

Response Mechanism of Plants to Cadmium Pollution in Soil

Baichuan Jiang^{1,a,*}

¹*School of Life Sciences, Northeast Normal University, No. 5268, Renmin Street, Nanguan District, Changchun, China*

a. jiang4880@gmail.com

**corresponding author*

Abstract: Cadmium (Cd), as a widespread heavy metal pollutant in soil, has become one of the globally recognized contaminants due to its high toxicity and bioaccumulative properties. Soil cadmium pollution not only hinders the normal growth of plants but also poses a threat to human health through the food chain. Microbe-plant combined remediation is an essential approach for the treatment of heavy metal contamination in soil. Plants primarily respond to cadmium stress through intrinsic physiological and biochemical adjustments, including inhibiting cadmium absorption, promoting cadmium compartmentalization in vacuoles, and facilitating cadmium efflux from cells. Moreover, plants enhance their tolerance to cadmium through mechanisms such as the regulation of plant hormones. Gene expression regulation is the molecular mechanism underlying plant cadmium tolerance. To date, multiple resistance genes, transcription factors, and microRNAs involved in cadmium tolerance have been identified. Exogenous additives mitigate the effects of cadmium stress on plants by chemical adsorption, enhancing plant cadmium tolerance, and improving the physical and chemical properties of the soil, as well as the structure of soil microbial communities. Investigating the mechanisms by which plants respond to cadmium stress and exploring remediation measures for cadmium pollution will provide a basis for developing effective pollution control and remediation strategies.

Keywords: Environmental toxicology, resistance genes, cadmium stress

1. Introduction

Cadmium (Cd) is one of the most toxic heavy metal elements, posing a severe threat to plant growth and human health, with high mobility in the environment. The issue of cadmium pollution has become increasingly prominent in the process of industrialization and urbanization. Cadmium has wide applications in industries such as semiconductors, phosphors, nuclear reactors, aviation, navigation, mining, and metallurgy, leading to its inevitable release into the biosphere. Moreover, cadmium is also present in considerable quantities in phosphate fertilizers and sludge. These pollution sources contribute to the accumulation of cadmium in soil, where it is absorbed and transported by plant roots, ultimately affecting plant physiological and biochemical processes. This results in vegetation damage, abnormal physiological traits, and impaired growth and development. Cadmium not only inhibits plant metabolic processes but also accumulates in the edible parts of plants through root absorption and internal transport, thereby endangering both ecosystems and human health. In 2017, a serious

incident involving cadmium-contaminated rice occurred in Jiujiang, Jiangxi, which drew significant public attention to the issue of heavy metal cadmium pollution (Liu et al., 2018) [1].

To date, cadmium pollution has posed a severe threat to ecosystems, agricultural development, and public health, necessitating the exploration of remediation technologies and the resistance mechanisms of plants under cadmium stress. Soil microorganisms are a vital component of the soil ecosystem, serving not only as indicators of the ecosystem's stability in contaminated soils but also possessing great potential for environmental remediation. The biological activity of microorganisms can influence the bioavailability of heavy metals and enhance the effectiveness of phytoremediation. Microbe-plant combined remediation is an important approach for managing soil heavy metal pollution. This paper aims to investigate the mechanisms of cadmium absorption and transport in plants, uncover the molecular mechanisms of plant responses to cadmium stress, and propose effective pollution control and remediation strategies based on these findings.

2. Mechanisms of Cadmium Absorption and Transport in Plants

2.1. Cadmium Absorption Patterns in Different Plants

Different plants respond to cadmium (Cd) stress in various ways. Taking cereal crops as an example, the identification concentration for wheat's cadmium tolerance screening is set at $80 \text{ mg} \cdot \text{L}^{-1}$. Among the strains, Yunmai 399 is highly sensitive to cadmium, while 98-6188 exhibits strong cadmium tolerance (Zhong et al., 2024) [2]. Ma et al. (2024) evaluated the cadmium tolerance of 37 corn varieties, ultimately categorizing them into four types: three highly tolerant varieties, 18 moderately tolerant varieties, 12 low-tolerance varieties, and four sensitive varieties (Ma et al., 2024) [3]. Additionally, a three-year experiment on rice varieties indicated significant differences in cadmium accumulation across 13 tested rice varieties. Specifically, Yongyou 9 demonstrated high cadmium accumulation, while Yongyou 362, Yongyou 1540, and Yongyou 538 showed low accumulation characteristics (Wang et al., 2024) [4].

