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Effect of Cadmium on the Growth and Physiology of Paddy (*Oryza sativa L.*) Plants

Dr. Pratibha Srivastava
Assistant Professor in Botany, Govt. Raza P. G. College, Rampur, India

ABSTRACT

Cadmium (Cd) pollution in agricultural soils has emerged as a critical environmental concern, particularly for rice cultivation, due to its detrimental effects on plant development, physiological functions, and overall productivity. Since rice is an essential meal for a large percentage of people worldwide, it is crucial to comprehend how the plant reacts to cadmium stress in order to ensure food security for sustainable agriculture. This study investigates the physiological and growth responses of three widely cultivated Indian rice varieties—IR64, Swarna, and BPT 5204—under varying levels of cadmium exposure (0, 1, 2, and 3 mg/L). The objective is to analyze how these cultivars respond to different concentrations of Cd, with particular attention to growth parameters, cadmium accumulation in plant tissues, dry biomass, tolerance index, and nutrient uptake efficiency.The experimental results indicate that Cd exposure leads to a dose-dependent reduction in plant growth and physiological performance in all three rice varieties. Significant declines were observed in dry weight and overall plant vigor, particularly at higher Cd concentrations. However, notable differences were recorded in the degree of tolerance among the cultivars. Among the tested varieties, BPT 5204 showed comparatively greater resilience to Cd toxicity, exhibiting less reduction in dry weight and higher tolerance index values across the tested concentrations. In contrast, IR64 proved to be more vulnerable, with considerable buildup of Cd in both shoots and roots, accompanied with severe growth restriction. Additionally, cadmium stress disrupted the nutritional balance and further hampered plant growth and metabolism by negatively affecting the uptake of vital minerals like potassium (K), phosphorus (P), and nitrogen (N). The interference of Cd with nutrient transport mechanisms suggests a critical interaction that exacerbates toxic effects of heavy metals. Pattern of Cd accumulation also varied among the varieties, with higher concentrations typically sequestered in roots rather than shoots, indicating a possible defence mechanism to restrict Cd translocation to aerial parts and grains.This varietal variation in response to cadmium exposure has significant implications for rice breeding and crop improvement programs. Identifying and promoting cultivars with intrinsic tolerance mechanisms can be an effective strategy for mitigating the effects of Cd-contaminated environments. The results of this study highlight the need for more research into creating stress-resilient rice cultivars and offer significant insights regarding physiological & biochemical underpinnings of cadmium tolerance in rice. Future breeding programs can improve the sustainability and security of rice production in areas impacted by Cd by combining physiological screening with molecular & genetic techniques.In conclusion, the differential responses of IR64, Swarna, and BPT 5204 to cadmium stress highlight the potential for varietal selection in improving crop performance under heavy metal stress. Such efforts are essential for safeguarding agricultural productivity and protecting human health from heavy metal accumulation in food crops.

Keywords : Cadmium toxicity, Rice varieties, Physiological response, Heavy metals, Tolerance index, Oryza sativa.

1. Introduction- Worldwide, agricultural ecosystems are seriously threatened by the extremely hazardous, non-essential heavy element cadmium (Cd). It is widely recognized for its persistence in soils and its ability to

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interfere with plant physiological and biochemical processes. The increasing levels of Cd contamination in agricultural fields are primarily attributed to anthropogenic activities such as mining, industrial discharges, the application of phosphate-based fertilizers, sewage sludge, and wastewater irrigation. Over time, these activities have led to the accumulation of cadmium in arable soils, with concentrations often surpassing the permissible thresholds set by international regulatory bodies. As a result, Cd contamination has become a growing concern for food safety, agricultural productivity, and environmental sustainability.

