Genomics and Applied Biology 2026, Vol.17, No.4, 213-225
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Research Insight Open Access

Effects of Planting Density on Yield Formation in Pepper

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Genomics and Applied Biology, 2026, Vol.17, No.4 doi: 10.5376/gab.2026.17.0017
Received: 10 Jun., 2026
Accepted: 14 Jul., 2026
Published: 26 Jul., 2026

Preferred citation for this article:
Yan J.Q., 2026, Effects of planting density on yield formation in pepper, Genomics and Applied Biology, 17(4): 213-225 (doi: 10.5376/gab.2026.17.0017)

Abstract Planting density is a critical agronomic factor regulating crop population structure, resource utilization, and yield formation in pepper (*Capsicum annuum* L.) production. Improper planting density can lead to excessive competition for light, water, and nutrients, resulting in reduced photosynthetic efficiency, imbalanced biomass allocation, and unstable yield performance. This review summarizes the effects and underlying mechanisms of planting density on pepper growth, physiological processes, yield components, and fruit quality. Changes in planting density influence canopy architecture, leaf area index, light interception, root development, and microclimatic conditions, thereby affecting carbon assimilation and resource acquisition. Moderate planting density optimizes source–sink relationships, improves photosynthetic capacity, enhances nutrient and water use efficiency, and promotes reproductive development, including flowering, fruit setting, and fruit expansion. Excessive density often causes canopy shading, increased disease risks, and reduced individual plant productivity, whereas insufficient density limits land resource utilization and decreases population yield potential. Furthermore, this review discusses the physiological, ecological, and molecular mechanisms involved in density-induced adaptation, as well as strategies integrating planting density with irrigation, fertilization, and precision agriculture technologies. A case study is presented to demonstrate the practical application of density optimization for improving pepper yield formation and production efficiency. Future research should focus on developing dynamic density management strategies based on cultivar characteristics, environmental conditions, and intelligent agricultural technologies to achieve sustainable and high-yield pepper production.
Keywords Planting density; Pepper production; Yield formation; Canopy architecture; Resource use efficiency

1 Introduction

Pepper is an economically important vegetable crop in which yield and fruit quality depend strongly on how efficiently light, space, water, and nutrients are captured and converted into marketable fruit. Within this production system, planting density is one of the most practical management variables because it directly determines canopy structure, radiation interception, and the intensity of competition among neighboring plants. Recent agronomic work in pepper has therefore treated density management as a central component of yield improvement strategies rather than as a simple spacing decision. In field and protected systems alike, increasing density can improve land-use efficiency and raise output per unit area, especially when it is coordinated with cultivar choice and nutrient supply (Tian et al., 2024). In organic sweet pepper, higher planting density has likewise been proposed as a way to reduce production costs and increase fruit production within limited physical space, highlighting its relevance not only for biological productivity but also for production economics and system sustainability (Silva et al., 2021).

The relationship between planting density and pepper yield formation is complex because yield per unit land area and yield per plant do not respond in the same way. Multiple studies show that as density increases, total yield per hectare often rises, whereas individual plant performance tends to decline because each plant has access to fewer resources. In sweet pepper grown under field conditions, increasing plant density reduced fruit weight, fruit volume, and yield per plant, yet total yield per hectare still increased, indicating a compensatory population effect (Aminifard et al., 2012). Comparable patterns were reported in paprika pepper, where yield per hectare increased mainly because fruit number per unit area increased with density, while fruit number and dry fruit weight per plant declined and gains became marginal beyond very high densities, suggesting the existence of an agronomic optimum rather than an unlimited positive response.

Yield formation under different planting densities is further mediated by changes in crop architecture, dry matter accumulation, and assimilate partitioning. Evidence from bell pepper indicates that higher population density increases fruit yield per land area and that node number is a major yield component underlying density responses, pointing to structural adjustment of the plant population as a key mechanism of productivity change. Greenhouse research also shows that density alters leaf area index, canopy interception of photosynthetically active radiation, and dry matter partitioning between vegetative and reproductive organs; specifically, leaf dry matter partition increases and fruit dry matter partition decreases as density rises, while harvest index remains closely related to cumulative intercepted radiation. Together, these findings suggest that pepper yield formation under density stress depends not only on plant number, but also on how effectively the crop canopy captures light and directs assimilates toward fruit production.

