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Effects of Planting Density on Plant Architecture, Fruit Setting and Yield Performance of Tomato

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Abstract Planting density is an important cultivation factor affecting tomato plant architecture, fruit set characteristics, and yield performance. This study analyzed the effects of planting density on tomato population structure, reproductive characteristics, and yield formation. Previous studies showed that planting density regulated tomato canopy development by influencing plant height, internode length, stem diameter, leaf area index, and canopy light distribution. Moderate increases in planting density generally improved light interception per unit area and land-use efficiency, whereas excessive density intensified plant competition, resulting in reduced biomass accumulation per plant, canopy closure, and decreased photosynthetic efficiency. During the reproductive growth stage, an appropriate planting density maintained the balance between vegetative and reproductive growth, maintained favorable fruit set, and enhanced fruit development. However, excessive planting density increased the risk of flower and fruit abortion due to insufficient assimilate supply and negatively affected fruit quality. In terms of yield formation, planting density regulated yield per unit area by balancing individual plant productivity and population productivity. Future tomato density management should integrate cultivar characteristics, environmental conditions, and cultivation practices, and utilize canopy monitoring, modeling prediction, and intelligent regulation technologies to achieve dynamic and precise density management. This study provides a theoretical basis for efficient tomato cultivation, population structure optimization, and precision production in protected agriculture.
Keywords Planting density; Tomato; Plant architecture; Fruit set characteristics; Yield formation

1 Introduction

Tomato production depends strongly on planting density regulation because density determines how efficiently a crop captures light, water, nutrients, and cultivation space, while also shaping fruit yield, fruit quality, and economic return. Tomato is a major crop for fresh and processing markets worldwide, and growers increasingly seek management practices that raise productivity per unit area without compromising marketability (Caradonia et al., 2023; Francesca et al., 2026). Across production systems, planting density is recognized as a core agronomic factor because excessive crowding intensifies intraspecific competition for solar radiation, water, nutrients, and physical space, whereas overly sparse stands underuse the available land area (Sievidov and Sievidov, 2020; Ayarna et al., 2021). Proper density selection can optimize light interception, improve resource-use efficiency, and increase water productivity, which is especially important in greenhouse, high-tunnel, hydroponic, and organic systems where input costs are high and production efficiency is critical (Chau and Chinh, 2021; Torres-Quezada and Gandini-Taveras, 2023). At the same time, density management also affects canopy microclimate, including shading and relative humidity, with implications for disease pressure, fruit health, and the use of plant protection inputs (Ansari et al., 2017).

The importance of density control is further reinforced by the physiological responses that tomato plants show when neighboring plants are close. Competition can begin as soon as plants detect proximity signals such as reduced light intensity, altered red:far-red balance, and leaf contact, which trigger shifts in morphology and assimilate partitioning even before severe resource depletion occurs (Karpe et al., 2024). Under dense canopies, tomato plants often express shade-avoidance traits and low-light adaptations, including stem or internode elongation, higher slenderness, thinner leaves, and increased senescence, all of which can alter plant architecture and reproductive performance (Francesca et al., 2026). Several studies also show that higher density can increase plant height while reducing vegetative biomass per plant or modifying leaf area relationships, indicating that architectural responses are central to density adaptation rather than secondary effects (Tuan and Mao, 2015; Sievidov and Sievidov, 2020; Ayarna et al., 2021). For this reason, regulating planting density is not only a matter of fitting more plants into a field or greenhouse, but also a way of steering canopy structure, source-sink balance, and the conditions under which flowers set and fruits develop (Ansari et al., 2017; Evangelista et al., 2025).

Research on the effects of planting density on tomato growth and development shows a consistent trade-off between yield per plant and yield per unit area, although the exact optimum varies with cultivar, environment, and management system. In greenhouse tomato in northwest China, increasing density reduced fruit number per plant, mean fruit weight, and yield per plant, yet total yield increased, with an economic optimum of 3.7~4.4 plants/m^2. Similar responses have been reported in hydroponic and soilless systems, where raising density increased yield per square meter but often reduced average fruit weight and shifted yield toward greater fruit number per area (Ayarna et al., 2021). Studies in field and greenhouse conditions likewise show that moderate rather than extreme densities frequently maximize marketable or total yield, with reported optima near 25 974~28 571 plants/ha, 33 000~45 830 plants/ha, or about 3.5 plants/m^2 depending on genotype and production context (Tuan and Mao, 2015; Sievidov and Sievidov, 2020; Dinh and Dang, 2023). Even so, responses are not uniform: some studies found little effect on yield per hectare, others found cultivar-specific quadratic responses, and high-tunnel trials reported yield losses per plant of 32%~46% when density exceeded the locally suitable arrangement (Maboko and Du Plooy, 2018; Torres-Quezada and Gandini-Taveras, 2023; Evangelista et al., 2025).

