Plant Sci. Arc.
Plant Science Archives
An International Journal of Plant Biology

Short Communication
ISSN 2518-6965
www.plantarc.com

Mechanisms of Heavy Metal Tolerance in Plants: A Molecular Perspective

Sara Mathew

Department of Ethnobotany, Institute of Botany, Ilia State University, Tbilisi, Georgia.

Citation: Sara Mathew (2022). Mechanisms of Heavy Metal Tolerance in Plants: A Molecular Perspective. *Plant Science Archives*. **17-19. DOI: https://doi.org/10.51470/PSA.2022.7.2.17**

Corresponding Author: **Sara Mathew** | E-Mail: **(mathewsara121@gmail.com)**

Received 26 February 2022 | Revised 24 March 2022 | Accepted 14 June 2022 | Available Online 18 June 2022

ABSTRACT

Heavy metal contamination poses a significant threat to plant growth and productivity, impacting agricultural systems and food safety. Understanding the molecular mechanisms underlying heavy metal tolerance in plants is crucial for developing strategies to mitigate these effects. This review explores the latest advances in the molecular basis of heavy metal tolerance, including metal uptake, transport, sequestration, and detoxification. We discuss the roles of key genes, proteins, and signaling pathways involved in these processes, with a focus on phytochelatins, metallothioneins, and transporter proteins. Additionally, we highlight the genetic and biotechnological approaches used to enhance heavy metal tolerance in plants. Future research directions and potential applications for phytoremediation and sustainable agriculture are also addressed.

Keywords: *This review explores the latest advances in the molecular basis of heavy metal tolerance, including metal uptake, transport, sequestration, and detoxification.*

1. Introduction

Heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), and chromium (Cr) are toxic pollutants that can accumulate in soils and water bodies due to industrial activities, mining, and the use of agrochemicals [1-3]. These metals can be detrimental to plant health, causing oxidative stress, disrupting cellular functions, and inhibiting growth. Plants have evolved various mechanisms to tolerate and detoxify heavy metals, enabling them to survive in contaminated environments. Understanding these mechanisms at the molecular level is essential for developing crops with enhanced heavy metal tolerance and for using plants in phytoremediation efforts [4].

2. Mechanisms of Heavy Metal Uptake and Transport

2.1 Metal Uptake

Heavy metal uptake in plants primarily occurs through the roots. Transporters located in the root cell membranes play a crucial role in the selective uptake of metal ions from the soil. For instance, ZIP (Zinc/Iron-regulated Transporter-like Protein) family transporters are involved in the uptake of Zn and other metals, while NRAMP (Natural Resistance-Associated Macrophage Protein) transporters facilitate the uptake of Fe and Mn, and can also transport other metals like Cd [5].

2.2 Metal Transport

Once inside the plant, heavy metals are translocated to different tissues through the xylem and phloem. The HMA (Heavy Metal ATPase) family of transporters are key players in this process. HMA2 and HMA4, for example, are involved in Zn and Cd translocation from roots to shoots. Additionally, vacuolar transporters such as CAX (Cation Exchanger) and MTP (Metal Tolerance Protein) sequester metals into vacuoles, reducing their cytosolic concentrations and toxicity [6-7].

3. Mechanisms of Heavy Metal Detoxification and Sequestration

3.1 Phytochelatins and Metallothioneins

Phytochelatins (PCs) and metallothioneins (MTs) are small, cysteine-rich peptides that bind heavy metals and facilitate their sequestration. PCs are synthesized from glutathione in response to metal exposure and form complexes with metals, which are then transported into vacuoles by ABC (ATP-Binding Cassette) transporters. MTs, on the other hand, directly bind heavy metals through thiol groups, providing protection against metal-induced oxidative damage [8].

3.2 Antioxidative Defense Mechanisms

Heavy metals induce oxidative stress by generating reactive oxygen species (ROS). Plants combat this stress through antioxidative defense mechanisms involving enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidases (POD). These enzymes scavenge ROS and mitigate oxidative damage, contributing to heavy metal tolerance [9].

4. Signaling Pathways and Regulation

4.1 Hormonal Regulation

Plant hormones such as abscisic acid (ABA), ethylene, and jasmonic acid (JA) play crucial roles in modulating plant responses to heavy metal stress. ABA, for instance, regulates the expression of metal transporters and detoxification enzymes, enhancing metal tolerance. Ethylene and JA are involved in signaling pathways that activate defense genes and antioxidative responses [10].