Against this background, a review of planting density effects on yield formation in pepper is timely because published results indicate both broad agreement and important context dependence across cultivars, production systems, and target quality traits. For example, organic protected cultivation showed that higher densities increased yield and shortened the production cycle without necessarily reducing fruit size or quality in some genotypes, with the highest yields occurring at 6 to 8 plants/m^2 depending on genotype (Silva et al., 2021). In greenhouse bell pepper, marketable yield responded positively and linearly to increased density even though fruit set per plant declined, reinforcing that optimal density must be defined at the crop-population level rather than at the single-plant level. Therefore, the objective of this review is to synthesize current evidence on the importance of planting density management in pepper production, clarify the mechanisms linking density to yield formation, and identify how density interacts with genotype, canopy traits, and cultivation environment to shape both productivity and fruit quality.

2 Planting Density Regulation and Population Structure of Pepper

2.1 Canopy architecture and light interception

Planting density directly regulates pepper population structure by changing canopy closure, leaf area development, and the spatial pattern through which incoming radiation is distributed within the crop. In greenhouse sweet pepper, canopy light interception increased progressively after planting and reached about 92% at maturity, showing that dense, trained pepper stands can capture most incident radiation once the canopy is fully developed. Density also shapes canopy size through its effect on leaf area index, which follows a logistic increase after planting and reaches density-dependent maxima under protected cultivation. Together, these results indicate that population density is not simply a numerical stand attribute, but a structural regulator of canopy formation that determines how quickly pepper crops occupy space and intercept available light.

The effect of density on light interception depends not only on plant number but also on canopy geometry and within-row shading. In glasshouse pepper, light transmission below the canopy varied strongly by position and time of day, with much less light beneath rows than in the gaps between them, indicating that denser canopies create pronounced internal light gradients. At the same time, studies of pepper growth under modified light environments show that reduced light promotes taller plants and wider crowns through increases in canopy spread and branching, which helps explain why density-driven crowding often induces architectural adjustment as plants compete for radiation (Febrianto et al., 2024). Thus, the influence of planting density on pepper light capture operates through both canopy closure and plastic changes in plant architecture.

2.2 Plant growth and biomass accumulation

Planting density alters the balance between individual plant growth and biomass production per unit land area. Field evidence in sweet pepper shows that increasing density reduces vegetative growth traits such as lateral stem number and leaf dry matter, while also lowering fruit weight and yield per plant, even though total yield per hectare increases (Aminifard et al., 2012). A similar trade-off was reported under open-field conditions in another pepper study, where higher densities produced taller plants and greater total fruit production, whereas lower densities improved yield per plant and the proportion of marketable fruit. These findings show that density intensifies competition among neighboring plants, shifting performance away from individual vigor and toward collective productivity per unit area.

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).

3.2 Water and nutrient use efficiency

The effect of planting density on water and nutrient use efficiency is not monotonic, because denser stands can improve resource capture per unit area while also intensifying competition among neighboring plants. In chili pepper under precision fertigation, higher densities up to 106,666 plants/ha increased total yield and had positive effects on water use efficiency, nitrogen use efficiency, and phosphorus use efficiency, even though individual plant performance declined (Susila et al., 2025). Across crops more broadly, optimized rather than maximal density tends to give the best integrated outcome; in rainfed maize, increasing density improved leaf area index and intercepted radiation, but precipitation use efficiency, radiation use efficiency, and nitrogen use efficiency followed a parabolic response, indicating that excessive crowding raises resource demand faster than resource conversion efficiency (Zhang et al., 2021).

Resource-use responses also depend on how density changes canopy cover, transpiration, and nutrient acquisition pathways. In sweet pepper grown under greenhouse conditions, improvement of canopy light distribution by interlighting increased both light use efficiency and water use efficiency, because dry matter and fruit yield increased faster than water consumption, suggesting that density-related inefficiencies can be partly offset when more of the canopy remains photosynthetically productive (Kwon et al., 2023). Root-based studies from other crops further show that increasing planting density can shift water uptake toward the topsoil and alter the balance between water consumption and productivity, while higher density in wheat often improves nitrogen uptake per unit area but can reduce water use efficiency when evapotranspiration rises without sufficient yield compensation (Gao et al., 2022; Zhou et al., 2026).

