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Physiological and Morphological Response of Heavy Metal Stress in Vigna mungo (L.) Hepper

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ABSTRACT

Introduction: Heavy metals such as manganese (Mn), magnesium (Mg), chromium (Cr), and nickel (Ni) negatively impact plant growth and productivity. Understanding plant responses to heavy metal stress is crucial for developing strategies to mitigate these effects in agriculture.

Aim/Objectives: This study aims to investigate the impact of various heavy metals (Mn, Mg, Cr, and Ni) on the physiological and morphological responses of *Vigna Mungo* (L.) Hepper. Key objectives include evaluating the effects of different concentrations of these heavy metals on plant growth, productivity and photosynthetic efficiency.

Method/Materials: A field experiment was conducted using a series of pots filled with soil, treated with different concentrations of $MnCl_2$, $MgSO_4$, Cr_2O_3, and Ni. Control samples without heavy metals were also maintained. Key parameters, including plant height, number of branches, number of pods, pod length, fresh and dry weight of pods, number of seeds per pod, weight of 100 seeds, root nodules, and chlorophyll content, were recorded and statistically analysed.

Results: Heavy metal stress significantly inhibited plant growth and productivity, with decrease in plant height, number of branches, pods per plant, pod length, fresh and dry pod weight, and seeds per pod. High chromium concentrations prevented pod formation. Root nodules decreased, affecting nitrogen fixation. Chlorophyll content decreased in Mn, Ni, and Mg-treated plants but unexpectedly increased at higher Cr concentrations, indicating complex interactions with chlorophyll synthesis.

Discussion: The findings show that heavy metal stress significantly inhibits plant growth and productivity, consistent with previous studies. Symptoms such as stunting, and chlorosis indicate disruptions in metabolic processes. This study underscores the need to monitor and manage heavy metal levels in agricultural soils to protect crop health and productivity. Developing soil remediation strategies and heavy metal-tolerant plant varieties is crucial for sustainable agriculture. Further research is needed to understand plant responses to heavy metal stress and enhance plant tolerance.

Key Words: *V. Mungo*, Heavy metal stress, Physiological response, Morphological traits, Mn (Manganese), Cr (Chromium), Ni (Nickel), Mg (Magnesium), Soil contamination, Plant growth and development and Environmental pollution

INTRODUCTION

V. Mungo (L.) Hepper, commonly known as "Black gram," is a leguminous crop esteemed for its high protein content. This crop holds significant importance in Indian agriculture, seamlessly fitting into various cropping systems and serving as a vital protein source for the predominantly vegetarian population. Pulses like *V. mungo* are integral to sustainable agricultural practices due to their nitrogen-fixing ability, which enhances soil fertility and reduces the need for chemical fertilizers.

However, the presence of heavy metals in the growth media poses a substantial threat to plant health and productivity. Heavy metals such as lead (Pb^{2+}), magnesium (Mg^{2+}), and zinc (Zn^{2+}) can function as stressors, causing physiological constraints that diminish plant vigor and inhibit growth. When these metal ions are present at elevated levels in the environment, they are absorbed by plants and accumulate in various tissues, leading to reduced growth, impaired metabolism, and decreased dry matter production.[1] This accumulation disrupts almost all life processes of plants, from photosynthesis to nutrient uptake. Research by Dass D et al. [2] has shown that sewage water, often used for irrigation in some agricultural practices, contains toxic elements and heavy metals such as chromium (Cr), copper (Cu), zinc (Zn), manganese (Mn), lead (Pb), nickel (Ni), cadmium (Cd), cobalt (Co),

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and iron (Fe). While many of these elements are essential nutrients for plants, they become phytotoxic at higher concentrations, causing detrimental effects on plant health and development. Moreover, excessive uptake of heavy metals poses serious risks to human health, as they can cause carcinogenic and mutagenic effects.[3]

Understanding the impact of heavy metals on *V. Mungo* is crucial for developing strategies to mitigate their adverse effects and enhance crop resilience. This study aims to evaluate the physiological and morphological responses of *V. Mungo* to heavy metal stress, providing insights into the plant's adaptability and potential agricultural practices in contaminated environments. By investigating the specific changes induced by heavy metals, we can better comprehend their role in plant stress and devise effective management practices to ensure sustainable crop production.