Beyond total yield, density also influences fruit set characteristics, marketable yield, and quality traits that are directly relevant to commercial production. Excessively high density can hamper fruit set, reduce fruit size, lower sweetness and acidity, and increase the risk of flower abortion when assimilate supply per plant becomes limiting (Karpe et al., 2024; Francesca et al., 2026). In contrast, lower or moderate densities often improve fruit set rate, fruit number per plant, and individual fruit weight, as observed in field and greenhouse studies in Vietnam and Bangladesh (Tuan and Mao, 2015; Chau and Chinh, 2021). Density effects on reproductive traits are nevertheless context-dependent: under summer heat stress, plant density did not affect fruit set in heat-tolerant hydroponic cultivars, while in a greenhouse study blossom drop decreased as density increased to 3.5 plants/m^2 (Ayarna et al., 2021). Fruit quality responses are equally nuanced. Higher density often reduces fruit size and some market attributes (Haque and Sakimin, 2022), but some studies report limited change in qualitative traits across density ranges or even gains in selected compounds such as lycopene under particular light environments (Talpur et al., 2023; Evangelista et al., 2025). These mixed findings indicate that the effect of planting density on tomato performance cannot be judged from yield alone, because architecture, flower retention, fruit set, fruit growth, and quality formation respond simultaneously and sometimes in opposite directions (Caradonia et al., 2023).

This article analyzes the effects of planting density on tomato plant architecture, fruit set characteristics, and yield performance, with particular attention to the mechanisms by which density regulation influences population structure and yield formation. Previous studies have mainly focused on individual indicators, such as total yield, planting spacing, water productivity, or fruit quality, while the integrated relationships among canopy structure, reproductive processes, and final yield formation have received comparatively less attention. By synthesizing existing evidence on plant architectural traits, flower and fruit development, and yield responses, this article examines why moderate planting densities can improve yield per unit area, whereas excessive density may result in smaller fruits, reduced marketable yield, or lower productivity per plant. Because suitable planting density is jointly affected by cultivar architecture, production environment, and associated cultivation practices, the article further discusses density optimization under different production systems and the potential application of precision management technologies. The analysis provides a reference for efficient tomato cultivation, population structure optimization, and precision density management under different production conditions.

2 Effects of Planting Density on Tomato Plant Architecture

2.1 Effects on plant morphological characteristics

Planting density clearly alters tomato plant morphological characteristics, but the direction and magnitude of change depend on genotype, stage, and production system. Across several experiments, higher density generally increased plant height or internode elongation while reducing stem thickness, compactness, or vegetative mass per plant, which is consistent with a shade-avoidance response under stronger neighbor competition. In controlled-environment tomato, increasing density promoted internode elongation and higher slenderness, while basal stem diameter declined, showing that plants became less compact as canopy crowding intensified (Karpe et al., 2024). A parallel density study under combined drought and non-drought conditions likewise found taller plants, longer internodes, reduced stem diameter, and lower leaf mass per area at high density, reinforcing that these responses are robust morphological signatures of dense planting (Francesca et al., 2026).

Field and greenhouse studies broadly support the same pattern, although not every trait responds in every environment. In Vietnam, the highest density tested produced the greatest plant height, whereas a moderate density gave better fruit set and yield, indicating that taller growth under crowding does not necessarily reflect superior whole-plant performance (Tuan and Mao, 2015). In a spring film greenhouse, increasing density raised plant height but reduced vegetative mass per plant, and the best overall biometric balance was reported at 3.5 plants/m^2 (Sievidov and Sievidov, 2020). Other studies show that density effects can be trait-specific or weak under some conditions: one field trial found significant density effects on most agronomic traits except plant height, and another reported no significant differences among planting distances for plant height, branches, leaves, flowering age, stem diameter, or harvested fruit traits (Ariefin et al., 2024). Seedling studies add that density strongly affects specific leaf area, health index, and dry matter ratios, whereas plant height and leaf area can be driven more by facility conditions than density alone (Zhang et al., 2025), so morphological responses should be interpreted in relation to environment and developmental stage.