3.3 Carbon allocation and assimilate distribution

Under density stress, yield formation depends not only on carbon assimilation but also on how efficiently assimilates are distributed between vegetative and reproductive sinks. In high-density maize, superior hybrids maintained higher net photosynthetic rate, stronger sucrose-metabolizing enzyme activity in grains, and greater leaf carbon transport efficiency, which increased the proportion of grain in total dry matter under crowded conditions (Ren et al., 2022). A broader synthesis of cereal physiology reaches the same conclusion: improvements in photosynthesis do not necessarily increase yield unless carbon allocation and sink utilization remain coordinated, because inadequate sugar transport to sinks can negate gains in source activity under stressful field conditions (Liang et al., 2023).

For pepper, available evidence suggests that density-induced shading and nutrient competition likely reshape assimilate partitioning in analogous ways. In *Capsicum*, specific leaf area responds strongly to both shading and nitrogen supply, with shading increasing SLA and nitrogen-driven metabolic changes modifying leaf thickness and density, indicating that source-leaf structure and carbon economy are highly sensitive to the same resource gradients intensified by dense planting (De Ávila Silva et al., 2021). Stress studies in other crops also show that when source limitation develops, carbon allocation can be redirected away from reproductive sinks toward survival-oriented organs such as roots, while post-anthesis yield loss is closely tied to reduced late photosynthesis and altered remobilization of stored carbohydrates, supporting the view that excessive pepper density may depress yield by disrupting assimilate flow as much as by reducing instantaneous photosynthesis (Rubia et al., 2025; Yang and Liang, 2025).

4 Effects of Planting Density on Yield Formation Components of Pepper

4.1 Flowering, fruit set, and reproductive development

Planting density affects pepper reproductive development mainly by altering the source–sink balance that supports young reproductive organs. In sweet pepper, reducing source strength through high plant density increases flower and fruit abortion linearly, and the first week after anthesis is the most abortion-sensitive stage. A broader review reaches the same conclusion that lower planting density increases assimilate availability per plant and reduces reproductive abortion, whereas abortion remains especially high in very young buds, buds near anthesis, and fruits up to 14 days after anthesis.

The effect of density on flowering time itself appears weaker and more variable than its effect on subsequent fruit retention. In open-field pepper, higher density did not significantly change flowering time, although it tended to increase yield in the first harvest and in total production. Likewise, in chilli pepper, planting density showed no significant effect on most reproductive timing and yield-related traits other than plant height, indicating that temperature, genotype, and sowing date can override density effects on flowering and fruit set under some field conditions (Mends-Cole et al., 2019).

4.2 Yield components and final yield formation

Planting density consistently shifts pepper yield formation from per-plant performance toward per-area productivity. In sweet pepper, increasing density reduced fruit volume, fruit weight, and yield per plant, but total yield per hectare still increased, with the highest yield recorded at the closest spacing tested (Aminifard et al., 2012). Direct-seeded paprika pepper showed the same pattern: fruit number and dry fruit weight per plant declined as density increased, while yield per hectare rose because the number of fruits per unit area increased.

The yield response is not unlimited, and several studies indicate a density optimum beyond which competition suppresses final production gains. In chili pepper, increasing plant population from 20,000 to 30,000 plants/ha raised total fruit yield by 52.58%, but yield then declined by 34.09% at 40,000 plants/ha (Setiawati et al., 2022). Bell pepper trials across five densities also found that fruit yield per land area increased with density, and yield-component analysis identified node number as the component most responsive to population density, linking final yield gains to structural changes in reproductive site formation.

4.3 Fruit quality characteristics

The interaction between planting density and fruit quality is genotype- and trait-dependent rather than uniform across pepper types. In an organic protected system, higher density increased yield and shortened the crop cycle without impairing fruit size or quality in the ‘TE 300’ and ‘Timor’ genotypes, although ‘Mallorca’ responded less favorably at densities above 4 plants/m^2 for fruit mass (Silva et al., 2021). Glasshouse pepper showed similarly limited density effects on commercial quality traits, with fruit weight, length, diameter, volume, dry matter, soluble solids, and flesh pH unaffected by plant density and shoot number.

