

Density effects on biomass accumulation are also expressed through growth rate, assimilate partitioning, and the yield components that support fruit production. In bell pepper, higher population densities decreased absolute growth rate but still increased shoot biomass accumulation per unit land area, and fruit yield per land area rose consistently with density. Greenhouse modeling work further showed that crop biomass per unit area was positively related to intercepted photosynthetically active radiation, while increasing density raised dry matter partitioning to leaves and reduced partitioning to fruits. This means that the biomass response to density is governed not only by plant competition, but also by how the denser canopy redistributes assimilates between vegetative and reproductive sinks during yield formation.

2.3 Root system development

Planting density is also expected to regulate pepper population structure belowground by modifying the space available for root expansion and the intensity of competition for water and nutrients. Although direct pepper evidence remains limited, broader plant studies consistently show that increasing density constrains root structural development. In Chinese fir, average root length and root volume were significantly greater at low and intermediate densities than at high density, indicating that crowded stands suppress root development through reduced growing space and stronger competition (Farooq et al., 2019). Similarly, rice grown at higher planting density showed a higher top-root ratio and a greater concentration of roots in the surface soil layer, indicating that root growth became relatively inferior to shoot growth and that root distribution shifted under crowding. These patterns provide a useful framework for interpreting likely root responses of pepper under dense planting.

Available pepper studies support the view that belowground responses contribute to density effects on aboveground growth and yield, even when root traits are not the primary target. In intercropped bell pepper, reduced biomass and yield were interpreted partly as consequences of stronger belowground competition for nutrients, especially under high-density conditions where nitrogen competition becomes more intense (Sandhu et al., 2021). Separate greenhouse work in sweet pepper showed that root length density is sensitive to soil physical conditions, confirming that pepper root proliferation responds measurably to changes in the rooting environment even when total dry matter production is not significantly altered (Grasso et al., 2021). Therefore, the influence of planting density on pepper root development likely operates through reduced root expansion, altered spatial distribution, and stronger competition for belowground resources, all of which can feed back on canopy growth and yield formation.

3 Effects of Planting Density on Photosynthesis and Resource Utilization

3.1 Photosynthetic characteristics

Planting density modifies pepper photosynthesis first through its effects on canopy development and the internal light environment. In bell pepper, leaf area index is a core variable for estimating canopy photosynthetic rate, and the light-intensity ratio between the upper and lower canopy declines exponentially as LAI increases, indicating that denser canopies generate stronger vertical light attenuation and less favorable light conditions for lower leaves (Lee et al., 2020). Glasshouse pepper studies similarly show that increasing plant density raises leaf area index at fruiting level but reduces photosynthetically active radiation within the canopy, confirming that the photosynthetic response to density is governed by the trade-off between greater light capture at the population level and deeper self-shading within the stand.

Once density exceeds the range that maintains balanced canopy light distribution, photosynthetic efficiency tends to decline even when total intercepted radiation increases. In maize, higher planting density significantly increased leaf area index and intercepted photosynthetically active radiation, but simultaneously reduced net photosynthetic rate, stomatal conductance, and chlorophyll content, and these changes were identified as key mechanisms behind lower productivity at excessive density (Zhang et al., 2021). Pepper evidence points in the same direction: high plant density creates poor light conditions in the middle and lower canopy through mutual shading, whereas supplemental interlighting improves vertical light distribution and increases canopy light use efficiency, showing that density stress acts largely through deterioration of within-canopy photosynthetic conditions rather than through reduced land-area light capture alone (Kwon et al., 2023).