MATERIALS AND METHODS

A field experiment was conducted using a series of pots filled with a mixture of garden soil and cow dung manure in a 3:1 ratio. To prevent soil contamination, the inner surface of each pot was lined with polythene sheeting. The soil was thoroughly dried before the addition of selected heavy metals at various concentrations per kilogram of soil. Pots without any added metals served as controls to compare the effects of metal exposure.

The concentrations of each heavy metal used in the study were as follows:

Manganese ($MnCl_2$): 5, 10, 20, 30, 40, 70, and 100 mg/kg of soil

Magnesium ($MgSO_4$): 50, 100, 200, 300, 400, and 500 mg/kg of soil

Chromium (Cr_2O_3): 5, 10, 20, 30, 50, 100, and 150 mg/kg of soil

Nickel (Ni): 5, 50, 100, 200, 300, 400, and 500 mg/kg of soil

Healthy and uniform seeds of *V. Mungo* were sterilized with 0.1% $HgCl_2$ solution and thoroughly rinsed with water to remove any residual mercury chloride. Ten seeds were sown in each pot, and three replicates were maintained for each treatment. Pots were irrigated twice daily to maintain soil moisture at field capacity. After five days of germination, plants were thinned to ensure uniform growth conditions.

At harvest, data was recorded on yield and yield attributes from ten tagged plants in each treatment. This setup allowed for the systematic evaluation of how varying concentrations of heavy metals affect the growth, development, and productivity of *V. Mungo*. The experiment was designed to provide insights into the physiological responses and morphological changes induced by different levels of metal contamination in the soil, contributing to the understanding of plant resilience and adaptation strategies in contaminated environments.

RESULTS

At the time of harvest, various growth and yield parameters of *V. Mungo* (L.) Hepper were recorded and statistically analyzed to assess the impact of different heavy metal treatments. The details were summarized below:

Table 1: Effect of Manganese on the biometrical and yield parameters of Black Gram at harvest

Concentration in mg/kg	Plant Height	Average No. of branches	No. of Pods	Length of Pods	Fresh weight of pods (g)	Dry weight of pods (g)	No. of Seeds / Pod	Weight of Seeds (g)	No. of root nodules
Control	32.0 + 0.078	3.95 + 0.162	7.9 + 0.294	5.57 + 0.268	14.7 + 0.132	9.1 + 0.019	6.02 + 0.014	4.0 + 0.126	30.5 + 0.092
5	17.0 + 0.278	4.35 + 0.028	4.1 + 0.026	3.8 + 0.162	3.47 + 0.182	2.1 + 0.016	2.7 + 0.088	2.8 + 0.016	24.2 + 0.664
50	16.7 + 0.281	4.47 + 0.016	3.2 + 0.016	3.4 + 0.860	3.21 + 0.186	2.1 + 0.018	2.7 + 0.088	2.4 + 0.083	22.4 + 0.983
100	16.3 + 0.075	3.92 + 0.098	2.4 + 0.126	2.6 + 0.019	2.5 + 0.018	1.9 + 0.386	2.4 + 0.065	2.2 + 0.064	22.4 + 0.983
200	16.1 + 0.089	3.83 + 0.026	2.2 + 0.145	2.4 + 0.018	2.5 + 0.018	1.8 + 0.342	2.2 + 0.093	2.1 + 0.076	21.6 + 0.897
300	15.5 + 0.278	3.52 + 0.083	1.8 + 0.368	2.2 + 0.116	2.2 + 0.126	1.8 + 0.342	1.3 + 0.245	2.0 + 0.080	20.2 + 0.282
400	15.1 + 0.281	3.40 + 0.064	1.8 + 0.368	1.8 + 0.123	2.1 + 0.128	1.4 + 0.465	1.2 + 0.262	1.8 + 0.326	20.2 + 0.282
500	14.6 + 2.210	3.20 + 0.065	1.2 + 0.384	1.8 + 0.123	1.5 + 0.268	1.6 + 0.004	1.2 + 0.262	1.8 + 0.326	19.1 + 1.092

Table 2: Effect of Chromium on the biometrical and yield parameters of Black gram at harvest

