

Protected systems also allow management combinations that change the effective density optimum. Dynamic spacing in controlled-environment dwarf tomato kept plants initially dense and then reduced spacing in steps to maintain 75% or 90% ground coverage, achieving much higher yield than constant low density while preserving fruit quality close to the low-density treatment (Karpe et al., 2024). Grafting can also shift the preferred density under stress: in Qatar, grafted ‘Velocity F1’ at 3.5 plants/m² improved photosynthesis, fruit set, and marketable yield relative to nongrafted plants, while in organic field production the combination of rootstock use and 2.5 plants/m² gave the better performance under suitable conditions (Caradonia et al., 2023; Dash et al., 2023). More broadly, protected soilless systems are attractive because closed-loop, electronically managed greenhouses reduce water, nutrient, and environmental burdens, making density optimization part of a larger resource-efficiency strategy rather than a stand-alone spacing decision (D’Amico et al., 2023; Ambore, 2025).

5.3 Density regulation based on precision cultivation

Precision cultivation shifts density regulation from a fixed recommendation to a responsive control problem based on canopy status, light capture, and real-time crop feedback (Wang et al., 2026). In dynamic spacing experiments, ground coverage was measured twice weekly with smartphone imaging and plants were re-spaced when coverage exceeded preset thresholds, providing a simple operational rule for maintaining productive competition without prolonged crowding (Karpe et al., 2024). Functional-structural modeling now supports more exact optimization of spacing geometry: in Chinese solar greenhouses, simulations across row patterns, path widths, and orientations 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. For vertical farming, a dwarf tomato FSP model validated across multiple densities accurately predicted fruit dry mass, total dry mass, and leaf area index, and showed that ideotype traits affecting light distribution become density-dependent design targets (Butturini et al., 2026).

Recent sensing and autonomous-control studies show how these tools can be used in practice. Greenhouse sensor networks now monitor temperature, humidity, light, and CO₂ at multiple canopy positions and can drive predictive control models with average errors below 5%, supporting intelligent environmental regulation around the chosen plant density. IoT-based weighing and photosynthesis modeling can estimate LAI and photosynthetic LAI non-destructively with high accuracy and update biomass predictions in real time, enabling closed-loop density and canopy management (Wang et al., 2026). In autonomous dwarf-tomato greenhouse production, algorithms managed density reductions from 56 toward 42, 30, and 20 plants/m²; keeping density high for too long increased production per area but also caused stretching, canopy entanglement, thin stems, and more small fruits, confirming that precision density control must optimize morphology and operability as well as yield (Maree et al., 2025).

6 Current Research Issues and Future Development Directions

6.1 Lack of unified density standards under different ecological conditions

Planting-density standards remain difficult to unify because the reported optimum varies widely across ecological conditions, cultivation systems, and tomato growth habits. Recommended densities span about 1.1 plants/m² for open-field determinate tomato and 3.6 plants/m² for indeterminate glasshouse crops (Francesca et al., 2026). Even within protected cultivation, economic optima differ by region, including 3.7–4.4 plants/m² in northwest China, 3.5 plants/m² in a spring film greenhouse in Ukraine (Sievidov and Sievidov, 2020), and higher densities in some hydroponic systems (Cardoso et al., 2018). Open-field studies are equally inconsistent, with optima reported at 28 571 plants/ha in Bangladesh, 45 830 plants/ha in Vietnam under drip irrigation (Dinh and Dang, 2023), and 16 000 plants/ha in field-grown indeterminate tomato when costs and pruning labor were considered (Maboko and Du Plooy, 2018).

These differences reflect real biological and environmental heterogeneity rather than simple experimental noise. Hybrid-specific responses are clear in the Brazilian Savanna, where CVR-2909 and N-901 responded positively or quadratically to denser planting, but U-2006 did not respond across the tested range because its compact architecture likely limited LAI change and light interception gains (Evangelista et al., 2025). Seasonal context also matters: determinate tomato in a closed hydroponic system benefited from 25 plants/m² in spring/summer but only