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OPINION ARTICLE

Effects, Response, and Tolerance to Cadmium (Cd) in Plants

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Description

Cadmium (Cd) is a heavy metal that poses significant risks to plants due to its high solubility in water and prolonged half-life. When Cd accumulates in soil, it can be absorbed by commercial crops, potentially entering the human and animal food chains. High concentrations of Cd are particularly toxic to plants, especially in the roots, where it is absorbed *via* apoplastic or symplastic pathways into the rhizodermis and root cortex, and then through the plasma membrane of the endodermis into the stele for long-distance transport.

Cd accumulation tends to be greater in the roots than in the aerial parts of the plant due to its efficient absorption and storage in root vacuoles or transport into the xylem. Like other toxic metals and metalloids, high levels of Cd can cause toxicity at physiological, morphological, and molecular levels. This can lead to a general decrease in plant growth, alterations in nutrient uptake and bioavailability, and changes in photosynthetic machinery. Physiologically, plants respond to Cd stress with shorter roots and slower growth. Cd also induces the expression of transport genes like *AtABCC3* in Arabidopsis thaliana. Upregulation of these genes can rescue the phenotype of an atabcc1 atabcc2 double knockout mutant under Cd toxicity conditions.

Cd competes with essential metallic elements like zinc (Zn), calcium (Ca), and iron (Fe) for transport, leading to mineral deficiencies and interfering with important enzyme activities, thereby inhibiting electron flow. Cd's high affinity for thiol groups allows it to react with oxygen and deplete reduced glutathione pools. High Cd concentrations also trigger elevated levels of *AtABCC3*. Both Cd and Zn are transported from roots to shoots by HMA4 and NAS2 in *A. thaliana* and *A. halleri*. *HMA4* encodes a heavy metal ATPase, while NAS2 contributes to increasing nicotinic acid, significant for metal/metalloid homeostasis.

Cd also triggers adaptive responses (AR) through metabolic blockers of protein kinase cascades, DNA repair mechanisms, oxidative stress responses, and *de novo* protein synthesis. General mechanisms of Cd tolerance in plants include:

- Reducing Cd absorption and transport from roots to shoots.
- Compartmentalizing Cd in the cell wall and chelating it in root cell vacuoles.
- Increasing antioxidant concentrations and autoxidation enzymatic activity.
- Enhancing Phyto-Chelatin (PC) synthesis and modifying heavy metal transporter gene expression.

Plants exhibit various adaptive mechanisms (uptake and exclusion transporters, organic acids (OAs), enzymatic and oxidative responses, and chelators) in response to the availability and distribution of metalloids that serve as nutrients or the presence of toxic, non-biological metals in soil. These adaptations are critical for plant responses to abiotic stress. Evolution has equipped plants with specialized mechanisms to tolerate such stresses, but domesticated crops have had to rapidly adapt to growing in contaminated soils. Research has shown that transporters and translocation machinery can be leveraged to mitigate metal/metalloid stress in both crop and non-crop plants.

A common strategy involves the use of pre-existing transporters to sequester toxic compounds within plant cells. This often occurs at the plant cell wall, the natural barrier between the plant cell and the

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rhizosphere. Under metal/metalloid toxicity, this barrier might change, highlighting the dynamic nature of plant defences.

The environmental application of these technologies could play a important role in addressing global soil pollution. Continued applied research, supported by both physiological studies and omics approaches, is essential to develop solutions for soil acidification and contamination. This is vital for preserving arable land and ensuring sustainable agricultural practices. The evolutionary specialization of plants to handle metal stress highlights the potential for leveraging these mechanisms in agricultural practices to manage soil contamination. Continued research integrating physiological and approaches is essential for developing strategies to reduce Cd toxicity and improve plant resilience, contributing to sustainable agriculture and environmental health.