Concen-tration in mg/kg	Plant Height	Average No. of branches	No. of Pods	Length of Pods	Fresh weight of pods (g)	Dry weight of pods (g)	No. of Seeds / Pod	Weight of Seeds (g)	No. of root nodules
Control	32.0 + 0.078	3.95 + 0.162	7.9 + 0.294	5.57 + 0.268	14.7 + 0.132	9.1 + 0.019	6.02 + 0.014	4.0 + 0.126	30.5 + 0.092
5	30.0 + 0.085	5.20 + 0.193	3.4 + 0.059	2.4 + 0.026	3.52 + 0.189	2.1 + 0.019	3.4 + 0.084	2.8 + 0.029	20.2 + 0.048
10	31.6 + 0.082	4.80 + 0.096	3.2 + 0.025	1.4 + 0.184	3.4 + 0.196	2.02 + 0.028	3.2 + 0.064	2.4 + 0.072	16.4 + 0.058
20	32.4 + 0.124	4.40 + 0.014	2.6 + 0.135	1.4 + 0.183	3.2 + 0.168	1.9 + 0.368	2.6 + 0.132	1.4 + 0.316	15.2 + 0.063
30	33.6 + 0.106	3.80 + 0.064	1.2 + 0.346	1.2 + 0.142	2.4 + 0.028	1.6 + 0.482	2.2 + 0.134	1.4 + 0.316	12.1 + 0.326
50	34.8 + 0.282	3.20 + 0.072	0.4 + 0.006	1.2 + 0.142	2.2 + 0.084	1.2 + 0.162	1.8 + 0.262	1.1 + 0.264	12.1 + 0.326
100	35.2 + 0.220	2.90 + 0.026	-	-	-	-	-	-	10.4 + 0.076
150	35.4 + 0.282	2.71 + 0.360	-	-	-	-	-	-	10.4 + 0.076

Mean + standard error

Table 3: Effect of Nickel on the biometrical and yield parameters of Black gram at harvest

Concen-tration in mg/kg	Plant Height	Average No. of branches	Average No. of Pods per plant	Average Length of Pods (cm)	Average Fresh weight of pods (g)	Aver-age Dry weight of pods (g)	Average No. of Seeds / Pod	Average Weight of 100 Seeds (g)	No. of root nodules
Control	32.0 + 0.-78	3.95 + 0.294	7.9 + 0.294	5.57 + 0.268	14.7 + 0.132	9.1 + 0.019	6.02 + 0.014	4.0 + 0.126	30.5 + 0.092
5	30.0 + 0.765	4.20 + 0.286	6.7 + 0.286	5.4 + 0.272	13.4 + 0.054	8.2 + 0.018	5.2 + 0.011	3.7 + 0.181	24.5 + 0.152
50	29.5 + 0.489	3.96 + 0.016	5.6 + 0.362	5.2 + 0.268	13.2 + 0.068	8.1 + 0.020	5.0 + 0.026	3.4 + 0.172	23.4 + 0.283
100	28.6 + 0.856	3.80 + 0.036	5.4 + 0.345	4.4 + 0.226	12.6 + 0.049	7.2 + 0.268	4.9 + 0.016	3.2 + 0.164	23.4 + 0.287
200	24.9 + 0.078	3.42 + 0.076	4.9 + 0.196	4.2 + 0.216	12.4 + 0.072	6.5 + 0.014	4.6 + 0.039	2.8 + 0.029	22.1 + 0.321
300	23.4 + 0.083	3.34 + 0.065	4.8 + 0.126	3.8 + 0.196	12.2 + 0.086	5.9 + 0.018	3.9 + 0.136	2.6 + 0.086	21.6 + 0.396
400	23.1 + 0.136	3.28 + 0.064	3.2 + 0.026	3.2 + 0.182	11.9 + 0.039	5.4 + 0.026	3.6 + 0.132	2.4 + 0.072	20.2 + 0.238
500	22.8 + 0.162	2.91 + 0.082	2.4 + 0.135	2.8 + 0.018	11.2 + 0.034	4.8 + 0.064	2.4 + 0.268	2.2 + 0.068	18.3 + 0.426

