Dense orchards usually have thicker canopies and higher LAI, which leads to more shading and longer leaf wetness duration. These conditions are closely related to increased disease risk.

Research on Huangguogan orchards shows that reducing planting density from 2 × 3 m to 4 × 5 m significantly changes the microenvironment. Under lower density, photosynthetically active radiation increases by more than 400%, while air and soil temperatures rise slightly, and air humidity and CO_2 concentration decrease (Dong et al., 2020).

In contrast, high-density orchards are usually cooler, more humid, and more shaded. These conditions favor the development of fungal and bacterial diseases and also reduce the effectiveness of pesticide penetration and drying.

Although higher root density can improve water and nutrient use efficiency, dense canopies make pest and disease control more difficult. This often requires more frequent or more precise spraying, and sometimes smaller equipment is needed to work in narrow row spacing.

5 Interaction Between Cultivar and Rootstock

5.1 Differences in cultivar adaptation to high-density planting

Different citrus cultivars vary greatly in growth habit and vigor, which directly affects how well they adapt to high-density systems. In a high-density trial with 2020 trees per hectare, studies on 'Hamlin' sweet orange, 'Valencia' sweet orange, 'Murcott' tangor, and 'Redblush' grapefruit showed that cultivars with moderate vigor, upright growth, and early bearing performed best. In contrast, those with overly strong vigor or excessive dwarfing performed poorly (Wheaton et al., 1991). Among them, 'Murcott' showed good adaptability because of its naturally small size and upright canopy. However, even under high-density conditions, it still showed clear alternate bearing. Grapefruit, which has the strongest vigor, produced relatively high yields under dense planting, but its canopy becomes difficult to manage in the long term.

In experiments with 'Valencia' sweet orange grafted onto 51 hybrid rootstocks, many dwarfing and semi-dwarfing combinations showed high productivity. However, some small-tree combinations were more sensitive to drought and had lower yields under rainfed conditions (Costa et al., 2021). For 'Shamouti' sweet orange, when grafted onto weak rootstocks such as 'Swingle' and 'C-13', the suitable planting density can reach about 337~363 trees ha^{-1}. In contrast, when grafted onto vigorous rootstocks like 'Rangpur', 'Sunki', or 'Cleopatra', trees become much larger (>4.2 m), making them suitable only for lower planting densities (Carvalho et al., 2022).

5.2 Effects of rootstocks on tree size and vigor

Rootstock selection is a key tool to match tree vigor with planting density. In a 9-year 'Valencia' trial in Brazil, four rootstocks with different vigor levels were tested: super-standard IAC 1710, standard diploid Swingle, semi-dwarf IAC 1697, and dwarf tetraploid Swingle. Even under the same density (513~1 000 trees ha^{-1}), there were large differences in tree size and yield (Girardi et al., 2021). Trees grafted onto the most vigorous rootstock produced about 2.5 times more fruit per tree than those grafted onto dwarf tetraploid Swingle. However, regardless of rootstock type, increasing density to 1000 trees ha^{-1} still raised cumulative yield per area by about 27%.

Fruit quality was influenced more by rootstock than by planting density, and dwarfing rootstocks often increased soluble solids content. It is also worth noting that the cumulative incidence of HLB symptoms on the vigorous IAC 1710 rootstock was about twice that on dwarf Swingle 4×. This suggests that smaller trees may be easier to manage under disease pressure. Dwarfing rootstocks such as 'Flying Dragon', 'US-897', 'FA 517', and 'HTR-051' are widely considered key tools for high-density orchards. They can limit tree height to about 2.5 m and reduce canopy volume to 40%~60% (semi-dwarf) or less than 40% (dwarf) of standard trees (Hayat et al., 2022).

A detailed physiological study of 'Shatangju' mandarin grafted onto 11 rootstocks showed that 'Flying Dragon' causes strong dwarfing by reducing node number, shortening internodes, and decreasing trunk diameter. This is also linked to changes in hormones and metabolites, such as lower ABA and GA levels and altered organic acids