At very high densities, yield tended to decline over time due to increased competition and shading (Wheaton et al., 1995). In long-term comparisons over more than 20 years, moderate density (e.g., 2 500 trees·hm^{-2} in Japan) performed better than extremely high density.

In high-density trials (2 020 trees·hm^{-2}) involving ‘Hamlin’, ‘Valencia’, ‘Murcott’, and grapefruit, yields reached 23~75 t·hm^{-2} after 7 years. Under Florida conditions, densities above about 1 000 trees·hm^{-2} did not show clear long-term advantages compared with moderate densities (350~900 trees·hm^{-2}) (Wheaton et al., 1991).

4 Effects of Planting Density on Tree Vigor

4.1 Vegetative growth characteristics

Tree height, canopy volume, and shoot growth show clear responses when plant spacing is reduced. Studies on citrus high-density planting (HDP) indicate that trees in dense orchards are usually taller but have smaller lateral canopy spread. This is mainly because competition for light promotes vertical growth, while limited space restricts horizontal expansion.

For example, in cultivars such as Kinnow mandarin, high-density planting increases tree height. However, under wider spacing, individual trees develop larger canopy volumes, since they can grow with less competition and maintain a more “natural” canopy structure.

In high-density Nagpur mandarin orchards (2 × 2 m), the highest planting density resulted in the tallest trees and the greatest interception of photosynthetically active radiation (PAR). However, the leaf area index (LAI) was the lowest, suggesting that the canopy became narrow and upright rather than well-layered (Ladaniya et al., 2021).

Young sweet orange trees also show faster canopy development under high-density conditions. When planting density increased from 447 trees·ha^{-1} to 897 trees·ha^{-1}, the leaf area per tree almost doubled during orchard establishment. Under sufficient irrigation, canopy volume also increased more rapidly in high-density treatments (Hamido and Morgan, 2020).

4.2 Root development

Irrigation experiments on citrus trees grown at different densities in sandy soils show that moderate irrigation (about 78%~81% ETc) improves fine root length density (FRLD), root survival, and lifespan. These effects are more obvious under low to medium densities. However, even at higher densities, root development remains good as long as water is not severely limited (Atta et al., 2024).

A study on 16-year-old ‘Pineapple’ sweet orange trees under different spacings (3.0 × 4.6 m, 4.6 × 6.1 m, and 6.1 × 7.6 m) showed that roots can extend to at least 1.9 m depth and are well distributed both within and between rows (Castle, 1980). Root density is highest in the topsoil and decreases with depth. Trees planted at wider spacing have lower root density, while at medium spacing, roots from neighboring trees tend to overlap. Under these soil and water conditions, root competition is not a major limiting factor in high-density citrus orchards.

Studies using minirhizotron techniques also show clear differences in root distribution among rootstocks. These differences are important for high-density systems. For example, trifoliate orange produces finer roots that grow deeper and closer to the trunk, while hybrid rootstocks such as Rusk citrange and sweet orange tend to have shallower or more horizontally spread roots (Zheng et al., 2024).

Fine roots are mainly concentrated in the 0~30 cm or 0~45 cm soil layers, but their vertical and horizontal distribution varies depending on the rootstock. This means that dwarfing or semi-dwarfing rootstocks not only affect shoot growth but also change how roots occupy soil space, which in turn influences root overlap and competition in dense orchards.

4.3 Susceptibility to pests and diseases

In high-density and ultra-high-density acid lime orchards, the incidence of leaf miner and bacterial canker is higher compared to traditional spacing (5 × 5 m). However, fruit quality is not significantly affected (Ladaniya et al., 2020).