

Vacuolar Calcium Signaling via CAX2 Modulates Cell Wall Remodeling Under Flooding and Spaceflight-Induced Stress

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Plants rely on tightly regulated calcium (Ca^{2+}) signaling to adapt to environmental stresses, including flooding and spaceflight-induced hypoxia. Emerging evidence highlights the vacuole as a critical hub for regulating cytosolic Ca^{2+} dynamics. Key players include the cation/ H^+ exchanger CAX2, which resides on the vacuolar membrane and influences Ca^{2+} fluxes that ultimately affect downstream signaling and developmental responses.

In our studies, we investigated how CAX2 loss-of-function shapes Ca^{2+} -dependent stress responses, with a particular focus on their impact on cell wall composition and plant stress resilience. Using *Arabidopsis* as a model system, we employed spaceflight and flooding stress treatments to evaluate physiological, biochemical, transcriptomic, and glycomic responses. *cax2* mutant plants showed constitutively elevated cytosolic Ca^{2+} levels and upregulation of core hypoxia-responsive genes, even under non-stressful conditions, suggesting pre-adaptation to low oxygen environments.

A comprehensive glycomics analysis revealed distinct patterns of cell wall remodeling in the *cax2* plants. These changes differed between shoots and roots and were correlated with stress resilience and growth. Together, our findings suggest that CAX2-mediated vacuolar regulation of Ca^{2+} signaling not only modulates early stress responses but also directly influences cell wall architecture, thereby establishing a mechanistic link between intracellular ion dynamics and extracellular structural adaptations. This work advances our understanding of how vacuolar Ca^{2+} transport intersects with cell wall dynamics to enhance plant survival in extreme environments both on Earth and in spaceflight, and it opens new avenues for engineering stress-resilient crops.