2.2 Effects on leaf arrangement and canopy structure

Planting density reshapes leaf arrangement and canopy structure mainly by changing leaf area deployment, leaf area index, mutual shading, and the vertical distribution of light within the stand. High density increased LAI sharply in dwarf tomato, reaching 6.7 compared with about 2.1~2.2 at lower-density treatments, while also accelerating loss of shaded basal leaves (Karpe et al., 2024). The same study showed that low density produced much greater leaf area and leaf dry weight per plant, indicating that sparse stands favor larger individual canopies, whereas dense stands favor greater canopy occupation per unit ground area rather than per-plant expansion. This canopy trade-off is central to tomato density responses because canopy coverage determines light interception, but excessive crowding worsens lower-canopy shading and leaf senescence (Jiang et al., 2017).

Several studies suggest that optimum canopy structure is achieved not by maximizing density indefinitely, but by reaching an LAI range that improves interception without excessive self-shading. For processing tomato, an LAI of about 4~5 has been identified as ideal for light interception and productivity, and densification early in the season was suggested where LAI is otherwise suboptimal (Evangelista et al., 2025). In winter single-truss tomato, the densest fixed treatment produced the tallest stems but the lowest leaf area and shoot dry weight, whereas movable or lower-density arrangements improved the lower-canopy light environment (Jiang et al., 2017). Modeling work further indicates that canopy performance depends not only on density per se but also on structural traits such as internode length and leaf dimensions, because longer internodes and optimized leaf shape can improve within-canopy light penetration and interception (Zhang et al., 2022). Recent imaging research also highlights LAI as a practical structural indicator for greenhouse tomato management, although measurement accuracy can decline when leaf density and occlusion increase (Naito et al., 2025).

2.3 Effects on photosynthetic characteristics and dry matter accumulation

Planting density affects photosynthetic characteristics primarily through its control over light interception, light distribution, and assimilate availability per plant. Greenhouse synthesis shows that total dry matter production is closely linked to intercepted light, with light interception determined largely by LAI and canopy light extinction characteristics. In three-truss tomato, higher density increased fruit yield per area relative to lower density, consistent with improved interception at the crop level rather than greater productivity of individual plants (Higashide, 2022). Likewise, in dwarf tomato, increasing density raised efficiency in converting incident and intercepted light into red-ripe fruits, and total plant dry weight per square meter increased with density before saturating at the highest constant density. However, per-plant assimilate availability fell under constant high density, and final whole-plant dry weight per area was not higher than a dynamic 90% ground-cover treatment, suggesting diminishing returns once crowding becomes excessive (Karpe et al., 2024).

Photosynthetic responses themselves are nuanced, because dense canopies can increase canopy light capture while depressing photosynthesis in shaded leaves. In winter greenhouse tomato, leaf photosynthesis was higher in the movable-bench and lower-density treatments than in the fixed high-density treatment, and those treatments also maintained greater leaf area and shoot dry weight (Jiang et al., 2017). By contrast, a recent study found that high density unexpectedly enhanced photosynthetic rates despite activating shade-avoidance morphology, implying that moderate canopy shade can sometimes improve physiological efficiency depending on water status and environment (Francesca et al., 2026). Classic modeling work further suggests that plant density has a smaller direct effect on dry matter partitioning than on dry matter production, because partitioning is governed more strongly by sink strength and fruit load, while LAI simulation remains highly influential for crop growth prediction. Seedling and greenhouse studies also show that higher density can raise radiation or light-use efficiency even when individual plants are smaller (Xu et al., 2024; Zhang et al., 2025), so the architectural effect of density on photosynthesis is best understood as a balance between greater canopy capture and lower per-plant light availability. In sum, planting density modifies tomato architecture by coordinating morphological plasticity, canopy organization, and crop-level carbon gain, with moderate or dynamically adjusted densities often producing the most favorable balance between structural development and biomass accumulation (Higashide, 2022; Karpe et al., 2024).