Other quality traits respond more sensitively to denser planting, especially in pungent or processing peppers. In paprika pepper, pigment content declined linearly as density increased even though moisture content at harvest remained unchanged, so the agronomic optimum was defined by both yield and color retention. In field-grown pungent pepper, the spacing that produced the highest yield per area also increased capsaicin and dihydrocapsaicin content, while Jalapeño pepper maintained fruit quality under denser planting even as acidity-related traits shifted modestly (Paulus et al., 2015; Ragassi et al., 2019).

5 Physiological and Ecological Mechanisms Underlying Density-Driven Yield Formation

5.1 Hormonal regulation and plant developmental responses

Planting density changes pepper development by altering the hormonal control of shoot expansion, root growth, and the transition between vegetative and reproductive growth. In *Capsicum*, plant architecture traits such as plant height and leaf size are tightly linked to endogenous hormone regulation, and transcriptome analysis has identified differential expression in auxin, gibberellin, cytokinin, abscisic acid, jasmonic acid, ethylene, and salicylic acid signaling pathways associated with structural variation (Xing et al., 2024). More generally, auxin and cytokinin act as a central antagonistic pair in regulating the shoot-to-root growth ratio, with cytokinin favoring shoot growth and limiting root growth, whereas auxin promotes root development and improves adaptation to water and nutrient limitation, a balance that is directly relevant when higher density intensifies above- and belowground competition (Kurepa and Smalle, 2022).

Hormonal effects on developmental plasticity also extend to reproductive allocation and stress buffering in pepper. Under salinity, contrasting rootstock-mediated yield responses in pepper were associated with shifts in hormonal balance, with higher leaf cytokinin concentrations clustering with productivity traits and the ethylene precursor ACC showing the opposite pattern, indicating that hormonal rebalancing can sustain fruit production under stress

(Gálvez et al., 2021). At the organ level, pepper fruit size depends strongly on early auxin and cytokinin accumulation that promotes rapid cell division, while high gibberellin accumulation supports later pericarp cell elongation and expansion, showing how hormone-regulated developmental processes can translate canopy resource status into final yield components (Figure 1) (Tang et al., 2025).

