

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/m² for 'TE 300' and 'Timor' and 6 plants/m² 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/m² and, together with 'Timor', achieved its highest total yield at 8 plants/m², while 'Mallorca' performed best at 6 plants/m². 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.