International Journal of Horticulture, 2026, Vol.16, No.5, 353-365
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Meta-Analysis Open Access

Effects of Exogenous Silicon on Growth, Photosynthesis, Antioxidant Defense, and Yield of Pepper under Salinity Stress: A Meta-Analysis

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International Journal of Horticulture, 2026, Vol.16, No.5 doi: 10.5376/ijh.2026.16.0030
Received: 20 Aug., 2026
Accepted: 25 Sep., 2026
Published: 22 Oct., 2026
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Preferred citation for this article:
Li M.H., and Wang L.T., 2026, Effects of exogenous silicon on growth, photosynthesis, antioxidant defense, and yield of pepper under salinity stress: a meta-analysis, International Journal of Horticulture, 16(5): 353-365 (doi: 10.5376/ijh.2026.16.0030)

Abstract Salinity stress restricts pepper growth, photosynthesis, and yield, and exogenous silicon (Si) has been proposed as a potential means of alleviating salt-induced damage. Based on available experiments involving pepper under salinity stress with Si application, this study conducted an exploratory meta-synthesis using response ratios to evaluate the effects of Si on growth, photosynthesis, water relations, antioxidant defense, ion homeostasis, and yield. The results showed that Si increased shoot dry weight, net photosynthetic rate, and leaf water status by representative median values of approximately 12%, 13%, and 14%, respectively. Malondialdehyde (MDA) content and electrolyte leakage decreased by about 31% and 33%, respectively, while the activities of SOD, CAT, APX, and GR were enhanced. In sweet pepper, tissue Na^+ concentration decreased by an average of approximately 45%, and total yield increased by 44%-56% in some studies. Overall, Si can alleviate salinity damage by improving plant water status, ion balance, and antioxidant capacity, although its effectiveness is influenced by salinity level, genotype, Si source, and application method. Yield-related evidence remains limited, and future studies should emphasize multi-location and full-season experiments and adopt standardized reporting of effect sizes and variance data to improve the reliability of meta-analyses.
Keywords Pepper (*Capsicum annuum* L.); Salinity stress; Silicon; Meta-analysis; Antioxidant defense; Ion homeostasis

1 Introduction

Pepper (*Capsicum annuum* L.) is a horticultural crop that is relatively sensitive to salinity, particularly during the seedling, flowering, and fruiting stages. Salinity problems are not restricted to conventionally salt-affected soils. Under protected cultivation, repeated fertilizer inputs, irrigation with saline water, and strong soil evaporation can progressively increase salt accumulation in the root zone. Giorio et al. (2020) reported a salinity threshold for pepper of approximately 1.5 dS/m, indicating that reductions in growth and yield may occur even at relatively moderate levels of root-zone salinity. Considerable genotypic variation also exists in pepper responses to salinity stress. Under the same salinity level, some genotypes are still able to maintain fruit set, whereas others already exhibit leaf senescence, reduced plant stature, and yield loss (Ntanasi et al., 2024). Long-term evidence further suggests that salt tolerance in pepper cannot be adequately assessed from short-term seedling responses alone, because ion accumulation, reproductive development, and fruit formation over the entire growth cycle are also important components of salinity tolerance (Qiu et al., 2017).

Salinity stress initially imposes an osmotic constraint by lowering the water potential around the root system, thereby reducing the availability of water for root uptake. With prolonged exposure, the continued entry and accumulation of Na^+ and Cl^- further induce ionic toxicity (Xue et al., 2021). Together, osmotic and ionic stress disrupt several physiological processes, including stomatal regulation, chlorophyll maintenance, and CO_2 assimilation, while also promoting the accumulation of reactive oxygen species. Salt-tolerant pepper genotypes generally maintain a more favorable ionic balance, characterized by higher K^+ retention and lower Na^+ accumulation, together with stronger antioxidant capacity and osmotic adjustment. In a transcriptomic study, the salt-tolerant genotype P300 maintained higher K^+ levels, antioxidant enzyme activities, and compatible solute contents under salinity stress, while accumulating less Na^+ than the sensitive genotype 323F3. These physiological responses were consistent with the better growth performance observed in P300 (Zhang et al., 2022).