Silicon (Si) is not considered essential for completion of the life cycle in all higher plants, but its beneficial effects often become more evident under abiotic stress. Previous studies have associated Si application with improved root water relations, enhanced membrane stability, reduced Na^+ transport to shoots, improved K^+ retention, and modulation of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) (Zhu et al., 2019). However, Si should not be regarded as a universally effective treatment for salinity stress. Plant species differ considerably in their capacity to absorb and accumulate Si, and the magnitude of the response may vary with Si source, application rate, and method of application. Direct evidence in pepper has nevertheless increased in recent years. In 'Bugwang' pepper, Manivannan et al. (2016) found that 50 mM NaCl reduced net photosynthetic rate by 41.3%, whereas application of 1.8 mM Si substantially alleviated this decline and also reduced H_2O_2 accumulation, malondialdehyde (MDA) content, and electrolyte leakage. Similar responses were subsequently reported in salt-tolerant and salt-sensitive pepper genotypes by Altuntas et al. (2018). A sweet pepper study published in 2020 further showed that the physiological benefits associated with Si application could also be reflected in fruit yield. More recent studies conducted during 2024-2025, including work on nanosilicon and combined applications of Si with mycorrhizae or potassium, have added further evidence on antioxidant responses and yield-related effects.

This study focuses on direct experiments examining the effects of Si application on pepper under salinity stress and compares treatment responses using response ratios. An exploratory meta-analysis is conducted primarily on within-study comparisons for which original treatment means can be extracted. By quantitatively synthesizing the available evidence, this study aims to estimate the overall effects of Si application on pepper growth, photosynthetic performance, antioxidant defense, and yield, while also examining differences among response categories. The analysis explores major sources of variation in Si effectiveness, including salinity intensity, Si application rate, and genotype, with the aim of providing a more quantitative basis for future experimental design and the use of Si in salt-stressed pepper production.

2 Physiological Basis of Salinity Stress and Silicon-Mediated Tolerance in Pepper

2.1 Growth inhibition induced by salinity stress in pepper

Following NaCl exposure, the earliest response in pepper is not necessarily a marked increase in leaf Na^+ concentration, but rather a decline in the osmotic potential of the rhizosphere. Under these conditions, roots must expend more energy to acquire the same amount of water, leaf turgor decreases, and cell expansion consequently slows. At the whole-plant level, this is reflected in reduced plant height increment and restricted expansion of newly formed leaves. Root systems also reallocate growth resources in response to salinity. This salinity-induced "physiological drought" is not identical to actual water deficit, but both ultimately affect stomatal behavior and photosynthetic performance (Munns et al., 2020).

As the duration of stress exposure increases, the primary constraint gradually shifts from water uptake to ion homeostasis. Excessive Na^+ accumulation can interfere with K^+uptake, while K^+ plays important roles in stomatal regulation, enzyme activity, and osmotic adjustment (Gul et al., 2019). The uptake and homeostasis of other nutrients, including Ca^{2+}, Mg^{2+}, and phosphorus, may also be disrupted. Pepper genotypes differ considerably in their responses to these ionic disturbances. The salt-tolerant genotype P300 maintains higher K^+ and lower Na^+ levels under salinity stress, whereas the sensitive genotype 323F3 shows more pronounced Na^+ accumulation. In a long-term sweet pepper experiment, Zhang et al. (2022) found that the relatively salt-tolerant cultivar 'Quadrato D'Asti' was more effective at restricting Cl^- accumulation in green tissues. Thus, salinity tolerance is not simply a matter of taking up less Na^+; the spatial distribution and compartmentation of ions within the plant are also important.

2.2 Photosynthetic and oxidative damage induced by salinity stress

As salinity increases, chlorophyll loss and stomatal closure often occur simultaneously. In the pepper experiment conducted by Manivannan et al., 50 mM NaCl reduced net photosynthetic rate, stomatal conductance, and transpiration rate by 41.3%, 23.8%, and 19.1%, respectively. Altuntas et al. (2018) likewise observed reductions