Economic crops are also threatened by excessive cadmium levels. Among cotton, nightshade, and Chinese cabbage, cotton exhibited the highest cadmium accumulation at $1 \text{ mg} \cdot \text{kg}^{-1}$ cadmium stress, nightshade maintained substantial accumulation at $5 \text{ mg} \cdot \text{kg}^{-1}$ cadmium treatment, and Chinese cabbage showed strong cadmium absorption and transfer abilities, with the maximum aboveground accumulation of $630.3 \text{ } \mu\text{g}/\text{pot}$ at $10 \text{ mg} \cdot \text{kg}^{-1}$ cadmium stress. Therefore, cotton, nightshade, and Chinese cabbage are suitable for phytoremediation of calcareous soils contaminated with cadmium at concentrations of 1, 5, and $10 \text{ mg}/\text{kg}$, respectively (Chen et al., 2022) [5]. Cadmium stress significantly increased cadmium content and accumulation in the aboveground parts of ryegrass, with levels notably higher than in other varieties (Wang et al., 2024) [6]. Kudzu vine is a potential cadmium-tolerant plant, demonstrating strong cadmium accumulation capacity by regulating its antioxidant system and root retention to alleviate cadmium toxicity (Lin et al., 2024) [7]. The cadmium tolerance ranking of five ginger varieties, from strongest to weakest, is Shandong ginger > Guizhou small yellow ginger > Luoping small yellow ginger > Fengtou ginger > Zhugen ginger (Wang, 2023) [8]. Understanding the cadmium absorption patterns of different plants can aid in screening and cultivating plant resources with high cadmium stress tolerance, providing genetic resources for phytoremediation of cadmium-contaminated soils.

2.2. Alleviating Cadmium Stress with Exogenous Additives

Exogenous additives are commonly used in the remediation of heavy metal contamination, including plant growth substances, polyamines, and trace elements. These substances are involved in the physiological responses of plants to stress and soil remediation. Jasmonic acid, an endogenous growth regulator in higher plants, enhances cadmium binding to soluble pectin in the root system during the

seedling stage of rice, increasing cadmium fixation in the cell wall and inhibiting its transfer to the protoplast. This reduces cadmium content in both roots and shoots. Moreover, jasmonic acid application enhances levels of antioxidant enzymes (CAT, POD, APX) and glutathione (GSH), reduces hydrogen peroxide (H_2O_2) content, and mitigates membrane lipid peroxidation damage caused by cadmium. Foliar spraying of jasmonic acid reduced cadmium transfer from stems and roots to grains, lowering grain cadmium concentrations by 29.7% and 28.0% in high-cadmium and low-cadmium fields, respectively (Li et al., 2022) [9]. Polyamines, small organic acids that regulate plant growth and development, also play a crucial role in plant responses to biotic and abiotic stress. Spermidine (Spd) inhibited the accumulation of malondialdehyde (MDA) and hydrogen peroxide in leaves, significantly improving the transport coefficient, which increased the biomass and tolerance index of ryegrass under cadmium stress by 20.90% and 20.89%, respectively (Yu et al., 2023) [10].