3 Effects of Planting Density on Tomato Fruit Set Characteristics

3.1 Effects on inflorescence formation and flowering dynamics

Planting density influences inflorescence formation mainly by altering the balance between vegetative growth, assimilate supply, and the number of reproductive sites carried per unit area. In protected tomato, increasing density raised the number of trusses per ground area, but plants did not convert all additional flowers into fruits, indicating that reproductive structure formation can outpace the plant's capacity to sustain fruiting. In dwarf tomato pruned to a fixed flower number, high density still reduced reproductive success, showing that density effects persist even when the potential floral load is standardized (Karpe et al., 2024). Studies evaluating agronomic components also show that density significantly affects clusters per plant, flowers per cluster, distance between clusters, and blossom drop, confirming that flowering dynamics are structurally responsive to crop crowding.

The direction of response varies with production system and genotype. In Bangladesh field tomato, lower density increased flowers per cluster and supported higher fruits per cluster and fruits per plant, suggesting that wider spacing favors stronger reproductive expression per individual plant. In a spring greenhouse in Ukraine, density had little effect on the timing of developmental phases, indicating that planting density can modify reproductive intensity more than phenological schedule (Sievidov and Sievidov, 2020). Additional evidence from seedling-density work shows that higher nursery density later increased flower number and yield per plant after transplanting, likely because early restriction of vegetative growth redirected photoassimilates toward inflorescences in formation (Moreno-Pérez et al., 2021). More broadly, yield analyses across genotypes identify flowers per cluster and fruits per cluster as important positive contributors to yield, which helps explain why density effects on flowering traits propagate into final productivity (Muntaha et al., 2023; Ramana et al., 2025).

3.2 Effects on fruit set rate and fruit development

Planting density has a clear effect on fruit set rate and fruit development, but the response is not monotonic. Several studies found that moderate or lower densities improved fruit set, fruits per cluster, fruits per plant, and individual fruit weight. In Vietnam field conditions, 25 974 plants/ha gave the best fruit set, fruit number, fruit weight, and overall yield (Tuan and Mao, 2015). In greenhouse tomato, 25 000 plants/ha produced the highest fruit setting rate at 75.35%, along with 94.84 fruits per plant and 113.24 g average fruit weight (Chau and Chinh, 2021). A similar pattern appeared in Bangladesh, where 25 000 plants/ha maximized fruits per cluster, fruits per plant, and fruit yield per plant, while 28 571 plants/ha maximized total and marketable yield.

At higher density, tomato often compensates by increasing yield per area despite weaker per-plant fruiting. In soilless greenhouse culture, raising density to 3.5 plants/m² increased yield per square meter in all cultivars, and fruit yield per square meter correlated strongly with fruit number per plant but negatively with average fruit weight. In dwarf tomato, despite lower fruit number per plant, constant high density produced 11.1 kg/m² and 72% flower fruiting success, but fruit number per plant was lower and distal flowers were preferentially aborted, consistent with assimilate limitation during fruit set (Karpe et al., 2024). Earlier protected-cultivation work reached a similar conclusion: tomato adjusts the number of set fruits by aborting excess flowers, and 6.7 plants/m² appeared to be the upper practical limit for maximizing set fruit number under the tested leaf-to-inflorescence balance. Not all systems respond identically, however. In one field study, higher density reduced fruit number and yield per plant but did not change marketable or total yield per hectare (Maboko and Du Plooy, 2018), while under combined drought and high density, yield per plant declined even though high density alone increased yield per hectare and produced larger fruits in irrigated plants (Francesca et al., 2026).

3.3 Effects on fruit quality formation

Fruit quality formation is one of the most density-sensitive outcomes, but evidence is mixed because different quality traits respond in different directions. Strong evidence shows that constant high density reduces individual fruit size and several market traits. In dwarf tomato, high density lowered fruit fresh weight, fruit size, hardness, total soluble solids, and citric acid content, and made soluble solids less uniform across fruits. That same study found that dynamic spacing maintained quality similar to low density while preserving much higher yield per area, suggesting that quality losses are tied more to sustained crowding than to temporary canopy closure (Karpe et al., 2024). In organic field tomato, higher density reduced marketable yield per plant mainly through fewer fruits, but it also reduced fruit loss from infection, showing that density can alter fruit health as well as intrinsic quality (Caradonia et al., 2023).