1. **Plant Height:** Plant height above ground level was measured for all treatment groups. Control samples, which did not receive any heavy metal treatments, showed an average plant height of 32 cm. Plants treated with manganese (Mn), nickel (Ni), and magnesium (Mg) generally exhibited a gradual decrease in height as the concentration of these metals increased. In contrast, plants treated with chromium (Cr) showed an increase in plant height, reaching an average of 35.4 cm (Table 4).
2. **Average Number of Branches:** The formation of branches was assessed to understand the branching pattern under different heavy metal treatments. Control plants displayed an average of 3.95 branches per plant. Lower concentrations of Mn, Cr, Ni, and Mg tended to promote branching compared to the control, while higher concentrations often led to a reduction in the number of branches formed (Tables 1, 2, 3, 4).
3. **Number of Pods:** The total number of pods per plant was counted at harvest. Results showed varying trends across different heavy metal treatments, reflecting the influence of metal toxicity on pod formation.
4. **Length of Pods:** The length of pods was measured to evaluate the effect of heavy metals on pod development. Differences in pod length were observed among treatments, indicating potential impacts on reproductive growth.
5. **Fresh Weight of Pods (g):** Fresh weights of pods were recorded to assess the overall biomass accumulation in terms of pod production under different treatments.
6. **Dry Weight of Pods (g):** Dry weights of pods were measured after drying to a constant weight, providing insights into biomass productivity and the potential impacts of heavy metals on plant metabolism.
7. **Number of Seeds per Pod:** The average number of seeds per pod was determined to evaluate the reproductive output and seed development under varying metal concentrations.
8. **Weight of 100 Seeds:** The weight of 100 seeds was measured to assess seed quality and the potential impacts of heavy metals on seed development.

Table 4: Effect of Magnesium on the biometrical and yield parameters of a Black gram at harvest

Concentration in mg/kg	Plant Height	Average No. of branches	No. of Pods	Length of Pods	Fresh weight of pods (g)	Dry weight of pods (g)	No. of Seeds / Pod	Weight of Seeds (g)	No. of root nodules
Control	32.0 + 0.078	3.95 + 0.162	7.9 + 0.294	5.57 + 0.268	14.7 + 0.132	9.1 + 0.019	6.02 + 0.014	4.0 + 0.126	30.5 + 0.092
5	30.5 + 0.296	6.80 + 0.018	6.2 + 0.292	5.2 + 0.284	13.2 + 0.032	8.4 + 0.018	5.4 + 0.016	3.8 + 0.192	25.2 + 0.713
50	29.4 + 0.152	5.40 + 0.082	5.9 + 0.382	5.1 + 0.286	13.1 + 0.038	8.2 + 0.028	5.2 + 0.028	3.7 + 0.126	24.1 + 0.172
100	28.6 + 0.148	4.80 + 0.072	5.2 + 0.356	4.7 + 0.201	12.9 + 0.034	7.6 + 0.272	4.9 + 0.019	3.4 + 0.184	24.1 + 0.172
200	27.2 + 0.837	3.60 + 0.039	4.7 + 0.182	4.4 + 0.214	12.6 + 0.026	7.2 + 0.282	4.8 + 0.022	2.9 + 0.096	21.2 + 0.166
300	26.4 + 0.075	3.50 + 0.047	4.4 + 0.169	3.8 + 0.186	12.4 + 0.072	6.4 + 0.016	4.7 + 0.036	2.7 + 0.082	20.2 + 0.136
400	25.2 + 0.083	3.40 + 0.078	4.2 + 0.136	3.7 + 0.189	11.7 + 0.042	6.1 + 0.029	3.9 + 0.142	2.2 + 0.083	18.1 + 0.056
500	24.2 + 0.052	2.91 + 0.086	4.1 + 0.142	3.2 + 0.172	11.4 + 0.036	5.9 + 0.069	3.6 + 0.165	2.2 + 0.064	16.1 + 0.036

Mean ± standard error

Table 5: Effect of Heavy Metals on Chlorophyll Content in *V. Mungo*

Parameter	Control	Mn ($MnCl_2$)	Mg ($MgSO_4$)	Cr (Cr_2O_3)	Ni
Plant Height (cm)	32	Decreased	Decreased	35.4	Decreased
Avg. No. of Branches	3.95	Variable	Variable	Variable	Variable
Number of Pods per Plant	7.96	Decreased	Decreased	Decreased (no pods at100 & 150 mg/kg)	Decreased
Length of Pods (cm)	5.57	Decreased	Decreased	Decreased	Decreased
Fresh Weight of Pods (g)	14.7	Decreased	Decreased	Decreased	Decreased
Dry Weight of Pods (g)	9.1	Decreased	Decreased	Decreased	Decreased
No. of Seeds per Pod	6.02	Decreased	Decreased	Decreased	Decreased
Weight of 100 Seeds (g)	4	Decreased	Decreased	Decreased	Decreased
No. of Root Nodules	30.5	Decreased	Decreased	Decreased	Decreased
Chlorophyll a (mg/g)	0.68	Decreased	Decreased	Variable	Decreased
Chlorophyll b (mg/g)	0.72	Decreased	Decreased	Variable	Decreased

