2.3 Physiological responses of citrus trees

At the leaf level, photosynthesis is strongly influenced by the local light environment. In citrus canopies with a clear vertical light gradient, upper leaves are usually close to light saturation, while lower leaves receive less light and therefore have lower net CO_2 assimilation rates.

Measurements across canopy layers under different citrus cultivation systems show that in traditional systems and wide-row-narrow-spacing systems, photosynthetic rate, stomatal conductance, and transpiration all decrease from the upper canopy to the lower canopy. In contrast, in systems with more uniform light distribution, such as hedgerow systems, lower leaves can maintain relatively high photosynthetic activity. In these improved canopy structures, higher photosynthetic nitrogen use efficiency (PNUE) indicates better coordination between light capture, nitrogen allocation, and photosynthetic capacity.

Besides photosynthesis, changes in microclimate and resource availability caused by planting density also affect plant hormone balance and growth patterns. Endogenous hormones such as auxin, cytokinin, gibberellin, and abscisic acid play key roles in regulating apical dominance, shoot elongation, branching, and the balance between vegetative and reproductive growth (Dhurve et al., 2025).

In dense canopies, changes in light quality (low red to far-red ratio) and increased shading trigger shade-avoidance responses through phytochrome signaling. This promotes shoot elongation, alters branching patterns, and shifts assimilate allocation toward stems (Jin et al., 2021; Murchie and Burgess, 2022). In contrast, more open canopies and moderate planting densities help maintain a more balanced hormonal environment.

3 Effects of Planting Density on Citrus Yield

3.1 Relationship between yield per tree and yield per unit area

In tropical fruit crops, including citrus, high-density planting usually leads to lower yield per tree but higher yield per unit area, especially during the early to mid-bearing stages.

In acid lime, ultra-high-density planting (1 600 trees·hm^{-2}) showed the lowest yield per tree, but the yield per unit area was more than twice that of conventional density (400 trees·hm^{-2}). By the fifth year, the maximum yields reached 35.36 t·hm^{-2} and 11.64 t·hm^{-2}, respectively (Ladaniya et al., 2020).

In Nagpur mandarin, a spacing of 2 × 2 m produced much higher yields per unit area during the first three years—26 times, 7.1 times, and 4.6 times higher than conventional planting—although the yield per tree decreased (Ladaniya et al., 2021).

In sweet orange, long-term experiments compared densities ranging from 513 to 1 000 trees·hm^{-2} under different rootstock vigor conditions. Increasing planting density consistently reduced yield per tree, especially with vigorous rootstocks. However, over a 9-year period, the cumulative yield per unit area at 1 000 trees·hm^{-2} increased by about 27%, and this trend was not affected by rootstock type (Girardi et al., 2021).

3.2 Fruit quality parameters

In sweet orange, smaller spacing (such as 2.40 × 4.50 m compared with 4.50 × 6.00 m) increased yield per unit area but reduced trunk growth and fruit size. However, total soluble solids (TSS), acidity, and juice content were not significantly affected in some studies (Haque and Sakimin, 2022).

In 'Ray Ruby' grapefruit under HLB conditions, high-density planting (975 trees·hm^{-2}) increased fruit acidity by 18%, and soluble solids content was also higher than in low-density planting (300 trees·hm^{-2}). This suggests that under disease pressure and intensive nutrient management, high density may even improve some quality traits (Phuyal et al., 2020). Across two growing seasons, fruit acidity and soluble solids content at 975 trees·hm^{-2} were consistently higher than those at 300~440 trees·hm^{-2}.

3.3 Yield stability and long-term productivity

Experiments conducted in Japan, Florida, and Australia across a wide range of planting densities (e.g., 1 250~10 000 trees·hm^{-2} for Satsuma mandarin and 359~718 trees·hm^{-2} for sweet orange in Florida) showed that the maximum annual yield at maturity was generally similar (about 50~100 t·hm^{-2}).