Other studies indicate that some quality attributes remain stable or even improve at higher density depending on environment and trait measured. In hydroponic greenhouse tomato, density affected pericarp thickness, pH, uniform ripening, and total soluble solids, but the highest density increased TSS only in one cultivar and lowered juice pH in two cultivars, indicating a genotype-dependent quality response. Under open-field high density, fruits showed lower titratable acidity but 72.75% higher lycopene, with no difference in firmness, suggesting that denser canopies can improve selected nutritional traits even when flavor chemistry shifts (Francesca et al., 2026). Broader genetic studies help interpret this variability: fruit weight, TSS, titratable acidity, pericarp thickness, and lycopene all vary widely among genotypes and are strongly tied to yield or processing quality, so density effects on fruit quality are likely filtered through cultivar-specific sink strength and biochemical capacity (Muntaha et al., 2023; Naik et al., 2025; Ramana et al., 2025).

4 Effects of Planting Density on Tomato Yield Performance

4.1 Effects on individual plant yield and population yield

Increasing planting density generally reduces yield per plant while improving land-use efficiency and often increasing yield per unit area (Maboko and Du Plooy, 2018; Haque and Sakimin, 2022). In greenhouse dwarf tomato, constant high density produced 111 g fruit fresh weight per plant but the highest harvestable yield per area, 11.1 kg/m², showing the classic trade-off between plant-scale and area-scale productivity (Karpe et al., 2024). In Bangladesh field tomato, 25 000 plants/ha gave the highest fruit yield per plant, but 28,571 plants/ha gave the highest total and marketable yield. In Vietnam field conditions, 25 974 plants/ha produced the maximum fruit yield, indicating that moderate rather than maximal density can optimize total yield when crowding starts to depress reproductive performance (Tuan and Mao, 2015).

The density that maximizes population yield varies substantially with system and genotype (Figure 1) (Dinh and Dang, 2023). In soilless greenhouse culture, increasing density to 3.5 plants/m² raised yield per square meter in all three cultivars tested. In a spring film greenhouse, the indeterminate hybrid Tobolsk F1 reached its maximum yield of 15.8 kg/m² at 3.5 plants/m² (Sievidov and Sievidov, 2020). In Brazilian processing tomato, yield responses were hybrid-specific: CVR-2909 and N-901 responded positively or quadratically to denser stands up to 40 000 plants/ha, whereas U-2006 did not respond across 20 000~40 000 plants/ha (Evangelista et al., 2025). In contrast, one field study on indeterminate tomato found that increasing density reduced marketable and total yield per plant but did not affect yield per hectare, and the lowest density without pruning tended to be most economical (Maboko and Du Plooy, 2018).

Figure 1 Relationship between sowing densities and plant parameters (Adopted from Dinh and Dang, 2023)
Image caption: a) a sowing density of 50 000 plants/ha and b) a sowing density of 33 000 plants/ha (Adopted from Dinh and Dang, 2023)

4.2 Effects on yield components

Planting density changes yield through its effects on fruit number, fruit size, and mean fruit weight, and these components usually move in opposite directions (Cardoso et al., 2018). Higher density often lowers fruit number per plant and average fruit weight while increasing fruit number per unit area (Maboko and Du Plooy, 2018; Caradonia et al., 2023; Karpe et al., 2024). In the Golestan soilless study, fruit yield per m^2 correlated strongly and positively with number of fruits per plant but negatively with average fruit weight, showing that total yield gains under denser stands are driven more by fruit number than by fruit enlargement. In the Ukraine greenhouse study, fruit size and the yield of standard fruits declined as plant density increased, even though total yield still increased to an optimum (Sievidov and Sievidov, 2020). The same inverse pattern appears in broader review evidence: decreasing density tends to increase fruit size, whereas increasing density raises total yield only up to a threshold (Haque and Sakimin, 2022).

