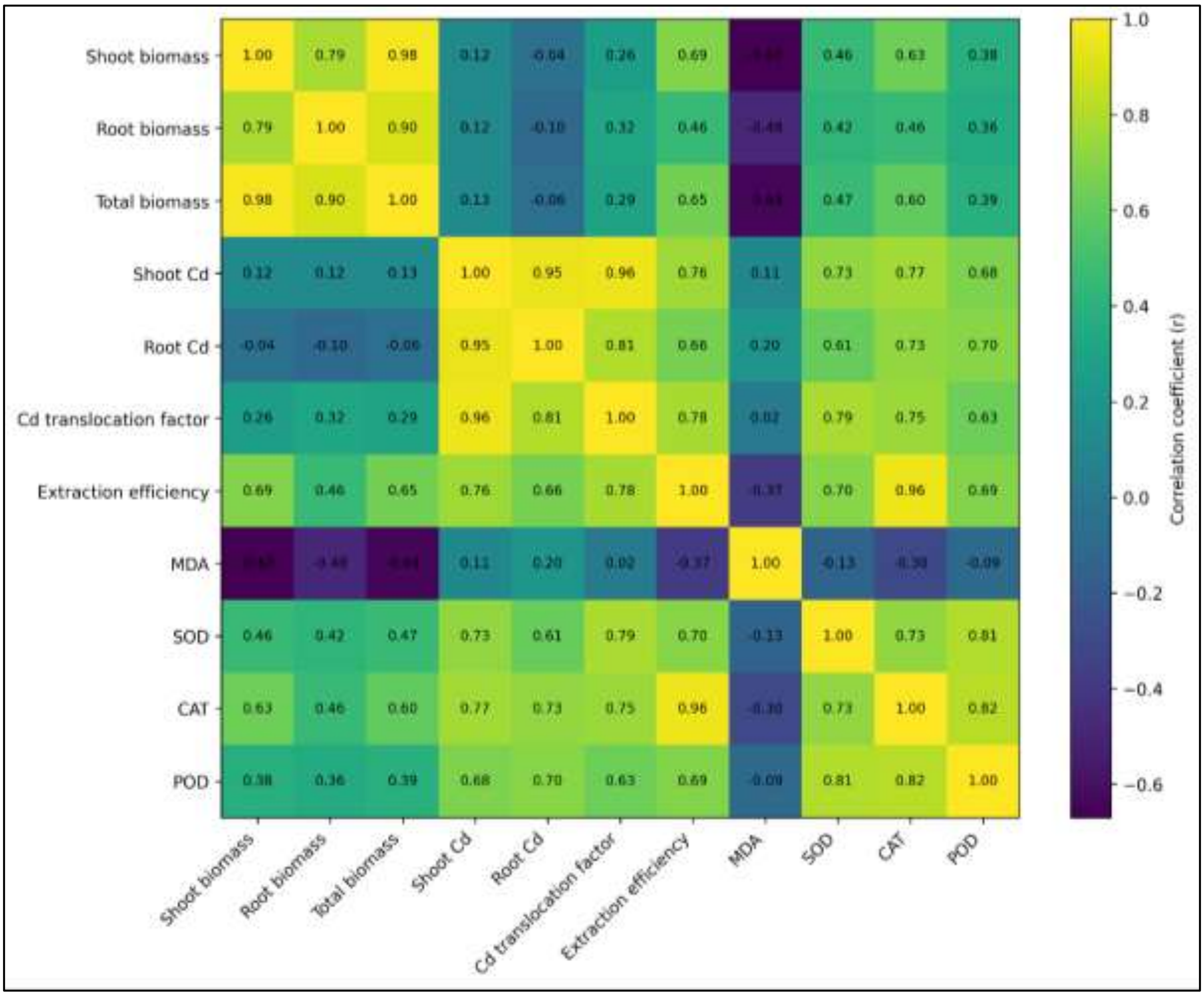

Figure 3. Correlation Heatmap of Anatomical, Physiological, and Cadmium-Response Variables

3.6 Integrated Treatment Performance

The integrated ranking integrated the anatomical, physiological, and cadmium-response indicators. The AG1 had the best overall performance due to the highest biomass, highest shoot Cd concentration, highest extraction efficiency, highest CAT activity, and lower MDA than the CK. The next best treatments were AG2, GG1, GG2, and AG3.

The outcomes revealed that anatomical and physiological alterations could be detected in maize plants growing in soil contaminated with cadmium. The alteration in the biomass accumulation and root–shoot growth pattern in the stunted plants with regard to the corresponding healthy controls showed the anatomical changes, while variation in antioxidant enzyme activity and lipid peroxidation indicated the physiological changes. The treatment of AG1 was found to be the most effective treatment for the improvement of growth, physiological defense, and cadmium extraction under heavy metal contamination.

4. DISCUSSION

The present study showed that measurable changes occurred in maize in the soil contaminated with Cadmium for all treatment groups, both in anatomical and physiological aspects. The changes were seen as a change in biomass accumulation, root and shoot morphology, cadmium uptake and extraction, lipid peroxidation, and antioxidant enzyme activity. Direct microscopic anatomical measurements were not a part of the data, and anatomical responses were therefore studied at the organ-growth level by shoot biomass, root biomass, total biomass, and root–shoot allocation. This interpretation was suitable as it described the impact of heavy metal exposure on the visible development of structures, root function, shoot expansion, and biomass distribution in crop plants.

