

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/m² 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