Several experiments quantify these component shifts under different management contexts. In hydroponic tomato, the highest total yield, 22.61 kg/m², occurred at 11.1 plants/m² with two bunches per plant, confirming that density interacts with pruning and truss number in determining sink load (Cardoso et al., 2018). Earlier processing-tomato work showed that low densities produced the most fruits per plant, but the highest process-fruit yield, 42.5 tons/acre, occurred at 78 408 plants/acre because fruit size remained relatively uniform and the larger plant population compensated for lower plant productivity. That study also found that densities of at least 9 801 plants/acre were needed to reach 30 tons/acre and that wider spacing increased sunburn and sunscald culls because reduced canopy cover exposed more fruits. More recent open-field optimization found an optimum near 45 830 plants/ha, with no significant differences in fruit weight per plant or fruit diameter across densities, underscoring that the dominant yield component can differ by cultivar and environment (Dinh and Dang, 2023).

4.3 Mechanisms of tomato yield formation under density regulation

The main mechanisms linking density regulation to tomato yield are light interception, leaf area index, dry matter production, and the balance between source supply and sink demand (Higashide, 2022). Total dry matter production is determined by intercepted light, and planting density changes yield chiefly by altering canopy light capture per unit ground area rather than by simply changing the efficiency of individual plants. In controlled tomato canopies, higher density increased plant dry weight per area and intercepted light, but whole-plant dry weight eventually saturated under constant high density, indicating diminishing returns once assimilate availability per plant becomes limiting (Karpe et al., 2024). Modeling and review work likewise identify LAI as a key control point: light interception depends on LAI and canopy extinction, simulated growth is highly sensitive to LAI, and optimal yield requires an LAI matched to solar radiation and crop stage (Figure 2) (Higashide, 2022).

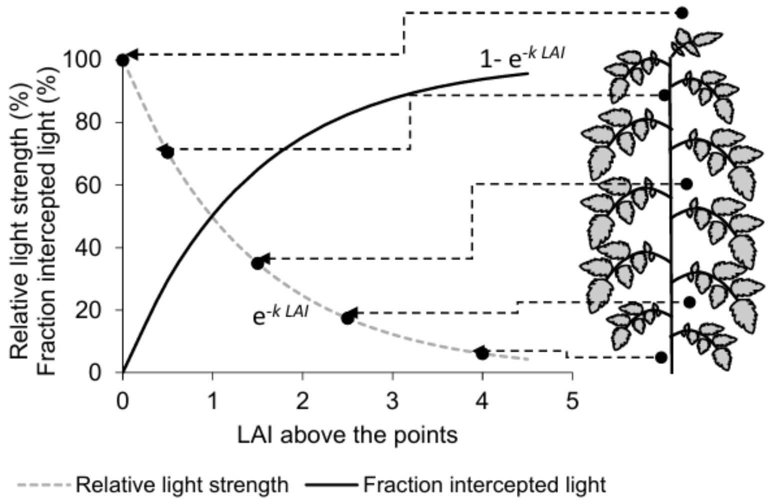

Figure 2 Relative light strength and intercepted light in a plant canopy as a function of leaf area index (LAI) at a light extinction coefficient (k) of 0.75 (Adopted from Higashide, 2022)

Density also regulates yield through dry matter partitioning and fruit sink strength, but the evidence suggests that partitioning responds more to fruit load than to density alone. Under constant high density, dry matter partitioned to fruits was slightly higher, yet fruit number per plant was lower and distal flowers were preferentially aborted, implying stronger sink demand in the remaining fruits but poorer fruit set under local assimilate shortage (Karpe et al., 2024). A classic quantitative analysis similarly found that assimilate supply altered by plant density had no direct influence on dry matter partitioning, whereas partitioning was strongly influenced by the number of fruits on the plant. Independent evidence from branching and light manipulation supports this interpretation: reduced yield can arise from smaller fruit size because of lower fruit sink strength, not necessarily because carbohydrate supply is limiting (Paponov et al., 2023). Under stress, these mechanisms shift further, since high density increased yield per hectare in the field but reduced yield per plant when combined with drought, showing that the outcome of density regulation depends on how canopy light capture interacts with water limitation (Francesca et al., 2026).

