Environmental Science and Pollution Research (2019) 26:22147–22158
https://doi.org/10.1007/s11356-019-05390-w

RESEARCH ARTICLE

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Cellular distribution of cadmium in two amaranth (*Amaranthus mangostanus* L.) cultivars differing in cadmium accumulation

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Received: 2 December 2018 / Accepted: 6 May 2019 / Published online: 21 May 2019

Abstract
Differences in cellular cadmium (Cd) distribution between Cd-tolerant and Cd-sensitive lines of amaranth (*Amaranthus mangostanus* L.) may reveal mechanisms involved in Cd tolerance and hyperaccumulation. We compared the cellular distribution and accumulation of Cd in roots, stems, and leaves between a low-Cd accumulating cultivar (Zibeixian, L-Cd) and a high-Cd accumulating cultivar (Tianxingmi, H-Cd) in a hydroponic experimental system. In all treatments, H-Cd grew better than L-Cd and accumulated more Cd. As the Cd concentration increased, the H-Cd plants grew normally and their biomass increased, except in the 60 μM Cd treatment. The biomass of L-Cd decreased with increasing Cd concentrations. The highest Cd concentration in the roots, stems, and leaves of H-Cd was 950 mg/kg, 305 mg/kg, and 205 mg/kg, respectively, compared with 269 mg/kg, 62.9 mg/kg, and 74.8 mg/kg, respectively, in L-Cd. The Cd distribution differed between the two cultivars. Scanning and transmission electron microscopy and energy-dispersive spectrometry analyses showed that Cd was distributed across the entire cross section of H-Cd roots but largely restricted to the epidermal cells and the exodermis of L-Cd roots. The main Cd storage sites were the root apoplast, cell walls, and intercellular spaces in H-Cd and the root epidermal cells and the exodermis in L-Cd. In H-Cd leaves, Cd accumulated mainly in vacuoles of epidermal cells and, at high external Cd concentrations, in the vacuoles of mesophyll cells.

Keywords Cadmium · Hyperaccumulation · Cellular and subcellular distribution · Electron microscopy

Introduction

Cadmium (Cd) has accumulated in agricultural soils as a result of industrial and agricultural activities and has become a serious threat to human health and environmental safety because of its high toxicity and potentially carcinogenic properties (Fu et al. 2011; Xue et al. 2014). Cadmium is readily translocated from the soil into crops and then moves into the human body via the food chain (Khaokaew and Landrot 2015; Norton et al. 2015; Rizwan et al. 2017). Therefore, the remediation of Cd-contaminated soil is a worldwide concern. Phytoextraction has emerged as a clean, simple, cost-effective, and environmentally friendly technology to remove Cd from contaminated soil (Khaokaew and Landrot 2015; Gong et al. 2018). The transport and storage of heavy metals are the most critical systems in hyperaccumulating plants because heavy metals can damage the plant before they are stored. Thus, hyperaccumulators are a topic of great interest. Hundreds of hyperaccumulators have been identified, but many grow slowly, have a low shoot biomass, and/or are poorly adapted for growth in farmland soil (Wu et al. 2004; Maestri et al. 2010). Therefore, it is important to screen for new hyperaccumulators that are suited to growth in the farmland environment, grow rapidly, and have a strong reproductive capacity (Lin et al. 2014b).

Amaranth (*Amaranthus mangostanus* L.) is native to China, India, and Southeast Asia, and it has been consumed as a wild vegetable since ancient times. It is easy to grow and resistant to drought, high humidity, and high temperature. In

The original version of this article was revised due to Retrospective Open Access cancellation.

Responsible editor: Elena Maestri

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