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Silicon distribution in leaves and roots of rice and maize in response to cadmium and zinc toxicity and the associated histological variations

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Abstract

At present, the levels of cadmium (Cd) and zinc (Zn) in arable land are high and affect the growth and development of important food crops, including rice and maize. However, the application of silicon (Si) in contaminated areas increases the metal tolerance potential of these plants. This work aimed to study the variations in the distribution pattern of endogenous Si in various tissue regions in roots and leaves of rice and maize exposed to cadmium (Cd) and zinc (Zn) stresses. For these experiments, 45 day-old rice (var. Varsha) and maize (var. CoHM6) seedlings were treated with 1.95 g Zn and 0.45 g Cd kg^{-1} soil. Under Cd stress, the distribution of Si was high in the cortical region of the root, but under Zn stress, the highest Si deposition was found in the endodermis. In leaves, Si deposition was high in both the mesodermis and stelar regions of Cd-treated plants but more Si was deposited in the mesodermis tissue of Zn-treated plants. Heavy metal (Cd and Zn) accumulation and Si deposition showed a strong negative correlation in the roots of rice and maize plants. Complexation with metal ions and redistribution of Si were considered the major mechanisms in Si-mediated mitigation of Cd and Zn stress. Cd- and Zn-induced anatomical changes, such as endodermal thickening, deposits in the xylary elements and aerenchyma formation in the roots of rice and maize, were also associated with the Si distribution.

1 | INTRODUCTION

Rice and maize are the two most important crop plants in the world, and the productivity of these crop plants is adversely affected by heavy metal stress (Fahad et al., 2019). Exceeding the maximum tolerable cadmium (Cd) and zinc (Zn) concentrations in agricultural fields as a consequence of industrialization and various anthropogenic activities is a concern for rice and maize production (Fahad et al., 2019; Shahid et al., 2015). The translocation of toxic metal ions to the grains of these plants increases the possibility of hyperaccumulation of these metals in humans, which leads to bone mineralization and cancer (Ma et al., 2015). In addition, Cd and Zn toxicity negatively affects plant metabolic processes, including photosynthesis, respiration, transpiration, and nitrogen metabolism, ultimately impacting the normal growth and development of plants (Lin et al., 2016). Furthermore, these metals cause an imbalance in the ionic homeostasis of cells, resulting in the accumulation of reactive oxygen species (ROS), which induces oxidative stress in plants (Anjum et al., 2015; Islam et al., 2014). The introduction of novel strategies to mitigate the impact of the intensity of Cd and Zn stress on rice and maize growth can be considered a current need.

Silicon (Si), a metalloid, is the second most abundant element in the Earth's crust and has the ability to enhance the metal tolerance of plants. Most Gramineae members accumulate Si to an extent of 10% of their dry weight, although Si is not considered an essential element (Bhat et al., 2019; Song et al., 2014). Under different biotic and abiotic stresses, plants increase their absorption of Si from soil, highlighting the role of Si in stress tolerance (Song et al., 2011). External application of Si increases Cd

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action of Si toward heavy metals was made clear with the application of Si in heavy metal-contaminated areas, resulting in reduced uptake of heavy metals and the prevention of metal-induced lignification in the plant cell wall (Schwanz et al., 2001).

4.3 | Bioaccumulation

Exogenous application of Si has been found to alleviate Cd toxicity by reducing Cd uptake by rice roots and shoots. Likewise, the present study suggested that the endogenous Si distribution under Cd and Zn stress also plays an important role in metal tolerance. The reduction in Cd uptake in rice was due to the accumulation of more Si toward the periphery of the root, which plays a greater role in the prevention of Cd ion uptake by roots (Bhat et al., 2019). Maize roots also distributed the Si content to the root periphery but at a lower level than the Si content in the epicortical regions of rice during Cd stress, which also protects the root from the overaccumulation of Cd in roots. Therefore, the redistribution of Si to the root periphery can be considered a prominent metal tolerance mechanism in the roots of these two crop plants. Rice and maize plants distributed more Si to the endodermis and thus accumulated the least Zn in the endodermis, which helped minimize the translocation of Zn ions to xylem vessels. The increase in Zn accumulation, higher metal tolerance of rice and reduced translocation to roots indicates the potential of rice roots to stabilize more Zn ions in the roots.

The BCF value represents the ratio between the metal content within the plant and that present in the growth medium. The BCF of Zn in the control stands was high because the low Zn content in the medium resulted in the uptake of a higher proportion of Zn given it is an essential element. As the Zn content of the growth medium was high under the treatment conditions and the uptake of this element was restricted from exceeding the limit, the calculated BCF was lower in treated plants than in the control. A similar result was obtained when *Bruguiera cylindrica* was exposed to another essential element, that is, copper, where BCF was higher in the control than in the metal-treated plants (Sruthi & Puthur, 2019). However, in the case of Cd, the increase in the BCF value in treated plants indicates an increased concentration of this toxic metal in the growth medium, while the plant could regulate the uptake and transport of Cd. Similar results were found in *Acanthus ilicifolius* upon exposure to different concentrations of $CdCl_2$ (Shackira & Puthur, 2019).

5 | CONCLUSION

Endogenous Si deposition and heavy metal (Cd and Zn) accumulation showed a negative correlation in the roots of rice and maize, indicating that the partitioning of Si in the roots of these two grasses under metal stress, either by complexation with metal ions and/or by redistribution to specific tissue regions, can further prevent metal uptake. The anatomical modifications induced by the higher concentrations of Zn and Cd showed the hypersensitivity of maize versus rice toward Cd. Moreover, these anatomical modifications, specifically cell wall thickening, showed a correlation with Si distribution in rice and maize.

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AUTHOR CONTRIBUTIONS

Edappayil Janeeshma performed the analysis, processed the experimental data and interpreted the results. Jos T. Puthur provided critical feedback and helped draft the manuscript. Parvaiz Ahmad revised the manuscript to the present form.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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