More than half of the world's population, especially in Asia, depends on rice (Oryza sativa L.), one of the most extensively grown cereal crops, as a staple diet. In India, rice cultivation plays a critical role in food security, rural livelihoods, and economic development. However, rice plants are especially vulnerable to cadmium contamination due to their cultivation in submerged or flooded conditions. The bioavailability and solubility of Cd are enhanced by these anaerobic soil conditions, which makes it easier for rice roots to absorb it and for it to go to aerial portions, such as edible grains. Because prolonged exposure to cd is known to result in bone demineralization, kidney damage, and other serious health conditions in humans, the introduction of cadmium into the food chain through rice consumption has consequently created considerable public health concerns.At the plant level, cadmium stress manifests in a multitude of ways. It disrupts key physiological processes such as photosynthesis, respiration, and transpiration. Cd interferes with chlorophyll biosynthesis, damages photosynthetic apparatus, and reduces CO_2 assimilation rates, thereby limiting energy production and plant biomass accumulation. Furthermore, cadmium interferes with the intake and homeostasis of vital minerals that are necessary for the development and growth of plants, including potassium (K), phosphorus (P), and nitrogen (N). Additionally, it alters a number of enzymatic processes and causes oxidative stress by producing reactive oxygen species (ROS), which results in DNA breakage, membrane damage, and protein denaturation.

Despite the widespread implications of cadmium toxicity in rice, there exists considerable genetic variation among rice genotypes in terms of their tolerance and ability to accumulate or exclude cadmium. Some rice varieties exhibit innate mechanisms such as Cd sequestration in root vacuoles, reduced translocation to shoots and grains, and enhanced antioxidant defense systems. Exploring these varietal differences is vital for identifying and promoting Cd-tolerant cultivars, which can serve as potential candidates in breeding programs aimed at developing low-Cd accumulating rice lines. Such efforts are essential for maintaining rice productivity in contaminated regions and minimizing the health risks associated with dietary cadmium intake.In this context, the present study was designed to evaluate the growth and physiological responses of three popular Indian rice varieties—IR64, Swarna, and BPT 5204—under varying cadmium stress levels. These varieties are widely cultivated across India and possess distinct agronomic traits. The specific objectives of the study were to assess the extent of Cd accumulation in plant tissues (roots, shoots, and grains), evaluate changes in dry biomass and tolerance indices, and analyze the impact of Cd on nutrient uptake. The findings are expected to contribute to a better understanding of varietal differences in cadmium tolerance and provide a foundation for future breeding strategies focused on developing cadmium-resilient rice cultivars.

2. Literature Review

Llamas Andreu et al., (2000): The study investigates the adverse effects of cadmium (Cd^{2+}) on rice root physiology, focusing on nutrient acquisition mechanisms. Exposure to 0.1 or 1 mM Cd^{2+} led to rapid depolarization of root cell membranes, with recovery within 6–8 hours. Notably, 1 mM Cd^{2+} inhibited root respiration after 2 hours, lasting up to 4 hours. Cd^{2+} also increased membrane permeability, causing sustained potassium (K^+) efflux for at least 8 hours. These physiological disruptions are closely linked to the observed decline in essential mineral nutrient content in Cd^{2+}-treated plants, emphasizing the metal's negative impact on nutrient uptake and root functionality.

Adhikari Tapan et al. (2006): This study investigates varietal differences in cadmium (Cd) uptake and distribution in rice (Oryza sativa) through nutrient-solution experiments using 'Khitish' and 'CNRH3' genotypes under varying pCd and pFe levels. The results revealed that Cd exposure significantly reduced plant growth and yield, with 'Khitish' showing higher sensitivity. Root Cd uptake exceeded shoot uptake, and higher Cd levels decreased the absorption of other essential metals. Cd toxicity also impaired chlorophyll content and enzyme activities (POD and SOD), with early enzyme responses indicating potential biomarkers of Cd stress. Genotypic differences in Cd accumulation suggest the potential for breeding low-Cd-accumulating rice varieties.

Rizk A. H., et. al., (2014): A sand culture experiment conducted at Al-Azhar University in May 2013 examined the impact of varying cadmium (Cd) concentrations (1.00, 2.00, and 3.00 mg/L) on the growth, nutrient content, and tolerance index of four rice varieties—Sakha 106, Sakha 104, Giza 177, and Giza 178. Results showed that lower Cd concentrations led to higher dry matter yields in roots, shoots, and grains, while Cd uptake increased with concentration, particularly in roots. Cadmium exposure significantly reduced nitrogen, potassium, and micronutrient content in plant tissues. Grain yield declined with increasing Cd levels. Giza 178 showed better tolerance at lower Cd levels, while Sakha 104 performed best at the highest concentration.