Table 6: Effect of Mn, Ni, Cr, Mg on chlorophyll content of V. mungo

Concentrations in mg/L				Chlorophyll 'a' content	Chlorophyll 'b' content	Total chlorophyll
Mn	Ni	Cr	Mg			
Control				0.68	0.72	1.40
5	-	-	-	0.38	0.54	0.92
10	-	-	-	0.36	0.52	0.88
20	-	-	-	0.32	0.51	0.83
30	-	-	-	0.29	0.39	0.68
40	-	-	-	0.27	0.38	0.65
70	-	-	-	0.25	0.37	0.62
100	-	-	-	0.22	0.35	0.59
-	5	-	-	0.67	0.70	1.37
-	50	-	-	0.63	0.68	1.31
-	100	-	-	0.50	0.65	1.15
-	200	-	-	0.39	0.57	0.96
-	300	-	-	0.28	0.45	0.75
-	400	-	-	0.26	0.35	0.61
-	500	-	-	0.22	0.32	0.54

Table 6: *(Continued)*

Concentrations in mg/L				Chlorophyll 'a' content	Chlorophyll 'b' content	Total chlorophyll
Mn	Ni	Cr	Mg			
-	-	5	-	0.67	0.70	1.30
-	-	10	-	0.67	0.70	1.30
-	-	20	-	0.68	0.72	1.40
-	-	30	-	0.70	0.73	1.43
-	-	50	-	0.72	0.75	1.47
-	-	100	-	0.73	0.76	1.49
-	-	150	-	0.74	0.78	1.52
-	-	-	5	0.68	0.72	1.40
-	-	-	50	0.68	0.72	1.40
-	-	-	100	0.70	0.75	1.45
-	-	-	200	0.67	0.70	1.37
-	-	-	300	0.58	0.65	1.23
-	-	-	400	0.43	0.55	0.98
-	-	-	500	0.35	0.47	0.82

Additionally, chlorophyll content was analyzed at the flowering stage to understand any physiological changes induced by heavy metal stress.

Statistical analyses were performed to validate the differences observed among treatments, ensuring a robust interpretation of the experimental results. These findings contribute to our understanding of how heavy metal contamination in soil can affect the growth, development, and yield of *V. mungo*, highlighting potential implications for agricultural practices and environmental management strategies.

Number of Root Nodules: The average number of root nodules in control samples was recorded at 30.5 during the flowering stage. In samples treated with various heavy metals, the number of root nodules decreased as the concentration of the metals increased. This indicates a negative impact of heavy metal stress on the nodulation process, which is crucial for nitrogen fixation in leguminous plants like *V. mungo*.

Chlorophyll Content: Chlorophyll content was measured in terms of chlorophyll a and b at the flowering stage. Control samples showed chlorophyll a and b concentrations of 0.68 and 0.72 respectively (Table 5). The results for treated samples are summarized below:

- Mn, Ni, and Mg Treated Samples: The chlorophyll content (both a and b) gradually decreased with increasing concentrations of these heavy metals. This trend was observed consistently across all concentrations tested. The reduction in chlorophyll content reflects the negative impact of Mn, Ni, and Mg stress on the photosynthetic efficiency of the plants.
- Cr Treated Samples: A different trend was observed with chromium treatments. In lower concentrations of Cr (5, 10, and 20 mg/kg), there was a gradual decrease in chlorophyll content. However, at higher concentrations, there was an unexpected increase in chlorophyll a and b levels, surpassing the control samples. This anomaly suggests a complex interaction between chromium and the chlorophyll synthesis pathway.