5 Optimization of Suitable Planting Density under Different Cultivation Systems

5.1 Differences in density requirements among tomato varieties

Tomato varieties differ in their density requirements because plant architecture, vigor, and sink capacity change how effectively a canopy converts added plants into added yield. In industrial processing tomato, hybrid responses were not uniform: CVR-2909 and N-901 showed quadratic or positive yield responses to increasing density, whereas U-2006 showed little response between 20 000 and 40 000 plants/ha. The weak density response of U-2006 was attributed to its smaller, more compact habit and probably lower leaf area index and light interception (Evangelista et al., 2025). In contrast, greenhouse hydroponic hybrids Dafnis, Izmono, and Hirad all produced their highest yield per square meter at 3.5 plants/m², but the size of the gain differed among cultivars, indicating shared direction but cultivar-specific magnitude.

Determinate and indeterminate tomatoes also differ in how density should be optimized across seasons and systems. For determinate cultivars in a closed hydroponic gravel-film system, spring/summer marketable yield improved at 20~25 plants/m², whereas in summer/fall 10 plants/m² was more cost-effective because higher density no longer increased yield under lower radiation. In a spring film greenhouse, the indeterminate hybrid Tobolsk F1 reached maximum yield at 3.5 plants/m², consistent with breeder recommendations centered around 2.5~3.5 plants/m² for indeterminate types under those conditions (Sievidov and Sievidov, 2020). Under summer heat in NFT hydroponics, cultivar choice also determined whether high density was useful: the heat-tolerant cultivar benefited from denser planting, while Jaguar was uneconomical because blossom end rot sharply reduced marketable yield (Ayarna et al., 2021). In organically grown hydroponic tomato under abiotic stress, grafted 'Velocity F1' at 3.5 plants/m² outperformed the denser 5.5 plants/m² treatment, showing that the optimum for vigorous indeterminate material under stress can shift downward rather than upward (Figure 3) (Dash et al., 2023).

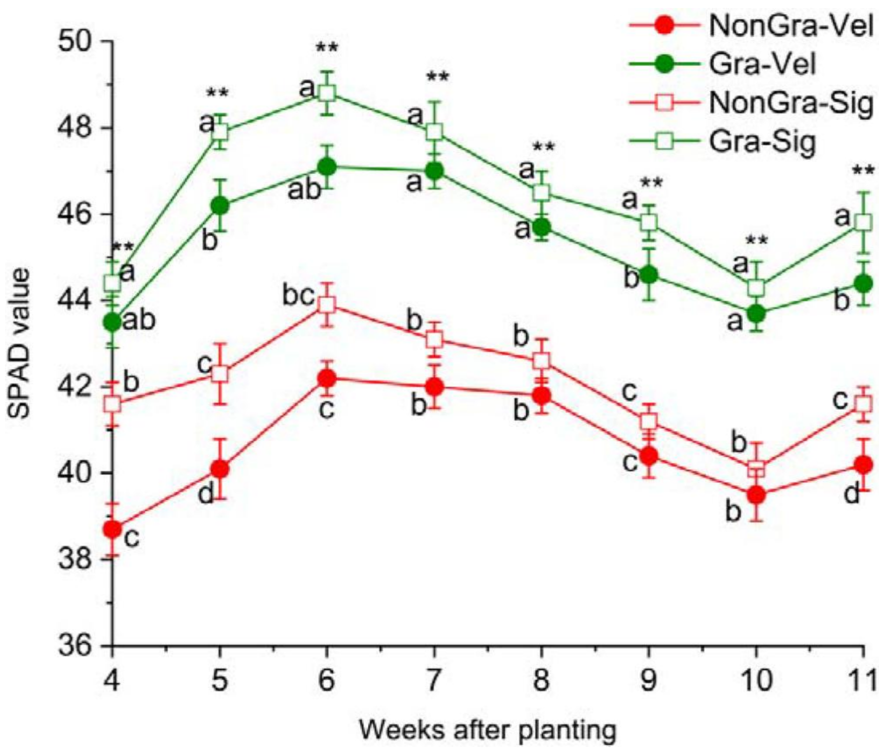

Figure 3 Effect of grafting and cultivar on the soil plant analysis development value of tomato (Adopted from Dash et al., 2023)
Image caption: Vertical bar represents the SE; Dissimilar letters on the line graph show statistical differences, the same letters show statistical similarities according to Tukey's honest significant difference test at P<0.05. NonGra-Vel=nongrafted 'Velocity F1'; Gra-Vel=grafted 'Velocity F1'; NonGra-Sig=non-grafted 'Sigma F1'; Gra-Sig=grafted 'Sigma F1'; Significant at P<0.01 (Adopted from Dash et al., 2023)