4.2 Transcriptional Regulation

Transcription factors such as WRKY, MYB, and bZIP regulate the expression of genes involved in heavy metal tolerance. These factors bind to specific promoter regions of target genes, modulating their transcription in response to metal stress. Understanding the regulatory networks controlled by these transcription factors is key to manipulating plant responses to heavy metals [11].

5. Genetic and Biotechnological Approaches

5.1 Genetic Engineering

Genetic engineering has been employed to enhance heavy metal tolerance in plants by overexpressing genes encoding metal transporters, PCs, MTs, and antioxidative enzymes. For example, transgenic plants overexpressing the yeast metallothionein gene (CUP1) exhibit increased tolerance to Cd and Pb [12].

5.2 Genome Editing

CRISPR/Cas9 technology offers precise genome editing capabilities, enabling the modification of specific genes associated with metal tolerance. This approach has been used to knockout negative regulators of metal tolerance or to enhance the expression of beneficial genes [13].

6. Applications in Phytoremediation

Phytoremediation utilizes plants to remove, stabilize, or degrade pollutants from the environment. Plants with enhanced heavy metal tolerance can be used to remediate contaminated soils and water bodies. Hyperaccumulator plants, which naturally accumulate high levels of heavy metals, are particularly valuable for phytoremediation efforts. Genetic engineering and breeding programs aim to develop hyperaccumulators with improved tolerance and accumulation capacity [14-19].

7. Future Directions

Future research should focus on elucidating the complex regulatory networks governing heavy metal tolerance, identifying novel genes and pathways involved in metal detoxification, and developing crops with enhanced tolerance through advanced biotechnological approaches. Additionally, integrating omics technologies, such as genomics, transcriptomics, proteomics, and metabolomics, will provide a holistic understanding of plant responses to heavy metals [20-22].

8. Conclusion

Understanding the molecular mechanisms of heavy metal tolerance in plants is crucial for developing strategies to mitigate the adverse effects of heavy metal contamination on agriculture and the environment. Advances in genetic and biotechnological approaches hold promise for enhancing heavy metal tolerance in crops, contributing to sustainable agriculture and effective phytoremediation. Continued research and collaboration across disciplines are essential to fully harness the potential of plants in addressing heavy metal pollution.

Category	Mechanism/Strategy	Key Components	Function
Heavy Metal Uptake	Transporter Proteins	ZIP family, NRAMP family	Uptake of metals (e.g., Zn, Fe, Cd) from the soil
	Ion Channels	Various metal ion channels	Facilitate metal entry into root cells
Heavy Metal Transport	Xylem and Phloem Transport	HMA family (HMA2, HMA4), NRT1.5, YSL proteins	Translocation of metals from roots to shoots
	Vacuolar Sequestration	CAX family, MTP family	Compartmentalization of metals into vacuoles
Heavy Metal Detoxification	Phytochelatins (PCs)	PC synthase, ABC transporters	Binding and sequestration of metals in vacuoles
	Metallothioneins (MTs)	Various MT genes	Binding of metals, reducing oxidative stress
	Antioxidative Enzymes	SOD, CAT, POD, APX	Scavenging reactive oxygen species (ROS)
Signaling Pathways	Hormonal Regulation	ABA, Ethylene, Jasmonic Acid	Regulation of metal stress responses
	ROS Signaling	Various ROS-responsive genes and proteins	Activation of stress response pathways
	Calcium Signaling	Calcium-dependent protein kinases (CDPKs), Calmodulin	Modulation of metal stress responses
Transcriptiona l Regulation	Transcription Factors	WRKY, MYB, bZIP, NAC	Regulation of genes involved in metal tolerance
Genetic Engineering	Overexpression of Key Genes	Metal transporters, PCs, MTs, Antioxidative enzymes	Enhancing metal uptake, detoxification, and tolerance
	CRISPR/Cas9 Genome Editing	Targeted modification of tolerance-related genes	Precise enhancement of metal tolerance traits
Phytoremediat ion	Hyperaccumulator Plants	Thlaspi caerulescens, Arabidopsis halleri	Natural accumulation and tolerance of high metal concentrations
	Transgenic Plants	Engineered with metal tolerance genes	Enhanced metal uptake and accumulation for soil remediation
Case Studies	Overexpression of Yeast Metallothionein in Brassica juncea	CUP1 gene	Increased tolerance and accumulation of Cd and Pb
	CRISPR/Cas9 Editing of OsNRAMP5 in Rice	OsNRAMP5 gene	Reduced Cd uptake and accumulation in rice grains
Future Directions	Integrating Omics Technologies	Genomics, Transcriptomics, Proteomics, Metabolomics	Comprehensive understanding of metal tolerance mechanisms
	Multidisciplinary Approaches	Collaboration across molecular biology, genetics, and environmental science	Innovative solutions for heavy metal tolerance and phytoremediation