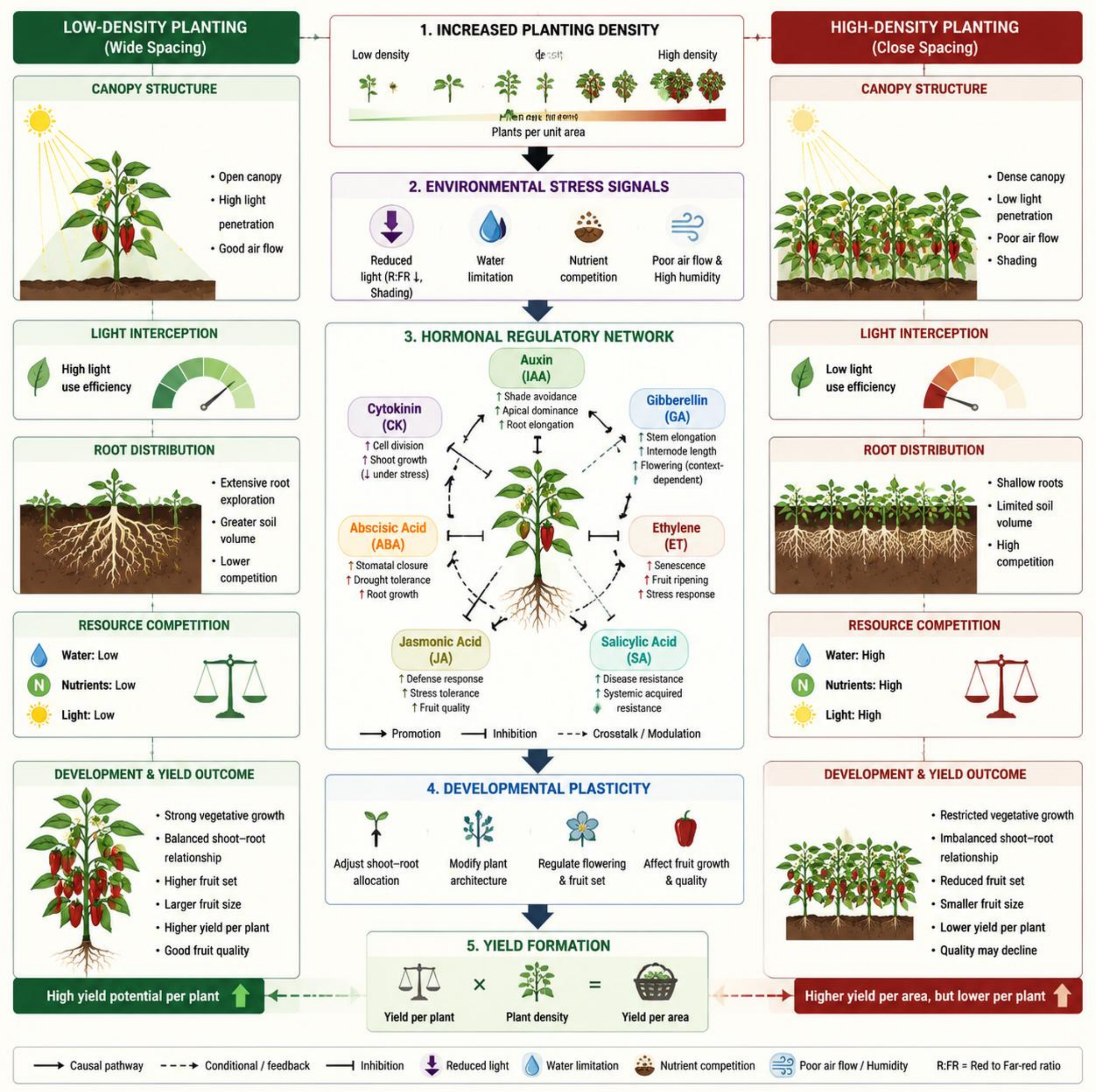

Figure 1 Conceptual model illustrating the regulation of pepper (*Capsicum annuum* L.) development by planting density-mediated hormonal pathways

5.2 Microclimate changes within pepper populations

Density-driven yield formation is also mediated by microclimate changes within the crop stand, especially shifts in light, temperature, and humidity. Studies on pepper-related systems show that denser or more shaded canopies reduce irradiance and temperature while increasing relative humidity, thereby creating a cooler but less illuminated internal environment (Oliosi et al., 2021). This general canopy effect is consistent with broader microclimate evidence showing that higher crown density is strongly associated with lower light intensity and temperature and with higher humidity, which helps explain why dense pepper populations often experience reduced evaporative demand but greater within-canopy shading (Kartika and Marjenah, 2023).

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/m^2 for ‘TE 300’ and ‘Timor’ and at 6 plants/m^2 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 significant density × nitrogen interaction for fruit volume and fruit weight, confirming that density recommendations should be linked to fertilizer regime rather than chosen independently (Aminifard et al., 2012).

Recent irrigation studies reinforce that the best density is the one matched to a specific water-delivery system. Under automated protected cultivation, sensor-based irrigation at 75% available soil moisture combined with 125% recommended fertilizer produced 60,089 kg/ha and the highest water and nutrient use efficiencies (Ningoji et al., 2024). In precision-fertigated chili pepper, higher densities up to 106,666 plants/ha increased total yield and improved WUE, NUE, and PUE, but double drip lines raised yield while reducing water use efficiency, showing that irrigation layout can shift the agronomic optimum for density (Susila et al., 2025).

6.3 Precision technologies

Precision agriculture offers a way to regulate planting density more dynamically by linking stand establishment, canopy monitoring, and input delivery to spatial variability within the crop. In greenhouse pepper, sensor networks and machine-learning-based control systems are being developed to improve decision-making, resource use, and sustainability, while fertigation regimes tailored to crop response already improve productivity under monitored microclimate conditions (Fadare et al., 2025). More broadly in vegetable systems, integrating weather stations, soil sensors, and remote sensing into decision-support systems helps farmers evaluate crop growth, yield potential, and resource use, which is directly relevant for refining density management over time (Chaudhari et al., 2024).