The detailed chlorophyll content data is presented in Table 5 and illustrated in Figure 1

Summary of Findings

- Plant Height: Decreased in Mn, Ni, and Mg treated samples; increased in Cr treated samples.
- Average Number of Branches: Increased at lower concentrations and decreased at higher concentrations of heavy metals.
- Number of Pods per Plant: Decreased in all heavy metal treated samples, with no pods at the highest Cr concentrations.
- Length of Pods: Decreased in all heavy metal treated samples.
- Fresh and Dry Weight of Pods: Both weights decreased in all heavy metal treated samples.
- Number of Seeds per Pod: Decreased in all heavy metal treated samples.
- Weight of 100 Seeds: Decreased in all heavy metal treated samples.
- Number of Root Nodules: Decreased with increasing concentrations of all heavy metals.
- Chlorophyll Content: Decreased with increasing concentrations of Mn, Ni, and Mg. An increase was noted in higher concentrations of Cr treated samples after an initial decrease at lower concentrations.(Table 6)

DISCUSSION

This study revealed significant effects of heavy metals on the physiological and morphological parameters of *V. Mungo.* Hepper. Our findings align with previous research on the impact of heavy metal toxicity on plant growth and development.

Variation in Plant Traits: High variation in the number of branches per plant and pods per plant has been reported in green gram by [4, 5,6,7] noted high heritability for plant height and pods per plant[8] emphasized that heritability combined with genetic advancement is more reliable for predicting the effect of selection. Our study supports these findings as we observed significant variation and heritability in the traits measured, particularly in response to heavy metal treatments.

Impact of Heavy Metals on Root Nodules and Nitrogen Fixation: [9] observed that higher concentrations of cadmium (Cd) are associated with changes in the ultrastructure of root nodules, leading to a reduction in the effective N_2-fixing area and a decrease in N_2-fixing cells. Similarly, our study found a decrease in the number of root nodules with increasing concentrations of heavy metals, indicating a negative impact on nitrogen fixation.

Effects of Iron and Other Heavy Metals [10]: noted the effects of higher iron concentrations in soybeans, while [11] reported significant character associations for pods per plant, pod length, seeds per pod, and seed weight at both phenotypic and genotypic levels [12], and [13] found similar results in mung bean. Our study also observed that higher concentrations of heavy metals, including iron, acted as inhibitory to plant growth, supporting the findings of [14] regarding the effects of higher metal concentrations in plants (Fig-1).

Direct Effects on *V. Mungo*: High direct effects on *V. Mungo* for pods per plant and days to flowering were reported by [15], for pod length and days to flowering by [16], and for pod length and pods per plant by [17]. Our findings are consistent with these studies, showing significant impacts on these traits under heavy metal stress.

Chlorophyll Content and Photosynthesis: The decrease in chlorophyll content with zinc (Zn) treatment observed in our study might be due to the toxic effect of Zn on chlorophyll biosynthesis, as reported by [18]. High concentrations of chromium also resulted in a decrease in total chlorophyll content, indicating chromium toxicity [19] described the general symptoms of metal phytotoxicity as stunting and chlorosis [20] suggested that the reduction in chlorophyll content and subsequent growth reductions in *Vigna radiata* might be due to changes in various metabolic processes, including photosynthesis, caused by the accumulation and deposition of chromium in the roots.

Recent studies have focused on the impact of cadmium (Cd) and lead (Pb) on the growth and yield of *V. mungo.* Research conducted by [21] demonstrated that both Cd and Pb significantly reduced plant height, number of pods, and overall yield. The study highlighted that Cd was particularly detrimental, causing a more pronounced reduction in chlorophyll content and photosynthetic efficiency compared to Pb. The presence of these heavy metals also impaired root development and decreased the number of nodules, adversely affecting nitrogen fixation.

A study by [22] explored the use of biochar as a soil amendment to mitigate the effects of heavy metal stress in *V. mungo.* The results indicated that biochar application improved soil properties, enhanced plant growth, and increased chlorophyll content. The study found that biochar could adsorb heavy metals, reducing their bioavailability and toxicity. This led to better root growth, increased number of pods, and improved yield. The research suggests that biochar could be an effective strategy for managing heavy metal contamination in agricultural soils.

Recent research by Kumar M et al.[23] investigated the antioxidant enzyme responses of *V. mungo* to heavy metal stress. The study revealed that heavy metal exposure, particularly to chromium (Cr) and nickel (Ni), induced oxidative stress in plants, as evidenced by increased levels of reactive oxygen species (ROS). In response, the activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) were significantly elevated. The enhanced antioxidant enzyme activity was seen as a protective mechanism to counteract the oxidative damage caused by heavy metals.