Foliar spraying of trace elements is often employed as an agronomic measure in plant-based remediation of heavy metal-contaminated soils to enhance plant resistance and soil remediation efficiency. Selenium, silicon, calcium, iron, and zinc are essential trace elements for plants with critical physiological functions. The application of $0.5 \text{ mg}\cdot\text{kg}^{-1}$ molybdenum reduced cadmium content in tobacco seedling leaves and roots by 17.39% and 40.00%, respectively, promoted molybdenum absorption, alleviated cadmium-induced stunted growth and leaf chlorosis, enhanced root growth, and improved photosynthesis and molybdenum enzyme activity in tobacco under cadmium stress, playing a vital role in regulating physiological metabolism under cadmium stress (Bi et al., 2024) [11]. In recent years, modified biochar has gained increasing attention in soil heavy metal remediation due to its cost-effectiveness, efficiency, in-situ applicability, and non-toxicity. Biochar has a large specific surface area, porous structure, and rich mineral content, which can remove heavy metals from soil through co-precipitation (Chen et al., 2012) [12]. Chemical adsorption is the primary mechanism by which modified biochar adsorbs cadmium, with ion exchange and functional group complexation as the main mechanisms for water hyacinth biochar (BC450) to adsorb cadmium (Zhang et al., 2017) [13]. Ion exchange likely occurs during interactions between cadmium and carbonates, with XPS showing that numerous hydroxyl and carboxyl functional groups participate in BC450's cadmium adsorption complexation process. Sugar-modified biochar (a passivator) improved soil physicochemical properties (such as pH, CEC, and SOM), increased nutrient content (AN, AP, and AK), and reduced available Cd content (Jiang et al., 2023) [14]. The application of biochar made from reed straw modified by ball-milling with potassium hydroxide and attapulgite significantly reduced cadmium availability in soil and cadmium accumulation in cultivated crops (Pan et al., 2024) [15]. Bacterial community structure is a crucial indicator of soil ecological function and fertility, with passivators providing raw materials for energy and carbohydrate metabolism of beneficial microorganisms. Applying appropriate amounts of passivators enhances microbial activity in the soil, thereby improving the absorption of Cd^{2+} in polluted soils [16]. Thus, the application of passivators increased the relative abundance of some beneficial microorganisms. These studies demonstrate that adding exogenous substances can alleviate the effects of cadmium pollution on plant growth by regulating physiological metabolism, improving soil physicochemical properties, and modulating soil microbial community structure.

3. Molecular Mechanism of Cadmium Tolerance in Plants

Plant hormones are key regulators of growth, development, and immune responses, and they play a crucial role in helping plants cope with heavy metal stress (such as cadmium pollution). These hormones include auxin (IAA), gibberellin (GA), abscisic acid (ABA), and ethylene (ETH). For instance, short-term treatment of plants with $CdCl_2$ solution can upregulate the expression of ABA synthesis-related genes (Glyma17G242200), leading to a significant increase in endogenous ABA levels (Bashir et al., 2019)[17]. ABA treatment can significantly enhance the activities of antioxidant

enzymes such as ascorbate peroxidase (APX) and peroxidase (POD) while reducing the activities of superoxide dismutase (SOD) and catalase (CAT), thereby restoring the cadmium-induced decrease in glutathione (GSH) levels (Li et al., 2014)[18]. Additionally, the application of appropriate concentrations of IAA and indolebutyric acid (IBA) can significantly reduce malondialdehyde (MDA) levels in maize seedlings, alleviating lipid peroxidation damage caused by cadmium stress (Chen et al., 2016)[19].

Plants' tolerance to cadmium stress relies on the expression of resistance genes. Studying the functions of these genes helps to reveal the mechanisms by which plants respond to cadmium stress. Several resistance genes involved in cadmium stress have already been reported. Overexpression of SIUDP in transgenic plants significantly enhances cadmium tolerance by regulating the antioxidant enzyme system, increasing reactive oxygen species (ROS) scavenging capacity, reducing membrane lipid peroxidation, and improving metal ion transport (Zhang et al., 2024)[20]. After short-term cadmium induction, the expression of the OsABCG36 gene in rice roots is significantly upregulated, indicating that OsABCG36 participates in the process of cadmium efflux and cadmium tolerance regulation in rice roots (Fu et al., 2019)[21]. The AtPDF2.5 gene may function as a positive regulator in cadmium detoxification and accumulation in plants by chelating intracellular cadmium and promoting its excretion, leading to increased cadmium accumulation in the plant apoplast (Luo et al., 2019)[22]. Additionally, silencing the TaMYB1 gene in wheat reduces malondialdehyde content and enhances antioxidant enzyme activity, thereby mitigating cadmium toxicity. Through gene editing, researchers have obtained transgenic wheat plants with enhanced cadmium tolerance (Zhang et al., 2024)[23].