Remote sensing and automation are especially useful for translating density management from fixed spacing recommendations into site-specific regulation. Remote sensing in precision agriculture supports crop monitoring, irrigation management, nutrient application, and yield prediction, and UAV platforms are increasingly favored because they provide high-resolution imagery needed for practical management decisions (Sishodia et al., 2020). In parallel, automated seeding and transplanting systems can improve the uniformity of plant spacing and reduce labor costs, which makes them a practical tool for achieving target pepper populations more accurately than manual establishment (Chaudhari et al., 2024).

7 Case Study: Effects of Different Planting Densities on Pepper Yield Formation

7.1 Experimental background and planting density treatments

Pepper density case studies have been conducted across open-field, greenhouse, protected organic, and soilless production systems, and they consistently use multi-level density gradients to quantify how stand structure affects yield formation. In protected organic sweet pepper, experiments compared three genotypes at 2, 4, 6, and 8 plants/m^2 in a duplicated randomized complete block design, while bell pepper trials in Canada tested 1.4, 1.9, 2.8, 5.6, and 11.1 plants/m^2 under mulch and row-cover conditions to capture both density and microenvironment effects (Silva et al., 2021). These designs are useful as case-study models because they span both moderate and very high densities and therefore allow identification of the point where greater land occupancy ceases to improve biological or commercial performance.

Other studies show that density treatments are also shaped by establishment method and local production practice. In field-grown sweet pepper, four spacing combinations—20 × 50, 30 × 50, 20 × 100, and 30 × 100 cm—were combined with nitrogen treatments, whereas direct-seeded paprika pepper was thinned to a very broad density range from 13,333 to more than 500,000 plants/ha, enabling evaluation of both yield and color responses under commercial-scale plant populations (Figure 2) (Aminifard et al., 2012). Together, these case studies show that meaningful density evaluation in pepper requires treatment ranges wide enough to detect not only yield increases at low-to-moderate crowding but also the threshold where competition begins to offset further gains.

7.2 Responses of growth characteristics and yield components

Across case studies, increasing planting density generally shifts pepper growth toward greater population productivity but weaker individual plant performance. In sweet pepper, higher density reduced vegetative and reproductive traits at the plant level, including lateral stem number, leaf dry matter, fruit volume, fruit weight, and yield per plant, even though total yield per hectare increased (Aminifard et al., 2012). A similar pattern was observed in paprika pepper, where fruit number and dry fruit weight per plant declined as population increased, while yield per hectare rose because fruit number per unit area increased. This confirms that density-driven yield formation depends less on maximizing the performance of each plant than on increasing the number of productive units occupying a given area.

