

10 plants/m² was cost-effective in summer/fall (Sievidov and Sievidov, 2020). Some locations show little response to spacing at all, as one recent field study found no significant effect of planting distance on measured growth and yield traits (Ariefin et al., 2024). Future work therefore needs ecology-specific density standards built around genotype, radiation regime, water availability, and production objective rather than a single universal recommendation (Francesca et al., 2026).

6.2 Insufficient research on the synergistic effects of planting density and other cultivation practices

A second major gap is the limited integration of planting density with other cultivation practices, even though existing studies show that these interactions can change the density optimum substantially. Density and fertilization interact strongly in greenhouse tomato: in Lam Dong, the combination of 25 000 plants/ha with the highest fertilizer rate produced the greatest fruit yield, marketable yield, and economic return (Chau and Chinh, 2021). Density also interacts with pruning and truss management in hydroponics, where the highest yield, 22.61 kg/m², occurred at 11.1 plants/m² with two bunches per plant (Cardoso et al., 2018). Field evidence similarly shows that plant density and stem pruning jointly affect performance, and under one indeterminate system the lowest density without pruning was the most practical recommendation (Maboko and Du Plooy, 2018).

The same pattern appears for grafting, irrigation, stress management, and pest control, but the literature remains fragmented. In organic tomato, rootstock use improved marketable yield per plant by more than 59%, while 2.5 plants/m² gave the better overall performance under suitable conditions (Caradonia et al., 2023). Under combined high density and drought, tomato responses became more complex: high density enhanced photosynthetic traits under adequate water, but high density plus drought reduced yield per plant more than either stress alone, indicating that density thresholds must be redefined under water limitation (Francesca et al., 2026). High-tunnel work in Virginia also suggests that irrigation or pollination, rather than light or nutrient competition, may explain yield losses at higher densities in that system (Torres-Quezada and Gandini-Taveras, 2023). In desert conditions, an intermediate spacing reduced some key insect pests and increased yield, showing that density can function as part of integrated pest management (Asiry et al., 2022). Future studies need more multifactor designs that test density together with fertigation, pruning, grafting, stress, and pest management in the same framework (Cardoso et al., 2018; Chau and Chinh, 2021).

6.3 Intelligent management based on canopy structure optimization as a future trend

A clear future direction is intelligent density management based on canopy structure optimization rather than static spacing rules. Recent work shows that canopy light interception, photosynthesis, and yield depend not only on plant number but on row orientation, spacing geometry, and the dynamic relationship between canopy structure and light distribution. In Chinese solar greenhouses, a 3D functional-structural model identified an east-west configuration with a plant distance of 0.32 m and a density of 39 000 plants/ha as optimal for mechanized planting. Modeling work also shows that total dry matter production is governed by intercepted light, that the optimal LAI depends on solar radiation, and that crop growth models can support management decisions for climate control, fertilization, and irrigation (Higashide, 2022).

The most promising systems now move from fixed density to dynamic canopy regulation. Dynamic plant spacing that maintained 75% or 90% ground coverage preserved fruit quality close to low-density treatments while greatly increasing yield per area, showing that density can be adjusted during growth to keep competition within a target range (Karpe et al., 2024). New digital tools make that strategy increasingly feasible: canopy photosynthesis models can separate the effects of canopy structure, light environment, and physiology across climates; plant factories provide stable, precisely controlled environments for density-dependent seedling production (Zhang et al., 2025); and recent greenhouse studies show that adjusting row spacing under current density can still improve accumulated canopy photosynthesis. The future trend is therefore density regulation by real-time canopy targets such as LAI, ground cover, and photosynthetic efficiency, supported by structural modeling and precision environmental control rather than fixed, one-size-fits-all spacing recommendations.