3. Materials and Methods

A controlled pot experiment was carried out in a greenhouse setting to look into how cadmium affected the physiology and growth of rice plants. Study was carried out using three widely grown Indian rice varieties: IR64, Swarna, and BPT 5204. These varieties were selected based on their agronomic relevance, wide adoption by farmers, and potential genetic diversity in response to abiotic stress.

Experimental Design and Cadmium Treatments

The experiment was laid out in a completely randomized design (CRD) with four levels of cadmium treatment:

- **Control (0 mg/L Cd)**
- **Low Cd (1 mg/L)**
- **Moderate Cd (2 mg/L)**
- **High Cd (3 mg/L)**

Cadmium was administered in the form of cadmium chloride ($CdCl_2$), which was thoroughly mixed into the irrigation water and applied to the pots containing rice plants throughout the growing season. The cadmium concentrations were selected based on literature-reported thresholds known to induce physiological responses in rice without causing immediate plant death. Each treatment was replicated three times for each variety to ensure statistical accuracy and reproducibility.

Plant Growth Conditions

Rice seeds of the three selected varieties were surface-sterilized and sown in earthen pots filled with homogenized, uncontaminated loamy soil. Uniform seedlings were transplanted after two weeks and grown under natural light conditions with regular watering to maintain field capacity. The pots were housed in a greenhouse with semi-controlled climatic conditions, with daytime temperatures between 28 and 35°C and nighttime temperatures between 20 and 25°C. Standard dosages of nitrogen (N), phosphorous (P), and potassium (K) were applied to the plants in order to guarantee proper nutrition and rule out nutritional deficiencies as a contributing cause.

Sampling and Measurement of Growth Parameters

At the flowering stage (approximately 60–70 days after transplanting), plants were carefully uprooted and washed to remove soil particles. Dry weight (D.W.) of each plant (including roots and shoots) was recorded after oven-drying at 70°C until constant weight was achieved. Dry weight was used as a primary indicator of growth performance under cadmium stress.

The relative value (R.V.) was calculated for each treatment by comparing the dry weight of Cd-treated plants to the corresponding control. The tolerance index (TI) was then derived using the following formula:

$$TI = \left(\frac{D.W.cd - treated}{D.W.control} \right) \times 100$$

This index provided a quantitative estimate of each variety's tolerance to cadmium exposure.

Determination of Cadmium Accumulation

To assess cadmium uptake and accumulation, plant tissues were separated into roots, shoots, and grains (where applicable), dried, and ground into fine powder. Samples were then digested using a mixture of nitric acid and perchloric acid, and the cadmium concentration was measured using Atomic Absorption Spectroscopy (AAS). This analysis enabled quantification of Cd distribution within different plant organs and identification of potential varietal differences in metal translocation.

Nutrient Content Analysis

The concentrations of essential macronutrients—nitrogen (N), phosphorus (P), and potassium (K)—in plant tissues were also analyzed to evaluate the impact of cadmium on nutrient uptake.

- **Nitrogen content** was estimated using the Kjeldahl method,
- The vanadomolybdate yellow method was used to determine **phosphorus**colorimetrically, and
- **Potassium** was measured using flame photometry.

These measurements provided insights into the interaction between cadmium toxicity and plant nutritional status.

4. Results and Discussion

4.1. Cadmium Uptake and Accumulation

Cadmium (Cd) accumulation in rice plants exhibited a concentration-dependent pattern, where higher external Cd levels led to correspondingly greater Cd uptake. Across all three varieties—IR64, Swarna, and BPT 5204—the trend in Cd distribution followed a consistent hierarchy: roots > shoots > grains. This finding aligns with previous research and reflects the plant's intrinsic strategy to limit Cd translocation to aerial tissues, particularly the edible grains. By sequestering Cd predominantly in the roots, the rice plants deploy a detoxification mechanism to minimize damage to critical photosynthetic organs and reproductive parts.