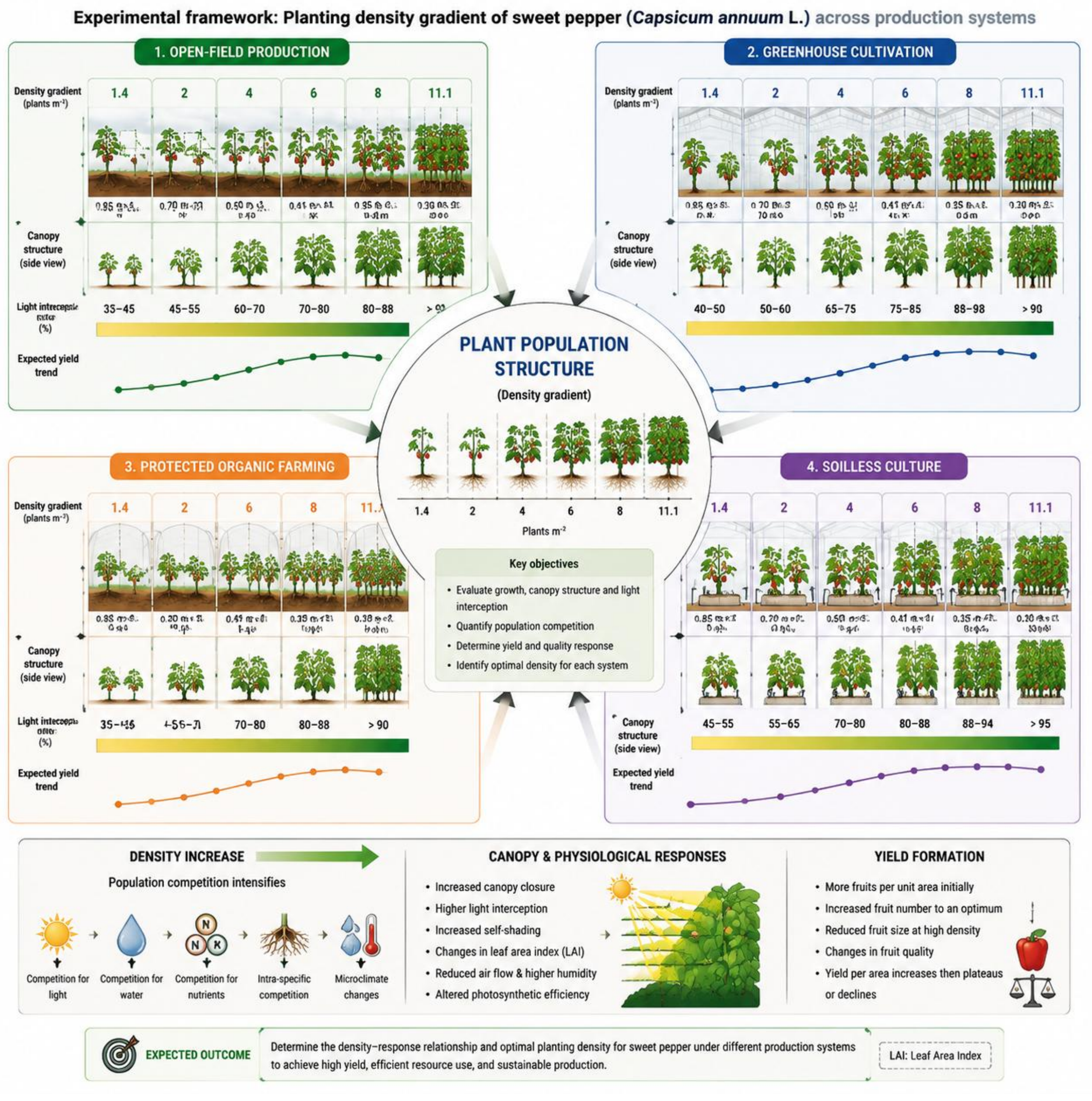

Figure 2 Conceptual framework of pepper density experiments across different production systems

Not all responses are linear, and several case studies identify clear biological limits to crowding. In chili pepper, raising density from 20,000 to 30,000 plants/ha increased total fruit yield by 52.58%, but increasing to 40,000 plants ha^{-1} caused yield to decline by 34.09%, showing that excessive competition can reverse the yield advantage of denser planting (Setiawati et al., 2022). Greenhouse bell pepper supports the same interpretation at the reproductive level: marketable yield increased linearly with density, but fruit set per plant decreased linearly as density increased, indicating that total yield gains arise from stand-level compensation rather than improved reproductive success of individual plants.

7.3 Optimal density and production implications

The optimal planting density in pepper is therefore context-specific, but most case studies favor an intermediate-to-moderately high density rather than the lowest or most crowded treatment. In bell pepper grown in the Caspian Sea region, 42,000 plants/ha produced the best yield without significant quality penalties, while a more recent field study in the Northern Guinea Savannah identified 50,000 plants/ha as the best compromise between plant competition and land-use efficiency. These findings suggest that the agronomic optimum is usually the density that preserves enough per-plant growth to maintain fruit size and reproductive function while still increasing fruit number per unit area.