5.2 Density optimization strategies under protected cultivation conditions

Under protected cultivation, density optimization is best treated as a balance between maximizing yield per area and avoiding the fruit-size, quality, and stress penalties of chronic overcrowding (Caradonia et al., 2023; Karpe et al., 2024). In greenhouse soilless culture in Golestan, increasing density to 3.5 plants/m^2 increased yield per square meter in all three hybrids tested, supporting denser planting than the commonly used 2~2.5 plants/m² (Dash et al., 2023). In a separate hydroponic greenhouse study, the highest total yield, 22.61 kg/m², was obtained at 11.1 plants/m² with two bunches per plant, showing that optimal density in protected systems depends on pruning intensity and planned sink load as well as spacing itself (Cardoso et al., 2018). In spring film-greenhouse production, 3.5 plants/m² was likewise optimal for Tobolsk F1, while in closed hydroponic determinate tomato the best density shifted with season because high density was less beneficial under shorter days and lower radiation (Sievidov and Sievidov, 2020).

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 CO_2 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

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/m^2 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.

7 Conclusion and Prospects

Planting density regulates tomato population performance by modifying plant architecture at both the individual-plant and canopy scales. Under constant high density, tomato shows a characteristic shade-response syndrome, including internode elongation, increased slenderness, higher specific leaf area, and lower assimilate availability per plant, while total plant weight per unit area increases and then saturates. In spring greenhouse tomato, increasing density increased plant height and reduced vegetative mass per plant, with 3.5 plants/m^2 giving the best balance among vegetative mass, height, and leaf area. Variety-specific responses reinforce that architecture mediates density effects: in the Brazilian Savanna, the compact hybrid U-2006 showed little yield response to density, likely because its smaller habit limited changes in leaf area index and light interception, whereas other hybrids responded positively up to 40 000 plants/ha. Seedling studies also show that density changes structural quality early, with low density improving health index and dry matter ratio, while high density can increase radiation use efficiency, indicating that architectural regulation begins before transplanting.

Appropriate planting density promotes fruit set and yield efficiency by balancing reproductive sink demand with canopy resource capture. Moderate densities often maximize fruit set, fruit number per plant, fruit weight, and yield per plant, as shown by optima around 25 000 plants/ha in greenhouse Vietnam and 25 974 plants/ha in field Vietnam. In Bangladesh, 25 000 plants/ha maximized flowers per cluster, fruits per cluster, fruits per plant, and yield per plant, while 28 571 plants/ha maximized total and marketable yield, illustrating the consistent trade-off between plant-level and area-level productivity. Comparable patterns appear in protected systems: higher densities increased yield per square meter in hydroponic and soilless tomato, including 3.5 plants/m^2 in Golestan, 25 plants/m^2 for determinate closed hydroponics in spring/summer, and 3.7~4.4 plants/m^2 as the economic optimum in northwest China’s solar greenhouses. But when density becomes excessive, fruit number per plant, average fruit weight, and yield per plant decline, and flower abortion becomes more likely, especially for distal flowers under assimilate shortage.

Precision density management is emerging as a major direction for high-efficiency tomato production because fixed spacing recommendations cannot accommodate variation among cultivars, seasons, pruning systems, and stress environments. Dynamic spacing that maintained 75% or 90% ground coverage preserved fruit quality close to low density while more than doubling harvestable yield per area relative to constant low density, showing that density can be managed as a moving canopy target rather than a static initial decision. This logic is strengthened by evidence that density optima shift with management context, including bunch number per plant in hydroponics, fertilizer regime in greenhouse production, grafting under abiotic stress, and season in determinate closed hydroponics. New functional-structural models now identify optimal canopy configurations for mechanized greenhouses and vertical farming, including an east-west layout at 39 000 plants/ha in Chinese solar greenhouses and density-responsive ideotype design for dwarf tomato indoors. Taken together, the evidence supports a shift from uniform density recommendations toward canopy-based, cultivar-specific, and dynamically adjusted density regulation to improve yield, quality, and resource-use efficiency across tomato production systems.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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