Among the three rice varieties studied, the highest Cd accumulation in roots was observed under the 3 mg/L treatment, with a marked difference from the 1 and 2 mg/L treatments. This suggests that as external Cd concentrations rise, the plant enhances its uptake capacity, possibly due to increased expression of metal transporters or altered membrane permeability. The restricted Cd levels in grains indicate the presence of internal barriers, such as the Casparian strip and transport proteins in nodes, which limit Cd mobility to seeds—a desirable trait for ensuring food safety.

Furthermore, the efficiency of Cd exclusion from grains varied across varieties, with BPT 5204 showing the lowest Cd content in grains, indicating a strong barrier to Cd translocation. This trait enhances the varietal suitability for cultivation in Cd-contaminated areas while maintaining grain quality and consumer safety.

4.2. Dry Weight and Tolerance Index

The effect of Cd stress on plant biomass was assessed through dry weight measurements at the flowering stage, providing a direct indicator of plant growth and health. A gradual decline in dry weight was observed with increasing Cd concentrations in all three rice varieties, but the extent of reduction varied significantly, highlighting genotypic differences in stress tolerance.

At 1 mg/L Cd, BPT 5204 retained 96.84% of its control biomass, indicating minimal impact and strong early-stage tolerance. Swarna and IR64 followed with 85.53% and 78.98%, respectively. At 2 mg/L Cd, the trend remained similar, with BPT 5204 maintaining a high tolerance index (82.53%) compared to Swarna (76.32%) and IR64 (64.97%).

However, under severe stress at 3 mg/L Cd, a notable shift occurred: Swarna exhibited the highest tolerance index (59.21%), surpassing both BPT 5204 (48.10%) and IR64 (43.31%). This shift suggests that Swarna may possess stress-responsive genetic mechanisms that become activated under extreme Cd exposure, such as enhanced antioxidant defense or upregulated detoxification pathways.

The tolerance index, calculated as the relative value (R.V.) of dry weight compared to control plants, serves as a quantitative measure of resilience under Cd stress. The data (Table 1) clearly demonstrate the superior adaptability of BPT 5204 under mild to moderate stress, while Swarna outperforms under high Cd levels, indicating stress-specific varietal resilience.

Table 1: Tolerance Indexes of Rice Varieties

Cd Treatment (mg/L)	IR64 (g/plant; R.V.)	Swarna (g/plant; R.V.)	BPT 5204 (g/plant; R.V.)
0 (Control)	7.85; 100%	7.60; 100%	7.90; 100%
1	6.20; 78.98%	6.50; 85.53%	7.65; 96.84%
2	5.10; 64.97%	5.80; 76.32%	6.52; 82.53%
3	3.40; 43.31%	4.50; 59.21%	3.80; 48.10%

4.3. Physiological and Nutrient Responses

Cd stress not only impacted biomass but also disrupted physiological functions critical to plant growth, particularly nutrient uptake. Essential macro-nutrients such as nitrogen (N), phosphorus (P), and potassium (K) showed a marked decline with increasing Cd concentrations. Cd interferes with nutrient transporters, competes for uptake sites, and alters root membrane integrity, thereby reducing nutrient availability.

Among the varieties, BPT 5204 showed better nutrient retention, especially under the 1 and 2 mg/L Cd treatments. This suggests that BPT 5204 might possess mechanisms that minimize Cd-induced damage to nutrient transport systems, such as enhanced expression of selective ion channels or antioxidant enzymes that protect membranes and maintain metabolic balance.

The reduction in nitrogen content under Cd stress likely affects chlorophyll synthesis and photosynthetic efficiency, while decreased phosphorus and potassium levels impair energy transfer and osmotic regulation, respectively. The combined effects manifest as stunted growth, leaf chlorosis, and reduced tillering.