Transcription factors play a key role in regulating plants' tolerance to cadmium stress. In tobacco and wild chrysanthemum overexpressing CiMYB4, cadmium accumulation and transport capacity are significantly increased, and the expression levels of cadmium-tolerance-related genes such as PCS1, GSH1, and HMA3 are markedly elevated, suggesting that CiMYB4 enhances cadmium tolerance by regulating gene expression (Li et al., 2024)[24]. Moreover, NtZIP7 and NtZIP28 possess cadmium transport capacity. Tobacco plants with silenced NtZIP7 and NtZIP28 exhibit higher chlorophyll content and antioxidant capacity, indicating reduced cadmium stress, while overexpressing lines display the opposite results (Deng et al., 2024)[25]. WRKY proteins, a plant-specific family of transcription factors, regulate the expression of downstream genes by binding to W-box elements. AtWRKY18, AtWRKY40, and AtWRKY60 negatively regulate cadmium tolerance in Arabidopsis (Liu et al., 2015)[26]. MYB transcription factors also play an important role in cadmium tolerance. Overexpression of AtMYB4 in the R2R3-MYB subfamily of Arabidopsis activates PCS1 and MT1C genes, promoting the synthesis of phytochelatin (PCs) and metallothioneins (MTs), thereby significantly reducing cadmium toxicity (Agarwal et al., 2020)[27]. Transcription factors enhance cadmium resistance in plants by regulating the antioxidant enzyme system and metal transport-related genes.

MicroRNAs (miRNAs) are small non-coding RNAs that widely participate in regulating plants' responses to environmental stress. In mustard roots, five miRNAs (miR156, miR397, miR398a, miR398b/c, and miR408) are significantly upregulated or downregulated under cadmium stress, suggesting that these miRNAs may participate in mustard's response to cadmium stress by regulating the expression of target genes such as laccase and SBP-box transcription factors (Liu et al., 2023)[28]. Ding et al. (2011)[29] identified 19 Cd-responsive miRNAs in rice under cadmium stress and found that the expression levels of these miRNAs were inversely correlated with their target genes. Expression of rice miR390 is significantly downregulated under Cd stress, while cadmium treatment induces significant upregulation of its target gene OsSRK, indicating that miR390 is a negative regulator (Ding et al., 2016)[30]. The expression levels of miR398-CSD in wheat roots and miR159-MYB3 and miR408-CLP in both leaves and roots are inversely correlated with cadmium stress

duration (Qiu et al., 2016)[31]. miRNAs help plants enhance heavy metal tolerance by regulating the expression of stress-related target genes. These discoveries provide potential targets for future genetic engineering to improve crop resistance to heavy metals.

4. Conclusion

This study explores the stress effects of cadmium, one of the major heavy metal pollutants in soil, on plant growth, development, and physiological-biochemical characteristics. By analyzing the mechanisms of cadmium absorption, transport, and cadmium tolerance in plants, it was found that different plant species exhibit significant variations in their cadmium absorption and tolerance. Furthermore, exogenous additives such as jasmonic acid, polyamines, and trace elements can alleviate the cadmium stress in plants. Plant hormones, resistance genes, transcription factors, and other elements play crucial regulatory roles in plant responses to cadmium stress, providing a theoretical basis for future pollution control and phytoremediation strategies.

In future research, several areas should be further investigated: (1) In-depth exploration of the molecular mechanisms of plant responses to cadmium stress, particularly the function of resistance genes, to reveal the mechanisms of cadmium tolerance and physiological regulation in plants; (2) Optimization of plant-microbe joint remediation techniques, investigating the bioavailability of heavy metals and their interactions with plants under cadmium stress; (3) Development of more efficient and cost-effective exogenous substances and bioremediation methods to enhance plant tolerance to cadmium stress and improve remediation efficiency.

In addressing cadmium stress, it is recommended to strengthen the screening and cultivation of highly cadmium-resistant plants. Additionally, combining microbial action with exogenous substances and bioremediation technologies could help formulate more practical pollution control and remediation strategies. These approaches will provide new solutions for agricultural production and environmental protection while ensuring food safety and the sustainable development of the ecological environment.

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