References

1. Clemens, S., & Ma, J. F. (2016). Toxic heavy metal and metalloid accumulation in crop plants and foods. *Annual Review of Plant Biology, 67*, 489-512.

2. Hall, J. L. (2002). Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany, 53*(366), 1-11.

3. Krämer, U. (2010). Metal hyperaccumulation in plants. *Annual Review of Plant Biology, 61*, 517-534.

4. Yadav, S. K. (2010). Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. *South African Journal of Botany, 76*(2), 167-179.

5. Sharma, P., & Dubey, R. S. (2005). Lead toxicity in plants. *Brazilian Journal of Plant Physiology, 17*(1), 35-52.

6. DalCorso, G., et al. (2013). Heavy metal toxicity and plant defense responses. *Biology, 2*(4), 164-187.

7. Hasan, S. A., & Prasad, M. (2015). Cadmium toxicity in plants and role of mineral nutrients in its alleviation. *American Journal of Plant Sciences, 6*, 856-875.

8. Song, W. Y., et al. (2010). A cadmium transport protein, OsIRT1, from rice is involved in iron and cadmium uptake and transport. *Plant Physiology, 152*(4), 1915-1925.

9. Guo, J., et al. (2014). Heavy metal lead-induced antagonistic and synergistic relationship among thallium, lead, and manganese in hydroponically cultivated crops. *Journal of Environmental Management, 143*, 154-160.

10. Ha, S. B., et al. (1999). Phytochelatin synthase genes from Arabidopsis and the yeast Schizosaccharomyces pombe. *The Plant Cell, 11*(6), 1153-1164.

11. Kim, D. Y., et al. (2007). Overexpression of yeast metallothionein in Brassica juncea enhances tolerance and accumulation of cadmium and arsenic. *Plant Biotechnology Journal, 5*(2), 167-175.

12. Zlobin, I. E. (2020). Biochemical and molecular mechanisms of plant adaptation to heavy metal stress. *Russian Journal of Plant Physiology, 67*(5), 709-726.

13. Clemens, S. (2006). Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. *Biochimie, 88*(11), 1707-1719.

14. Gill, S. S., & Tuteja, N. (2011). Cadmium stress tolerance in crop plants: Probing the role of sulphur. *Plant Signaling & Behavior, 6*(2), 215-222.

15. Xu, J., et al. (2017). Cross-talk between calcium and reactive oxygen species in heavy metal stress responses in plants. *Plant Signaling & Behavior, 12*(6), e1307458.

16. Verbruggen, N., et al. (2009). The metal hyper accumulators Arabidopsis halleri and Thlaspi caerulescens as models to study heavy metal homeostasis. *New Phytologist, 181*(4), 759-776.

17. Mendoza-Cózatl, D. G., et al. (2011). HMA2, a P1B-ATPase, plays a major role in maintaining Zn homeostasis in Arabidopsis embryos and seeds. *Plant Physiology, 156*(3), 1228-1240.

18. Rascio, N., & Navari-Izzo, F. (2011). Heavy metal hyperaccumulating plants: How and why do they do it? And what makes them so interesting? *Plant Science, 180*(2), 169-181.

19. Sharma, P., & Dietz, K. J. (2006). The significance of amino acids and amino acid-derived molecules in plant responses and adaptation to heavy metal stress. *Journal of Experimental Botany, 57*(4), 711-726.

20. Shanmugam, V., & Lo, J. C. (2012). Expression of a rice heme oxygenase gene under its native promoter confers aluminum tolerance in transgenic tobacco. *Journal of Plant Physiology, 169*(6), 598-603.

21. Tangahu, B. V., et al. (2011). A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *International Journal of Chemical Engineering, 2011*, 939161.

22. Thakur, S., et al. (2016). Phytoremediation: Role of plants in contaminated site management. *Environmental Sustainability, 1*(1), 67-78.