Nevertheless, BPT 5204 managed to maintain relatively stable physiological performance, possibly due to its ability to compartmentalize Cd into vacuoles, thereby reducing cytotoxicity. Swarna's improved performance at higher Cd levels suggests inducible stress-response systems, such as enhanced root exudation or phytochelatin synthesis, that help in detoxification and nutrient retention.

4.4. Genotypic Variation in Cd Tolerance

The observed differences in Cd uptake, dry weight retention, and nutrient profiles across the rice varieties point toward genotypic variation in Cd tolerance mechanisms. These variations stem from multiple physiological and molecular factors:

- **Root uptake efficiency:** Some varieties may possess lower affinity transporters for Cd or more selective uptake mechanisms that favor essential nutrients over toxic metals.
- **Phytochelatin-mediated detoxification:**Phytochelatins are metal-binding peptides that chelate Cd and sequester it into vacuoles. Varieties like BPT 5204 and Swarna may produce higher levels of these compounds, enhancing their tolerance.
- **Compartmentalization capacity:** Efficient sequestration of Cd into roots and vacuoles reduces its availability to shoots and grains, lowering phytotoxic effects and food safety risks.
- **Antioxidant defense systems:** Varieties differ in their ability to counteract oxidative stress caused by Cd through enzymatic antioxidants like SOD, CAT, and APX.

These findings suggest that BPT 5204 and Swarna are promising candidates for cultivation in Cd-contaminated areas, with potential applications in breeding programs focused on heavy metal tolerance. Such varieties can be used as parents in cross-breeding efforts or as models for genomic studies to identify Cd-tolerance-related genes.

In conclusion, this study highlights the complex interplay between Cd toxicity and plant response mechanisms, with varietal differences offering insights into adaptive strategies. Through a combination of physiological assessments and metal accumulation analyses, BPT 5204 and Swarna emerge as resilient rice varieties capable of maintaining growth and productivity under Cd stress. These findings pave the way for future research on molecular markers of Cd tolerance, phytoremediation strategies, and development of safe, high-yielding rice cultivars for contaminated agroecosystems.

5. Conclusion

This study underscores the significant varietal differences in the growth and physiological responses of rice plants exposed to cadmium (Cd) stress. The findings highlight the variability in tolerance to Cd among the three rice varieties: IR64, Swarna, and BPT 5204. BPT 5204 exhibited remarkable tolerance at lower Cd concentrations (1 and 2 mg/L), maintaining relatively stable growth and nutrient uptake compared to the other varieties. This suggests that BPT 5204 is well-equipped to withstand mild to moderate Cd exposure, making it a strong candidate for cultivation in Cd-contaminated soils.On the other hand, Swarna demonstrated superior tolerance at higher Cd concentrations (3 mg/L). While its performance was not as optimal at lower concentrations, it outperformed BPT 5204 and IR64 under severe Cd stress, suggesting that Swarna has developed mechanisms that help it thrive under high Cd exposure. This adaptability to extreme conditions is critical in areas where Cd contamination is prevalent, and such varieties can offer insights into the genetic pathways that confer heavy metal resistance.The study also revealed that Cd accumulation in rice plants was predominantly confined to the roots, with minimal translocation to the shoots and grains. This root-centric sequestration of Cd is a key defense strategy employed by rice plants to mitigate the toxic effects of heavy metals. The reduced movement of Cd into the edible parts of the plant is crucial for maintaining food safety and ensuring the sustainability of rice cultivation in contaminated environments.

Overall, the results suggest that BPT 5204 and Swarna are promising candidates for use in breeding programs aimed at developing Cd-tolerant rice cultivars. Their distinct mechanisms of Cd tolerance, which likely involve processes such as phytochelatin synthesis, root exudation, and compartmentalization of Cd, provide valuable genetic material for enhancing resistance to heavy metal toxicity. Further research into the underlying molecular mechanisms will aid in the identification of key genes responsible for Cd tolerance, ultimately contributing to the development of rice varieties that can thrive in Cd-contaminated agricultural areas, ensuring both food security and environmental sustainability.

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