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Stage-dependent Zinc Detoxification and Allocation in Rice Revealed by Zn Isotopes and Transporter Expression

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Zinc (Zn) is essential for rice but becomes toxic under excess supply, yet the processes governing Zn uptake, long-distance transport, and organ allocation remain unclear. Here we combine Zn stable isotopes (δ^{66}Zn; ε), transport efficiencies (φ), and expression of *OsZIP4*, *OsZIP1*, and *OsHMA2* to quantify Zn homeostasis across a Zn gradient at tillering and maturity. Under sufficient Zn, whole-plant δ^{66}Zn was lighter than the nutrient, indicating net uptake favoring light isotopes. Under high Zn, whole-plant δ^{66}Zn shifted heavier, consistent with preferential exclusion/export of light Zn and supported by strong *OsZIP1* induction. Shoots were consistently lighter than roots across treatments and stages, evidencing persistent kinetic fractionation during xylem loading. Development further modulated bulk flux independently of isotopic selectivity: at tillering, high Zn sharply reduced root-to-stem transport efficiency (φ_2/φ_1) while ε_2 changed little, indicating restricted translocation and enhanced root detoxification; at maturity, φ_2/φ_1 remained high with pronounced *OsHMA2* upregulation, sustaining long-distance Zn delivery. Meanwhile, Zn excess rerouted Zn away from grains and toward vegetative pools, coinciding with strong *OsZIP4* suppression in leaves. These patterns reveal a stage-dependent switch from "restricted transport and root detoxification" at tillering to "maintained transport but altered allocation" at maturity under Zn excess.