Biomass measurements revealed that the growth of the maize was significantly enhanced by the amendments compared to the control treatment, in which growth was reduced due to the cadmium contamination. Under cadmium stress, the highest total biomass was recorded by AG1, which suggests that the anatomical performance of the organs was better. High biomass in selected treatments indicated more stress tolerance and better maintenance of plant structure development. In maize – based remediation systems, similar results have been found where growth response was affected by both plant arrangement and level of soil contamination and remediation strategy. Maize-based intercropping systems have also been demonstrated to enhance the ecosystem performance, decrease the stress caused by metals in contaminated soils, and hence the plant growth responses are considered to be the key indicators for the success of remediation (Ye et al., 2025).

The effects of the amendments on shoot, root, and total biomass also demonstrated that the effects of cadmium toxicity could be mitigated by outside additions. The present data indicated high total biomass response in AG1, G2, and G1, and the highest root biomass response in GG3 compared to the CK. These results indicated that there were some treatments that favored above-ground growth and others that favored below-ground structural development. The same results have been found in maize under cadmium stress, where the application of zinc sulphate increased growth and biochemical responses, which could be attributed to the reduction in cadmium-induced injury and the enhancement of the physiological defense mechanisms (Saeed et al., 2025).

Cadmium uptake and extraction results also indicated the importance of using maize as a phytoremediation crop of contaminated soils. The treatment significantly increased metal uptake and above-ground accumulation: AG1 exhibited the highest shoot Cd concentration and the highest extraction efficiency. This is crucial since the key to a successful phytoextraction is both high metal load in plant biomass and high metal content in the soil. Maize has been mentioned as a potential species for phytomanagement due to its capacity to generate high biomass, adaptability, and measurable metal uptake capacity (Rizwan et al., 2017).

The greater extraction efficiency under AG1, AG2, and AG3 indicated that this was due to an increase in the mobility of Cd, uptake by plants, or internal transport within the plants caused by the different amendment-based strategies. The higher Cad translocation factor in AG1 suggested a higher transport of Cad from root to shoot, and this would be beneficial for above-ground phytoextraction. Similar results have been seen in phytoremediation experiments involving the use of biodegradable chelators, which showed that chelate-assisted remediation increased cadmium uptake and improved remediation in contaminated soil (Teng et al., 2022).

The changes in MDA, SOD, CAT, and POD activity were indicative of the physiological responses. The G2 and AG1 showed reduced lipid peroxidation and reduced membrane damage with MDA reduction as compared to CK. The higher antioxidant enzyme activity indicated that maize adapted defense response in response to several treatments to manage the cadmium-induced oxidative stress. This finding is in line with earlier research that reported a close relationship between plant growth and photosynthetic activity under heavy metal stress and physiological protection mechanisms and stress response metabolic regulation (Ali et al., 2024).

The strongest physiological association with extraction efficiency was observed for CAT activity. The best overall extraction and the highest activity of CAT were observed in AG1, which indicated a strong correlation between the detoxification of peroxide and Cd tolerance and phytoextraction ability. Similarly, positive correlations between antioxidant activity and cadmium stress tolerance are also reported in the beneficial microorganisms treated maize. For instance, Bacillus pumilus positively affected cadaverous maize by enhancing the physiological defence and mitigating cadaver-induced stress injury (Shahzad et al., 2021).

The correlation between MDA and extraction efficiency was negative, suggesting that less oxidative damage was beneficial for plant response to cadmium stress. In this relationship, it was interpreted that the remediation was successful if the plant could accumulate cadmium but not cause significant physiological damage. Cadmium stress studies have also revealed that Cadmium affects growth and physiological traits, such as oxidative stress indicators and antioxidant responses, that are responsible for the capacity of plants to tolerate Cadmium (Zhao et al., 2021).

AG1 showed the best treatment in the integrated treatment ranking due to having the highest total biomass, the highest shoot Cd concentration, the highest extraction efficiency, the highest CAT activity, and a lower MDA than the remaining treatments. In this integrated response, anatomical growth, physiological defense, and the extraction of cadmium were found to be functionally connected. Additionally, recent studies on maize indicated that ZnO nanoparticles have the ability to mitigate cadmium-induced toxicity by regulating certain primary metabolites and antioxidant activities, highlighting the need for multi-level responses for Cd tolerance (Hussain et al., 2024).

5. CONCLUSION

Clear anatomical and physiological changes were observed in the crop plants exposed to cadmium-contaminated soils as manifested in the treatment-wise differences in biomass, accumulation of cadmium, extraction efficiency, and activity of antioxidant enzymes, as well as lipid peroxidation. Anatomical responses occurred at the organ-growth level in terms of shoot biomass, root biomass, total biomass, and root–shoot allocation, and were highly noticeable in the amendment-based treatments relative to the control. Under Cadmium stress, the Physiological responses were confirmed by the decreased concentration of MDA and increment of the activity of SOD, CAT, and POD, indicating enhanced antioxidant defense. The best overall performance was observed for the treatment AG1, which led to a larger total biomass, shoot cadmium concentration, extraction efficiency, and CAT activity, and a smaller oxidative membrane damage. The results suggested that the simultaneous maintenance of the growth of the plants, their physiological tolerance, and their capacity to translocate the metal were important for the successful cadmium remediation. The dataset was adequate to assess the anatomical and physiological changes in maize due to heavy metal contamination, but future studies should include direct measurement of anatomical parameters using a microscope.

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