Production implications also depend on genotype and cultivation system. In protected organic cultivation, the best total yields were obtained at 8 plants/m^2 for 'TE 300' and 'Timor' and 6 plants/m^2 for 'Mallorca', showing that cultivar-specific adaptation to crowding is a practical determinant of density recommendations (Silva et al., 2021). In glasshouse pepper, 80 × 15 cm with two shoots per plant was suggested for maximum yield, whereas 80 × 30 cm with three shoots per plant was considered more economical when seed cost was high, indicating that density optimization should be integrated with pruning strategy and production costs rather than based on spacing alone. Overall, pepper yield formation is best supported by densities that intensify land use without pushing the crop into excessive competition, and the exact optimum should be calibrated to genotype, establishment method, and management system.

8 Conclusions and Future Perspectives

Across pepper systems, higher planting density generally increases total yield per hectare by increasing fruit number per unit area, even though fruit number or fruit mass per plant declines. In sweet pepper, greater density reduced fruit volume, fruit weight, and yield per plant but increased total yield, while in direct-seeded paprika pepper the yield gain from density was specifically driven by more fruits per hectare. This positive response is not unlimited, and most studies support an intermediate or moderately high density rather than maximum crowding. Chili pepper yield increased by 52.58% when population rose from 20,000 to 30,000 plants/ha but declined by 34.09% at 40,000 plants/ha, and a separate field study identified 50,000 plants/ha as the best balance between plant competition and land-use efficiency.

Density effects on yield formation also depend on genotype and cultivation system because varieties differ in their tolerance to competition and their ability to maintain fruit quality. In protected organic production, 'TE 300' maintained yield per plant across 2-8 plants/m^2 and, together with 'Timor', achieved its highest total yield at 8 plants/m^2, while 'Mallorca' performed best at 6 plants/m^2. At the physiological level, density influences yield formation through canopy light interception, resource competition, and reproductive success. Higher density increased leaf area index but reduced photosynthetically active radiation within the canopy in glasshouse pepper, and in sweet pepper reduced source strength was directly associated with higher flower and fruit abortion.

Future density research in pepper should move from single-factor spacing trials toward integrated designs that test density together with cultivar choice, fertilization, irrigation, and establishment traits. A recent two-year field experiment showed that suitable density, high-yield cultivars, and optimal nitrogen management jointly improved yield, nutrient uptake, and quality, while another study showed significant interactions between plant density and nitrogen for fruit volume and fruit weight. More work is also needed on density responses under advanced production systems, where the economic optimum may differ from the biological optimum. In greenhouse pepper, 80 × 15 cm with two shoots per plant was suggested for maximum yield, but 80 × 30 cm with three shoots per plant could be more economical when seed is expensive, and 3D ray-tracing models have been proposed to determine stem density and supplemental lighting levels during cultivation.

A second research priority is to improve site-specific density management using sensing and geospatial tools. Precision approaches that integrate soil attributes with NDVI can delineate management zones for more efficient decision-making, and automated sensor-driven irrigation and fertigation already improve pepper growth, yield, and resource-use efficiency under protected cultivation. Future studies should also expand the trait set used to define optimum density beyond yield alone to include harvestability, weed suppression, and quality preservation.

Higher density improved plant architecture and the percentage of marketable fruit for mechanical harvest in New Mexico green chile, whereas a moderate density of 37,037 plants ha⁻¹ in chili pepper improved yield while also providing moderate weed suppression.

For sustainable pepper production, the main implication is that optimized density can increase land productivity without proportionally increasing resource use, but only when density remains within the crop's tolerance range. Under precision fertigation, higher chili densities up to 106,666 plants ha⁻¹ increased total yield and had positive effects on water, nitrogen, and phosphorus use efficiency, while in rainfed maize moderate density rather than excessive density improved yield stability and resource-use efficiency, offering a useful principle for pepper systems. Sustainability also depends on matching density to microclimate management and climate stress adaptation. Moderate shading improved pepper productivity in some environments, but increasing shade intensity to 60% could reduce fruit yield or fruit number, showing that dense canopies and protective structures must be managed to avoid turning stress protection into light limitatio. At the production-system level, density optimization can support profitability, labor efficiency, and lower input waste when paired with modern management. Mechanized pepper systems showed that reduced planting density improved working conditions while maintaining strong productivity in some settings, and sustainability assessment of greenhouse pepper in southeastern Spain found that a high-productivity system can remain environmentally and economically robust when adapted to changing inputs and resistant cultivars.

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