

3.2 Water and nutrient use efficiency

The effect of planting density on water and nutrient use efficiency is not monotonic, because denser stands can improve resource capture per unit area while also intensifying competition among neighboring plants. In chili pepper under precision fertigation, higher densities up to 106,666 plants/ha increased total yield and had positive effects on water use efficiency, nitrogen use efficiency, and phosphorus use efficiency, even though individual plant performance declined (Susila et al., 2025). Across crops more broadly, optimized rather than maximal density tends to give the best integrated outcome; in rainfed maize, increasing density improved leaf area index and intercepted radiation, but precipitation use efficiency, radiation use efficiency, and nitrogen use efficiency followed a parabolic response, indicating that excessive crowding raises resource demand faster than resource conversion efficiency (Zhang et al., 2021).

Resource-use responses also depend on how density changes canopy cover, transpiration, and nutrient acquisition pathways. In sweet pepper grown under greenhouse conditions, improvement of canopy light distribution by interlighting increased both light use efficiency and water use efficiency, because dry matter and fruit yield increased faster than water consumption, suggesting that density-related inefficiencies can be partly offset when more of the canopy remains photosynthetically productive (Kwon et al., 2023). Root-based studies from other crops further show that increasing planting density can shift water uptake toward the topsoil and alter the balance between water consumption and productivity, while higher density in wheat often improves nitrogen uptake per unit area but can reduce water use efficiency when evapotranspiration rises without sufficient yield compensation (Gao et al., 2022; Zhou et al., 2026).

3.3 Carbon allocation and assimilate distribution

Under density stress, yield formation depends not only on carbon assimilation but also on how efficiently assimilates are distributed between vegetative and reproductive sinks. In high-density maize, superior hybrids maintained higher net photosynthetic rate, stronger sucrose-metabolizing enzyme activity in grains, and greater leaf carbon transport efficiency, which increased the proportion of grain in total dry matter under crowded conditions (Ren et al., 2022). A broader synthesis of cereal physiology reaches the same conclusion: improvements in photosynthesis do not necessarily increase yield unless carbon allocation and sink utilization remain coordinated, because inadequate sugar transport to sinks can negate gains in source activity under stressful field conditions (Liang et al., 2023).

For pepper, available evidence suggests that density-induced shading and nutrient competition likely reshape assimilate partitioning in analogous ways. In *Capsicum*, specific leaf area responds strongly to both shading and nitrogen supply, with shading increasing SLA and nitrogen-driven metabolic changes modifying leaf thickness and density, indicating that source-leaf structure and carbon economy are highly sensitive to the same resource gradients intensified by dense planting (De Ávila Silva et al., 2021). Stress studies in other crops also show that when source limitation develops, carbon allocation can be redirected away from reproductive sinks toward survival-oriented organs such as roots, while post-anthesis yield loss is closely tied to reduced late photosynthesis and altered remobilization of stored carbohydrates, supporting the view that excessive pepper density may depress yield by disrupting assimilate flow as much as by reducing instantaneous photosynthesis (Rubia et al., 2025; Yang and Liang, 2025).

4 Effects of Planting Density on Yield Formation Components of Pepper

4.1 Flowering, fruit set, and reproductive development

Planting density affects pepper reproductive development mainly by altering the source–sink balance that supports young reproductive organs. In sweet pepper, reducing source strength through high plant density increases flower and fruit abortion linearly, and the first week after anthesis is the most abortion-sensitive stage. A broader review reaches the same conclusion that lower planting density increases assimilate availability per plant and reduces reproductive abortion, whereas abortion remains especially high in very young buds, buds near anthesis, and fruits up to 14 days after anthesis.