A study conducted by Patel K et al.[24] assessed the phytoremediation potential of *V. mungo* for soils contaminated with multiple heavy metals. The research indicated that *V. mungo* has a moderate ability to accumulate heavy metals in its tissues, particularly in the roots. The study also found that the application of chelating agents like EDTA could enhance the uptake of heavy metals, making *V. mungo* a promising candidate for phytoremediation. However, the biomass yield was reduced under heavy metal stress, suggesting a trade-off between phytoremediation efficiency and plant growth.

Advances in genetic and molecular research have provided insights into the mechanisms underlying heavy metal tolerance in *V. mungo.* Recent work by Sharma A et al.[25] employed transcriptomic analysis to identify genes involved in heavy metal stress response. The study identified several genes related to metal transport, detoxification, and stress signalling pathways that were upregulated in response to heavy metal exposure. Understanding these molecular mechanisms could aid in developing genetically engineered varieties of *V. mungo* with enhanced tolerance to heavy metal stress.

These recent studies underscore the significant impact of heavy metal stress on *V. mungo* and highlight potential strategies for mitigation and management. Continued research is essential to develop effective approaches for enhancing the resilience of *V. mungo* and other crops in heavy metal-contaminated environments.

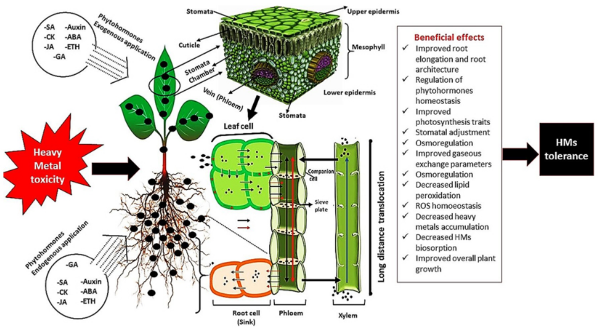

Figure 1: Role of phytohormones in heavy metal tolerance in plants:

CONCLUSION

This study investigated the impact of various heavy metals (Mn, Mg, Cr, and Ni) on the physiological and morphological responses of *V. mungo* (L.) Hepper. The findings highlight several critical aspects of heavy metal toxicity in plants and its implications for agricultural practices.

1. Plant Growth and Development:

Heavy metal stress led to a significant decrease in plant height, the number of branches, the number of pods per plant, pod length, fresh and dry weight of pods, and the number of seeds per pod. This indicates that heavy metal contamination severely inhibits plant growth and productivity. Notably, chromium at higher concentrations (100 and 150 mg/kg) resulted in no pod formation, underscoring its phytotoxic effects.

2. Root Nodulation and Nitrogen Fixation:

The average number of root nodules decreased with increasing concentrations of all heavy metals, indicating a detrimental effect on the plant's ability to fix nitrogen. This reduction in root nodulation can significantly affect soil fertility and plant health.

3. Chlorophyll Content and Photosynthesis:

The chlorophyll content (both chlorophyll a and b) decreased with increasing concentrations of Mn, Ni, and Mg, impacting the plant's photosynthetic efficiency.

An exception was noted with chromium, where higher concentrations led to an unexpected increase in chlorophyll content after an initial decrease at lower concentrations. This suggests a complex interaction between chromium and chlorophyll synthesis pathways.

4. Genetic Variability and Heritability:

The study corroborates previous findings on high variability and heritability for traits such as plant height and pods per plant, emphasizing the genetic influence on plant responses to heavy metal stress.

5. Toxicity Symptoms and Plant Metabolism:

The general symptoms of heavy metal toxicity observed included stunting, chlorosis, and reduced chlorophyll content. These symptoms are indicative of disruptions in various metabolic processes, including photosynthesis, due to the accumulation of heavy metals in plant tissues.

Implications for Agriculture

The results underscore the importance of monitoring and managing heavy metal concentrations in agricultural soils to prevent adverse effects on crop health and productivity. Strategies such as soil remediation, crop rotation, and the use of heavy metal-tolerant plant varieties could be essential in mitigating the impact of heavy metal contamination.

Future Research

Further research is needed to explore the mechanisms underlying the differential responses of plants to various heavy metals and to develop effective strategies for enhancing plant tolerance to heavy metal stress. Understanding these mechanisms can contribute to improving crop resilience and ensuring sustainable agricultural practices in environments contaminated with heavy metals.

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