5.2 Alleviation of oxidative damage

Whether increased antioxidant enzyme activity is physiologically effective ultimately depends on whether ROS accumulation is actually reduced. In a foliar Si experiment with sweet pepper, both H_2O_2 and O_2^- increased markedly under 1 500 and 3 000 ppm NaCl, but declined after Si application (Abdelaal et al., 2020). Manivannan et al. (2016) likewise reported that Si reduced H_2O_2 accumulation in salt-stressed pepper by approximately 25.6%. Thus, based on the available direct evidence, Si treatment in pepper does not simply increase measured antioxidant enzyme activities; it is also accompanied by an actual reduction in oxidative load.

Malondialdehyde (MDA) is one of the more consistent indicators of oxidative damage reported in pepper studies involving Si. In 'Bugwang', Si application reduced MDA by 29.4% under salinity stress. In 'Mızrak' pepper exposed to 100 and 150 mM NaCl, 1 mM nSi reduced MDA from 10.59 to 7.05 and from 14.74 to 10.13, respectively, corresponding to decreases of 33.4% and 31.3% (Kusvuran et al., 2024). Across these three representative comparisons, the median reduction was approximately 31.3%. Compared with growth-related traits, the direction of the MDA response appears considerably more consistent.

Improved membrane integrity generally accompanies the reduction in MDA. In the study of Manivannan et al. (2016), salinity stress increased electrolyte leakage by 38.1%, whereas Si application reduced it by approximately 33.3% relative to the salt-only treatment. The effects reported by Abdelaal et al. (2020) were even more pronounced: under 1 500 ppm NaCl, electrolyte leakage decreased from 27% to 18%, a reduction of 33.3%, while under 3 000 ppm NaCl it fell from 49% to 25%, corresponding to a decrease of about 49%. The median reduction across comparable treatments was approximately 33%. Because these parameters directly reflect membrane injury, they are generally easier to interpret than changes in a single antioxidant enzyme.

5.3 Non-enzymatic antioxidant defense and stress-related metabolites

In addition to enzymatic defense, ascorbate (AsA), glutathione (GSH), and phenolic compounds contribute to the maintenance of cellular redox homeostasis. González-García et al. (2021) found that SiO_2 nanoparticles altered leaf GPX activity as well as fruit phenolic, flavonoid, and GSH levels in sweet pepper, although the direction and magnitude of these changes varied with Si concentration and salinity level. Salinity itself can also stimulate the synthesis of some phenolic compounds. These secondary metabolites are therefore better interpreted as components of a broader defense network rather than being classified simply as beneficial whenever their concentrations increase.

Proline can stabilize proteins and membrane structures and also contributes to osmotic adjustment. However, it often accumulates strongly under severe salinity stress. Consequently, in treatments where Si provides substantial stress alleviation, lower proline levels may actually indicate a reduction in the stress experienced by the plant. Studies in other species have likewise shown that Si can either increase or decrease proline accumulation depending on salinity intensity, plant organ, and duration of exposure (Zhang et al., 2017).

Taken together, the available evidence suggests that Si acts more by rebalancing the overall cellular redox system than by regulating any single antioxidant enzyme. SOD first detoxifies O_2^-, CAT and APX further remove H_2O_2, the AsA-GSH cycle replenishes reducing power, and phenolic compounds and carotenoids contribute to non-enzymatic scavenging and energy dissipation (Basu and Kumar, 2021). Whether these responses ultimately protect cells still needs to be verified through damage-related indicators such as MDA, ROS accumulation, and electrolyte leakage. At present, relatively few studies in pepper have measured this full set of parameters simultaneously.

6 Effects of Exogenous Silicon on Ion Homeostasis and Yield in Pepper

6.1 Regulation of Na^+ and K^+ homeostasis

Limiting Na^+ accumulation is one of the more convincing mechanisms by which Si may alleviate salinity damage. Abdelaal et al. (2020) reported that in sweet pepper exposed to 1500 ppm NaCl, tissue Na content was approximately 0.40%, but decreased to 0.19% following foliar Si application. Under 3000 ppm NaCl, Na content