

The agronomic consequence of these microclimate shifts depends on their intensity and spatial distribution. In Mediterranean photovoltaic cultivation, pepper experienced lower solar radiation near structures, along with reduced air temperature, lower wind speed, higher relative humidity, and lower evapotranspirative demand, yet these modified conditions were still associated with reduced shoot and fruit fresh weight in some zones, indicating that microclimate amelioration can become light limitation when shading is excessive (Tucci et al., 2025). Controlled-environment evidence likewise shows that in high-density production systems, close canopy positioning to light sources can disturb canopy temperature, humidity, and airflow uniformity, reinforcing that dense stands change not only mean microclimate but also its spatial heterogeneity, which can affect crop performance (Yu et al., 2023).

5.3 Molecular responses to density stress

At the molecular level, density stress in pepper is likely expressed through regulatory networks that are also activated by drought, heat, salinity, and osmotic imbalance, because crowding modifies light capture, water relations, and resource competition in parallel ways. Large-scale transcriptome profiling in *Capsicum annuum* across heat, cold, salinity, and osmotic treatments generated time-resolved gene expression datasets specifically intended to identify complex stress-response networks and breeding-relevant traits (Kang et al., 2020). Complementing this, a deep RNA-seq analysis across 425 pepper samples identified 1,642,007 alternative splicing events and 4,354 differential alternative splicing genes associated with environmental stressors, tissues, and signaling molecules, indicating that transcript diversification is a major component of pepper stress adaptation (Kim et al., 2024).

Specific gene families further clarify how pepper may adapt to density-related stress. In hot pepper, SR genes contain cis-elements related to abiotic stress responses, and most CaSR genes showed alternative splicing under both normal and stress conditions, supporting a role for splice regulation in environmental adaptation (Li et al., 2025). HD-Zip transcription factors and SnRK2 kinases provide additional evidence of integrative stress signaling in *Capsicum*: CaHD-Zip promoters are enriched in light-, hormone-, and stress-responsive elements, while CcSnRK2.5 enhanced drought tolerance through ABA-responsive regulation and reduced water loss, suggesting that density stress adaptation likely depends on coordinated transcriptional and hormonal control rather than on a single pathway (Wang et al., 2025; Shu et al., 2026).

6 Optimization Strategies for Planting Density Management in Pepper Production

6.1 Optimal density by cultivation system

Optimal planting density in pepper depends on cultivation system, genotype, and the trade-off between per-plant performance and yield per unit area. In protected organic sweet pepper, the highest total yield occurred at 8 plants/m² for ‘TE 300’ and ‘Timor’ and at 6 plants/m² for ‘Mallorca’, while higher density also shortened the production cycle without reducing fruit quality in two of the three genotypes (Silva et al., 2021). Under unheated greenhouse conditions, planting arrangement also changed fruit morphology, with tighter configurations producing taller plants and thinner fruits, which shows that the best density in protected cultivation must be defined jointly by yield and market traits (Xushvaqtov et al., 2024).

Open-field studies point to a similar pattern: intermediate or moderately high density is usually optimal, whereas excessive crowding reduces returns. In bell pepper, 42,000 plants/ha produced the best yield without significant quality penalties. In field-grown chili pepper, both 50,000 plants/ha and 30,000 plants/ha were identified as practical optima in different environments, indicating that recommended density should be adjusted to local climate, seedling age, and management level rather than fixed as a universal value (Setiawati et al., 2022).

6.2 Density with irrigation and fertilization

Density optimization is more effective when coordinated with irrigation and fertilizer supply, because crowding raises competition for water and nutrients even when land productivity increases. A two-year pepper study showed that integrated management combining a suitable planting density, high-yielding cultivars, and reasonable nitrogen management was a practical route to higher yield and quality, and the densest tested spacing (0.4 m × 0.6 m) increased aboveground dry matter and yield (Tian et al., 2024). Separate field evidence likewise found a