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From stress to resilience: Unraveling the molecular mechanisms of cadmium toxicity, detoxification and tolerance in plants

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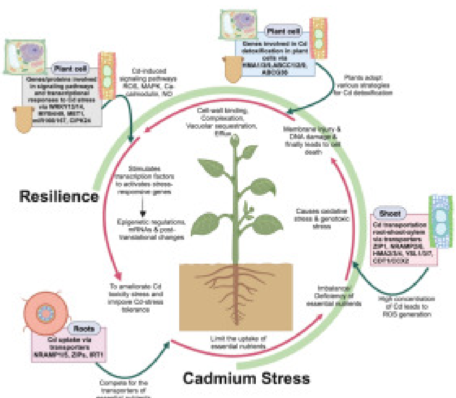
Highlights

- Plant employs multi-tiered strategies for cadmium (Cd) detoxification.
- Plants activate transporters, signaling and transcriptional responses to combat Cd stress.
- Epigenetic and post-translational modifications enhance plant Cd resilience.
- Molecular mechanisms with Cd mitigation strategies were integrated.

Abstract

Soil contamination with cadmium (Cd) has become a global issue due to increasing human activities. Cd contamination poses threats to plant growth as well as jeopardizing food safety and human health through the accumulation of Cd in edible parts of plants. Unraveling the Cd toxicity mechanisms and responses of plants to Cd stress is critical for promoting plant growth and ensuring food safety in Cd-contaminated soils. Toxicological research on plant responses to heavy metal stress has extensively studied Cd, as it can disrupt multiple physiological processes. In addition to morpho-anatomical, hormonal, and biochemical responses, plants rapidly initiate transcriptional modifications to combat Cd stress-induced oxidative and genotoxic damage. Various families of transcription factors play crucial roles in triggering such responses. Moreover, epigenetic modifications have been identified as essential players in maintaining plant genome stability under genotoxic stress. Plants have developed several detoxification strategies to mitigate Cd-induced toxicity, such as cell-wall binding, complexation, vacuolar sequestration, efflux, and translocation. This review provides a comprehensive update on understanding of molecular mechanisms involved in Cd uptake, transportation, and detoxification, with a particular emphasis on the signaling pathways that involve transcriptional and epigenetic responses in plants. This review highlights the innovative strategies for enhancing Cd tolerance and explores their potential application in various crops. Furthermore, this review offers strategies for increasing Cd tolerance and limiting Cd bioavailability in edible parts of plants, thereby improving the safety of food crops.

Graphical abstract



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Introduction

Soil contamination with toxic metals greatly affects crop production around the world. Cadmium (Cd) is most widely distributed in the earth's crust, which is considered a toxic metal for plant growth and human health (Hu et al., 2022). The primary natural source of Cd contaminants is the geological weathering of rocks, whereas the major anthropogenic sources of Cd are agrochemicals, industrial discharge, metal waste, pesticidal residues, and fossil fuels. Furthermore, improper and uncontrolled waste disposal practices, sewage water wastes, and petrochemical leakage also contribute to higher Cd concentrations in the soil (Haider et al., 2021). Consequently, Cd toxicity is becoming a global environmental hazard. Plants are the main source of Cd entry into the food chain, promoting its mobility in ecosystems and causing critical metabolic disorders in living organisms (Bouida et al., 2022). For instance, plants grown in Cd-contaminated soil readily assimilate Cd through their roots, transferring it to